

# Hadronic interactions and extensive air showers

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**Abstract.** Understanding hadronic multiparticle production is important for deriving the composition and energy spectrum of primary cosmic rays from air shower measurements at high energy. In this article, predictions of hadronic interaction models are discussed, emphasizing uncertainties and constraints due to model assumptions and accelerator measurements. The sensitivity of shower observables to model predictions is illustrated by considering two representative examples, the electron/muon shower size at different detection altitudes and the longitudinal shower profile, and the need for measuring several observables of each shower is stressed.

## 1. Introduction

The overall characteristics of air showers induced by hadrons and photons is determined by the physics of electromagnetic (em.) interactions. In a typical shower – except at very small and very large slant depths – em. particles are by far the most abundant particles and carry in total almost all of the energy of the shower. Therefore it is not surprising that the em. component of hadron- and photon-induced showers is qualitatively very similar in the energy range up to the ankle. For example, the shower profiles can be well described by a Gaisser-Hillas parametrization [?], only the parameters are different. Even the mean number of particles at shower maximum varies by less than 20% and many distributions are universal when measured as function of the shower age parameter [?, ?, ?, ?].

For determining the primary energy, the limited sensitivity of the em. shower component to the primary particle type is of advantage and, for example, made it possible to estimate shower energies in the past even without modern simulation tools (i.e. [?]). However, deriving the primary energy with an uncertainty of less than 20%, without considering the measurement uncertainties, or determining the primary particle mass turns out to be very difficult. The influence of the poorly known characteristics of hadronic particle production on the shower evolution together with the stochastic nature of particle interaction, production and decay processes lead to a significant systematic uncertainty. In fact, in recent experiments [?, ?, ?] the total uncertainty of composition analyses of EAS data is dominated by the uncertainty coming from the modelling of hadronic interactions. Moreover, there is no method known that allows

one to reliably estimate the range of uncertainty due to our limited understanding of hadronic multiparticle production.

In this article we will discuss the modelling of hadronic particle production in EAS, focussing on questions related to the reliability and predictive power of these models.

## 2. Characteristics and models of hadronic multiparticle production

So far it is impossible to calculate hadron production at low transverse momenta from first principles within QCD and one has to resort to phenomenological models. In the following the most promising model concepts are briefly introduced.

At low energy ( $E_{\text{lab}} < 5 \text{ GeV}$ ), close to the particle production threshold, hadronic interactions can be well described by resonance production and subsequent resonance decay. Depending on the spin of the resonance, particle production appears almost spherically symmetric, similar to a fireball. Knowing all relevant resonances for a given projectile-target combination and their decay channels and partial decay widths allows one to obtain a complete description of both interaction cross sections and hadron production. Collisions involving nuclei are understood on the basis of elementary hadron-hadron interactions whereas the hadron (i.e. proton and neutron) configurations are given by the wave functions of the nuclei and the impact parameter of the collision.

At higher energy particle production becomes highly asymmetric. Most particles are produced along the beam axis (projectile direction). Therefore it is not surprising that it is practically impossible to describe hadron production by resonances: even if the resonance parameters would be known, too many resonances of very short lifetime have to be considered. Instead, phenomenological string models like the Dual Parton Model (DPM) [?] or the Quark-Gluon Strings (QGS) Model [?] seem to be the most efficient way to describe particle production. String models also provide a natural explanation of the experimentally observed *leading particle effect*, e.g. a large fraction of the incoming particle momentum is carried by a secondary particle that contains at least one constituent (one or several quarks) of the projectile.

In string models, projectile and target particles are thought to be built up of color-charged objects (constituents). Due to exchange of color charge in the interaction process, the color constituents of the projectile get connected with the corresponding constituents of the target by color flux tubes, called strings. Finally, the successive fragmentation of these strings leads to hadron production.

In the intermediate energy range ( $5 \text{ GeV} < E_{\text{lab}} < 500 \text{ GeV}$ ), particle production is dominated by one- or two-string configurations and the number of model parameters is small. Assuming universality of string fragmentation and hadronization, one can use data from  $e^+e^-$  annihilation to tune the parameters of the string fragmentation model. Further parameters are related to the momentum distributions of the projectile/target constituents and the fraction of diffractive events, in which one or both of the scattering partners are excited to a higher state without color charge exchange. In addition, the cross section has to be parametrized, which is typically done using Reggeon and Pomeron

amplitudes.

