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LHC Update of the Hadronic Interaction Model SIBYLL 2.1

EUN-JOO AHN[1], RALPH ENGEL[2], THOMAS K. GAISSER[3], PAOLO LIPARI[4], FELIX RIEHN[2,3], TODOR STANEV[3].

[1] *Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL 60510-0500, USA*
[2] *Karlsruher Institut für Technologie, Institut für Kernphysik, Postfach 3640, 76021 Karlsruhe, Germany*
[3] *Bartol Research Institute, Department for Physics and Astronomy, University of Delaware, Newark, DE 19716, USA*
[4] *INFN sezione Roma "La Sapienza", Dipartimento di Fisica Universitá di Roma I, Piazzale Aldo Moro 2, I-00185 Roma, Italy*

felix.riehn@kit.edu

Abstract: SIBYLL 2.1 is an event generator for hadron interactions at the highest energies that is commonly used to analyze and interpret data on extensive air showers. We have compared the model to the results of the LHC collider at $\sqrt{s} = 7\,\mathrm{TeV}$. Some of the model parameters were tuned to reproduce better the experimental data. The updated model was then used to calculate air shower observables which were compared to the results before the update.

Keywords: hadron interaction models, LHC, extensive air showers

1 Introduction

SIBYLL [1] is a hadronic interaction model that is widely used for air shower simulations. It is available as one of the standard hadronic interaction models for high energy in the simulation packages AIRES, CORSIKA, CONEX and SENECA. SIBYLL is also used for calculating atmospheric lepton fluxes, see for example [2].

The current version of the model is SIBYLL 2.1 [3]. It is designed to describe experimental data up to TeVatron energies of $\sqrt{s} \sim 2\,\mathrm{TeV}$.

With the first data from the LHC being published, the energy extrapolation, which is the most important aspect of the model for air shower simulations, can be tested and further improved.

Another aspect of hadronic interactions that has come into focus again in recent years, which is important for the muon content of air showers, is the production of baryons [4].

In the first section we show that the current model is capable of describing the LHC data, albeit with minor changes in the cross section parameters. We also introduce an extension to the model to account for the increased baryon production at LHC. In the second section we discuss the consequences of the changes to the model for air shower simulations.

The changes introduced concerning charm production [5], have also been included in the version discussed here. Details of the treatment of charmed particles in the model and their role in the atmosphere, are discussed in a separate contribution [6].

2 LHC updates

Before discussing the update of the model it is worthwhile to mention that SIBYLL 2.1 already describes the general characteristics of hadronic interactions at 7 TeV remarkably well (see dashed blue histogram in Fig. 3 or [7]).

That does not mean the model is complete. It is a simplified model and there are many specific observables where one can see the results of the various simplifications. The overall scheme of extrapolating this simplified model to higher energies however seems to be robust.

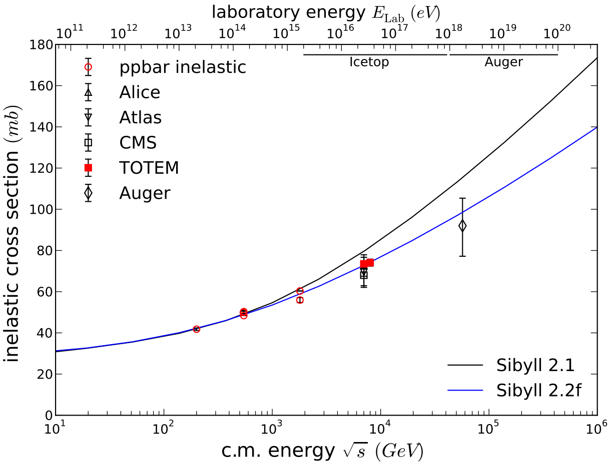

Figure 1: Inelastic *pp* cross section in SIBYLL. The updated cross section is shown in blue, the old version is in black. The red squares are the measurements by TOTEM [8]. The black diamond at the highest energy is the estimate by the Auger experiment [9].

2.1 Proton proton cross section

The hadron proton cross section in SIBYLL includes hard and soft interactions, separated by an energy dependent cutoff in $p_{\perp}$, and diffraction dissociation. More details on the structure of the model can be found in [3].

Measurements at the LHC suggest (see Fig. 1) that SIBYLL 2.1 overestimates the cross section at high energies. The inelastic cross section measured in the TOTEM experiment, which has the highest precision for a measurement of the total cross section at the LHC, is $73.5^{+1.9}_{-1.4}\,\mathrm{mb}$ [8] whereas SIBYLL predicts 80 mb. The rise of the *pp* cross section beyond 1 TeV is due to hard parton scattering (Fig.4 in [3]), which in SIBYLL is called *minijet* production.