At high energy ( $E_{\text{lab}} > 500 \text{ GeV}$ ), experimental data can only be described by also allowing for configurations of more than two strings. Such configurations are expected from general unitarity arguments and are naturally included in the DPM and QGS model. Furthermore, with increasing energy, hard interactions of quarks and gluons become more and more important. They are characterized by large momentum transfer (jet production) and can be calculated in perturbative QCD. For not too high an energy the number of quarks and gluons in a hadron is process-independent and can be described by an universal parton distribution function. Typically a transverse momentum cutoff,  $p_{\perp}^{\text{cutoff}}$ , is introduced to separate processes that can be treated in perturbation theory from soft interactions. This cutoff is an important parameter of the models and is, depending on the model, chosen to be constant or a function of the collision energy. However, only the inclusive cross section can be calculated in pert. QCD. The average jet multiplicity per collision is known from theory but the distribution of the jet multiplicity has again to be taken from phenomenological models.

Finally it should be mentioned that there are a number of conceptual, open problems of how to combine consistently the different treatments of soft and hard interactions in a single scattering amplitude. Only in a self-consistent scheme that satisfies general constraints such as unitarity and includes diffraction dissociation, it is possible to use the pert. QCD jet cross section to predict the total, elastic and diffractive hadron-hadron cross sections. Most models apply for this purpose Gribov's Reggeon theory [?]. Recent work focusses on improvements of this approximation and different approaches have been put forward [?, ?], see also [?].

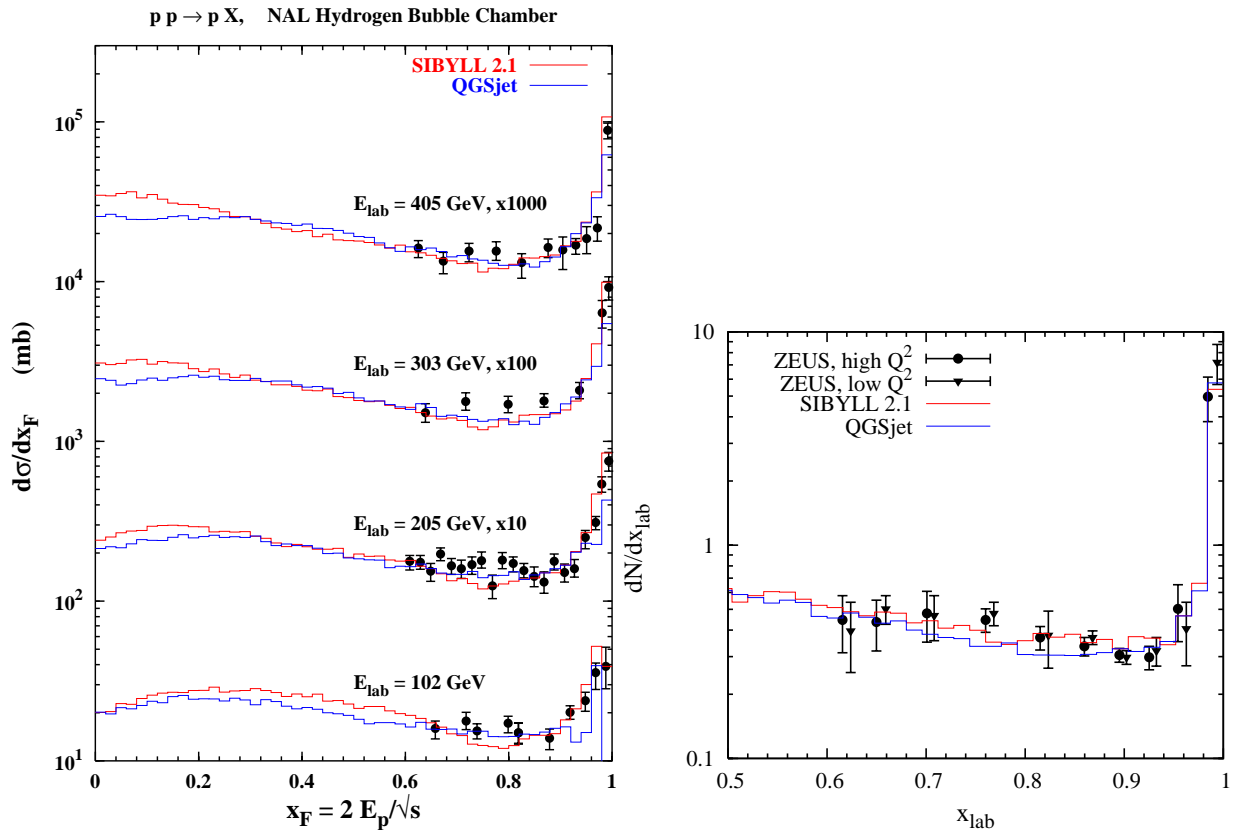
In principle, it is straight-forward to generalize models based on Gribov's Reggeon theory for hadron-hadron scattering to interactions with nuclei. The same scheme of building the scattering amplitude for hadrons can be applied to nuclei if the wave functions of the nucleons in the nucleus are known. Indeed, under certain approximations, the classical Glauber approximation [?] is obtained in these models.

### 3. Model constraints and uncertainties

There are various theoretical and experimental constraints on models of hadronic multiparticle production. Building a model that satisfies all constraints would only be possible if we had a calculable theory of hadronic interactions. Therefore available interaction models mainly differ in the set of constraints and concepts that are implemented in detail and those that are either ignored or even violated.

At very low energy ( $E_{\text{lab}} < 5 \text{ GeV}$ ) only resonance production and decay has to be calculated. The quality of a model can be judged by the number of resonances incorporated and the sophistication of the treatment of the decay processes. The only free parameters of these models are related to the treatment of nuclei and the determination of the relative phase of the different Breit-Wigner amplitudes. Fortunately rich data sets from fixed-target accelerator experiments exist, helping to

determine these parameters [?, ?]. General constraints such as unitarity of the scattering amplitude are satisfied by construction. In particular, the energy dependence of the cross section is known unambiguously. Examples for models of this type are HADRIN and NUCRIN [?, ?] for the simulation of hadron-hadron and hadron-nucleus collisions, respectively, and SOPHIA [?] for photon-hadron interaction.



**Figure 1.** Leading proton distributions measured in the FNAL hydrogen bubble chamber [?] (left) and at HERA [?] (right). The data are compared to QGSjet 01 and SIBYLL 2.1 predictions.

The situation is more complicated in the intermediate energy range. Color string models are of purely phenomenological nature and a large set of data is needed to constrain the parameters of the functions of string fragmentation and energy sharing of the hadron constituents. If not required by data, these parameters are assumed to be energy-independent. There is some ambiguity in determining the model parameters since the string fragmentation and hadron constituent distribution parameters are strongly correlated. As the Regge-type amplitude of two-string models does not satisfy unitarity if extrapolated in energy, one cannot apply such models at very high energy. Two-string models exhibit Feynman scaling which is known to hold at intermediate energies but is clearly violated at higher energy.

Concerning hadron-hadron scattering, many measurements from fixed target experiments are available. Even the leading particle distributions are known up to 400 GeV beam energy, see Fig. ???. However, there is a lack of data on hadron-nucleus

interactions (for example, see [?]) and almost no measurements of particle production in pion-nucleus collisions are available. Understanding pion-air interactions in this energy range is very important for predicting muon production in EAS [?, ?, ?] and a significant part of the uncertainty of air shower predictions is related to this interaction energy range [?, ?].

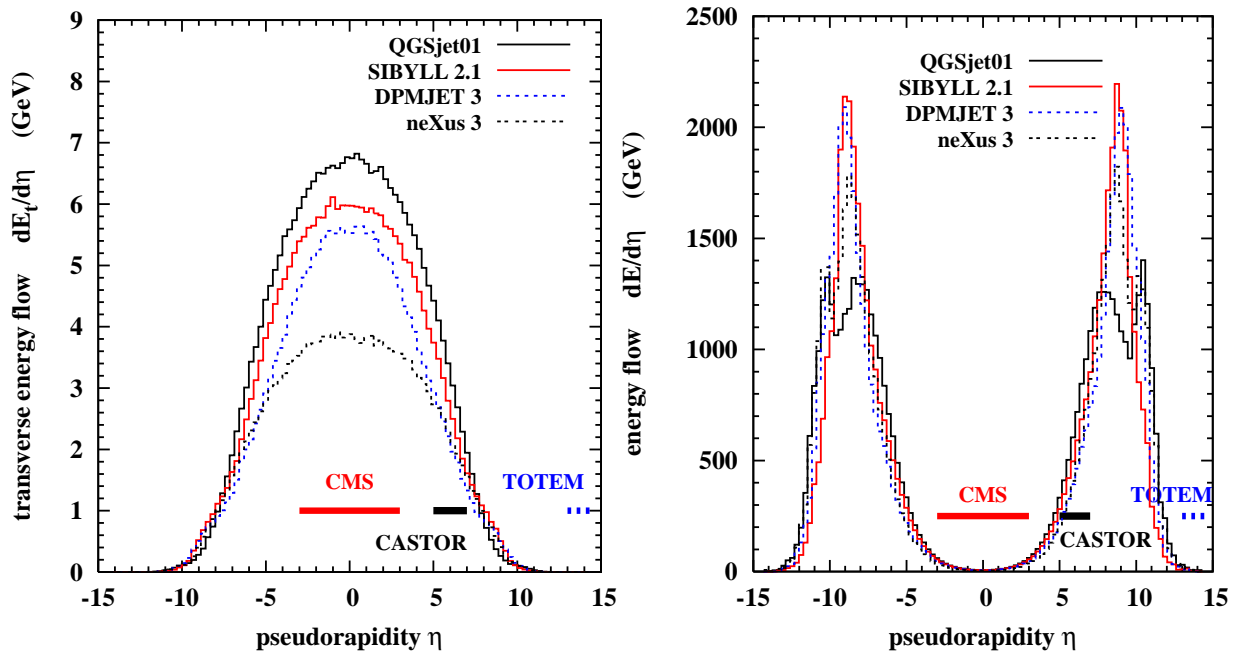
The cascade simulation package FLUKA [?] has a particularly well-tuned two-string interaction model built in for simulating interactions at intermediate energies and applies resonance superposition models at low energy. Alternative, less sophisticated but more flexible approaches are parametrizations of data. Typical models of this type are GHEISHA [?], UrQMD [?] and the Hillas splitting algorithm [?]. On one hand these parametrizations even more directly rely on data from fixed target experiments and have a smaller predictive power. On the other hand they offer a simple framework to study the impact of various assumptions on hadron production. Recent comparisons with data [?] show that both UrQMD and FLUKA describe fixed target data reasonably well whereas GHEISHA exhibits serious shortcomings.

The most complete and sophisticated high-energy interaction models for EAS simulation are DPMJET II.5 [?] and III [?, ?], neXus 2.0 [?] and 3.0 [?], QGSjet 01 [?] and QGSjet II [?], and SIBYLL 2.1 [?, ?, ?]. These models cover a lab. energy range from several 100 GeV to the highest energies observed, some of them (DPMJET, neXus) allow also simulation at much lower energy. For example, DPMJET can also be used to simulate particle production in hadron-hadron collisions even at energies as low as the particle production threshold.

As already mentioned, due to the complexity of the matter, none of these models is fully self-consistent and satisfies all theoretical constraints. In the following we give only a few representative examples for conceptual differences of the models.

(i) NeXus is the only model in which the theoretically predicted energy-momentum sharing between hadron constituents is consistently implemented even in the construction of the scattering amplitude [?, ?]. This energy-momentum sharing leads to a reduction of the secondary particle multiplicity in hadron collisions with nuclei and at very high energy. On the other hand, neXus is characterized by a rather phenomenological treatment of diffraction dissociation (more precisely, enhanced Pomeron graphs) at the amplitude level [?]. In contrast, QGSjet II has the most detailed model of enhanced Pomeron graphs implemented by summing all contributions to all orders [?], however, energy-momentum sharing at amplitude level is neglected. Both the detailed treatment of energy sharing and that of enhanced Pomeron graphs are technically very challenging and it is currently impossible to implement them together in a single model.

(ii) SIBYLL is the only model that is based on a dipole charge form factor for the Born scattering amplitude (single Pomeron exchange). It is well known that a simple exponential form factor, as used in all other models, does not give an adequate description of elastic scattering data. However, it is unclear whether a dipole-type form factor is also a good approximation at very high energy. Due to the expected large



**Figure 2.** Predicted energy flow at LHC. Model predictions are compared with the acceptance of the central CMS and the forward CASTOR and TOTEM detectors. The left hand panel shows the transverse energy flow which is the typical quantity measured in high energy physics experiments. The right hand panel shows the total energy flow which is the quantity of direct relevant to air shower simulations.

number of gluon splittings in parton cascades at high energy, the form factor could approach an exponential function (for example, see [?]). The different assumptions on the form factor lead to different energy dependences of the total cross section (a detailed discussion can be found in [?]). Still all models satisfy unitarity and the total cross section does not grow faster than the Froissart bound [?].

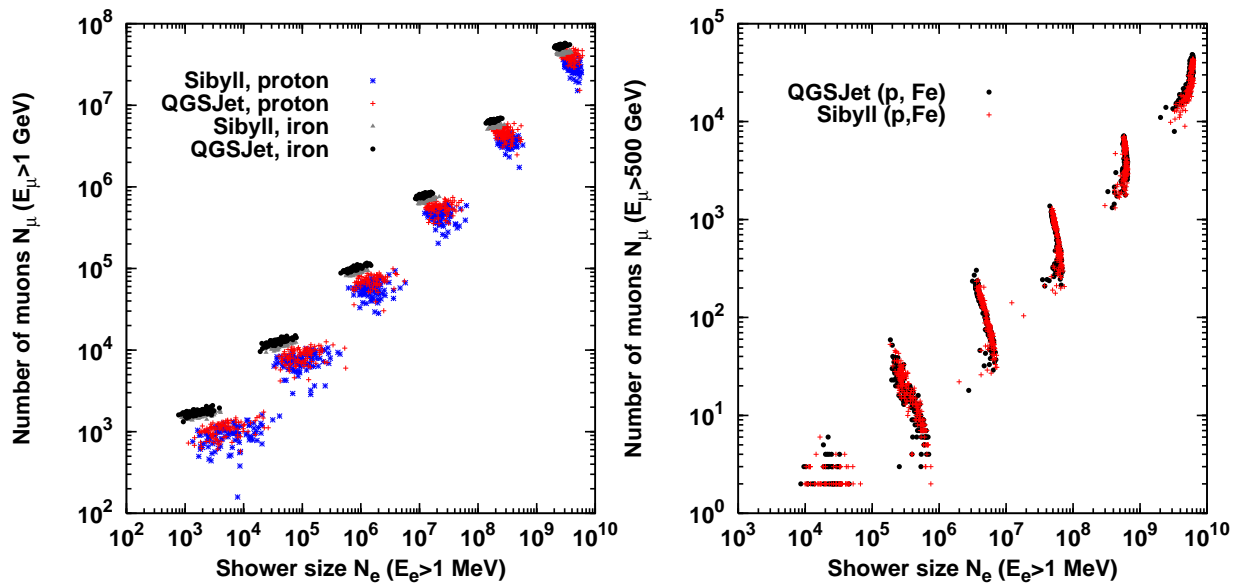
(iii) If an amplitude of a model approaches the black disk limit at high energy then the fraction of diffractive events decreases  $\sim 1/\ln E_{\text{lab}}$  (consequences of the black disk limit are discussed, i.e., in [?, ?]). DPMJET, SIBYLL, and also QGSjet II have the black disk limit implemented, whereas the older version of QGSjet 01 is based on the quasi-eikonal model, predicting a fixed fraction of diffractive events at high energy. These differences can lead to striking differences in the event-to-event fluctuations of the inelasticity of the collisions [?]. There is a general prejudice that the black disk limit is realized in nature but no sound theoretical justification for this expectation exists.

(iv) At high energy the number of partons in a hadron or nucleus might approach a density at which the individual parton wave functions begin to overlap and non-linear effects of parton-fusion become important [?]. So far the experimental signatures of such non-linear effects are subject of controversial debate [?]. Some authors believe that RHIC data strongly support the ideas of parton saturation (i.e. [?]), others don't see any need for such assumptions (i.e. [?]). The new QGSjet II model and a recent modification of the SIBYLL code [?] represent attempts to incorporate such effects in

cosmic ray models. In QGSjet II only the fusion of soft partons is calculated and the modified version of SIBYLL accounts for non-linear effects of only hard partons.

Despite the differences between the models, none of the considered models violates important theoretical principles. The models vary significantly in their degree of sophistication, however, all provide a reasonable description of existing collider data (a comprehensive comparison with data can be found in [?]). Therefore one cannot rule out any of the models from purely theoretical or experimental grounds. Only the comparison with more accelerator and cosmic ray data can help to reduce the spread of model predictions at very high energy. The recent HiRes measurement of the proton-air cross section [?] is an important step in this direction.

In addition to the uncertainties coming from the differences between the models, each model is characterized by a certain range of possible predictions depending on the values of the parameters employed to extrapolate to high energy. For example, the predictions of the SIBYLL model can be very similar to those of QGSJET 01 if the transverse momentum cutoff is changed [?]. Similar studies have been done with QGSjet 01 [?, ?], demonstrating the wide range of possible predictions.



**Figure 3.** Expected correlation of electron and muon shower sizes. Left: showers measured at sea level ( $1030 \text{ g/cm}^2$ ) with a muon energy threshold of 1 GeV. Right: showers measured at South Pole altitude ( $670 \text{ g/cm}^2$ ) with a muon threshold of 500 GeV. In both cases an electron energy threshold of 1 MeV was applied.

Finally it should be mentioned that DPMJET and neXus are also often used for the simulation of minimum bias events at colliders. This allows a direct feedback from collider experiments. However, there is the danger that most of the model development effort is directed toward tuning models in detail to collider data which might be unimportant for EAS simulations, diverting the attention from the important quantities such as leading particle production. Many of the quantities typically measured at colliders (CERN SPS, Tevatron, RHIC) are only of limited relevance to cosmic ray

interactions. This is illustrated in Fig. ?? comparing the transverse energy flow and the total energy flow in inelastic proton-proton collisions at LHC with the CMS, CASTOR [?], and TOTEM [?] detector acceptance ranges. Only the dedicated LHCf experiment will fully cover the pseudorapidity range of interest to EAS physics, namely  $\eta > 7.8$  [?].

#### 4. Model-insensitive observables

Given the uncertainties of hadronic interaction model predictions it is of great interest to find model-insensitive EAS observables.

One well-known model-insensitive observable is the integral over the ionization energy deposit along the shower trajectory, called calorimetric energy. It can be easily measured in fluorescence light experiments. A recent study [?] showed that even with no assumption on the mass of the hadronic primaries, the calorimetric energy can be determined with a precision better than 3% above  $10^{19}$  eV. The uncertainty estimated by using different interaction models is smaller than that due to the unknown primary cosmic ray composition. Even at low energy ( $\sim 10^{17}$  eV) the composition-related uncertainty is expected to be smaller than 10%.

Another model-insensitive observable can be formed by correlating high-energy muons with low-energy electrons. For a given energy, the shower size observed with a ground array depends directly on the depth of maximum of the shower. Similarly, high-energy muons are sensitive to the depth of the early part of the shower profile. The number of muons is slightly higher for shower developing high in the atmosphere and lower for deep showers. In Fig. ?? the expected correlation of electron and muon shower sizes is shown for 100 showers for each energy, model, and primary mass combination. The calculations have been carried out with the new hybrid EAS simulation code CONEX [?]. The left panel of Fig. ?? represents the situation at the KASCADE-Grande array [?]. Being located at sea level large shower-to-shower fluctuations limit the energy resolution of this installation. The composition sensitivity could be good if the model uncertainties are reduced. The right hand side of Fig. ?? illustrates the expectation at the IceCube/IceTop installation at South Pole [?]. Due to the high altitude, showers are measured near their maximum. This reduces significantly the fluctuations of the electron shower size. Taking in addition advantage of the IceCube detector that can measure muons of approx.  $E_\mu > 500$  GeV, a model- and composition-independent energy estimator of excellent energy resolution can be formed.

As demonstrated by these two examples, it is possible to find model-insensitive observables for measuring shower energy. However, it will not be possible to find model-independent observables of EAS that are sensitive to the primary particle mass.

#### 5. Summary

Hadron production at intermediate energy is important for understanding extensive air showers, in particular the production of muons. There is still a significant uncertainty

of the modelling of multiparticle production due to the lack of minimum bias proton- and pion-nucleus data in this energy range.

The limited understanding of hadronic interactions at very high energy is currently the main source of systematic uncertainties in modern cosmic ray experiments. There is no obvious reason or shortcoming that would justify disregarding the predictions of state-of-the-art models such as DPMJET, neXus, QGSjet, and SIBYLL. Therefore, the wide range of model predictions can only be reduced significantly by dedicated efforts for measuring relevant secondary particle distributions at colliders.

The sensitivity of air shower measurements to the uncertainties in the description of hadronic particle production can be tested by using different models for shower simulations. However, it is clear that the difference between the predictions of, for example, the QGSjet and SIBYLL models does not indicate the full range of uncertainty.

As the uncertainty in the extrapolation of hadron interaction models to high energy cannot be determined from first principles, the simultaneous measurement of several air shower observables is needed. It allows an independent consistency check of the reliability of the simulations applied to interpret the data.

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