SIBYLL uses an eikonal approximation to reconcile the parametrization of soft scatterings with the perturbative calculation of the minijets into an unitary amplitude, which then defines the total and elastic cross sections. The size of the soft and hard contributions in this formalism depends

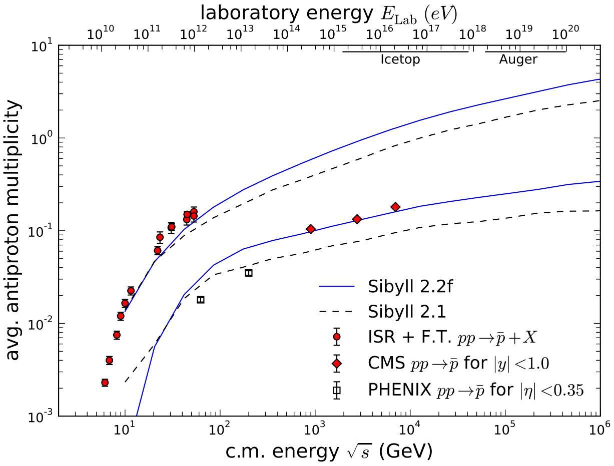

Figure 2: Average antiproton multiplicity with energy. The low energy data are from fixed target experiments that cover full phase space and the ISR [10]. The CMS data [11] are taken in phase space with $|y| < 1.0$. PHENIX [12] data are taken in $|\eta| < 0.35$.

on the size of the particular cross section and the profile function.

In order to make the inelastic cross section compatible with the TOTEM result without changing the hard cross section (calculated within QCD), the profile function has been made more narrow so that peripheral collisions are less likely to produce minijets.

The downside of this approach is that central collisions now exhibit very high parton densities (profile functions are normalized), leading to a large number of minijets and consequently a large number of final state particles and an unrealistic multiplicity distribution.

Since our goal is a model capable of describing interactions a decade and more higher in energy, the effects of high parton densities have to be considered, even if the mean multiplicity still agrees with current experiments. A microscopic model of parton density *saturation* would account for these effects. In the current model, saturation is in effect implemented as an energy-dependent lower $p_{\perp}$-cutoff for the minijets.

In addition to changing the hard profile function we adjust the parameters of the soft cross section parametrization.

The result is shown in Fig. 1 as a blue line, the old cross section for comparison is shown as a black solid line. The data point of the highest energy is the estimation of the *pp* cross section with the data by the Auger experiment using air showers at energies of about 10^9 GeV [9]. The value has not been used to fit the cross section model in SIBYLL and therefore can be seen as an indication that the prediction by the model is reasonable.

Since the proton profile also enters the meson nucleon cross sections, we refit the parametrization of the soft contribution there as well.

2.2 Baryon production

Particle production in interaction models primarily depends on the implementation of the fragmentation process. Fragmentation is a non-perturbative process so the rates of particle production cannot be calculated, which means the parameters in the model have to be set by experiment.

In SIBYLL *string fragmentation* is used as the fragmentation model. The string model simplifies hadronisation by assuming a uniform energy density in the color field stretched between two partons (analogous to a mechanical string) which eventually is split in two by quark-antiquark pair production. The splitting is continued until the remaining energy is not enough to form a hadron. Baryons are produced by introducing diquark - antidiquark pairs instead of $q\bar{q}$ pairs. The probability to produce a diquark pair rather than a quark pair ($P_{\mathrm{q/qq}}$) in the string is the parameter that controls baryon production. In version 2.1 it is set to 0.04.

For simplicity, only two string classes are distinguished in SIBYLL: the 2 string configuration for the $2 \to 2$ sea parton scattering and two single strings connecting valence quarks/diquarks. The essential difference between the two is that the latter configuration has flavor attached to the string ends, where as the former is in total flavor neutral. This distinction is necessary to describe the differences between the forward/backward regions and the central region of phase space.

The result of this treatment of baryon production in SIBYLL 2.1 for the antiproton multiplicity is shown in Fig. 2 as dashed black lines together with a compilation of data. The multiplicity for full phase space, typically measured in fixed target experiments at low energies, is shown in the upper set of lines whereas the multiplicity in the central region ($|\eta| < 2$), the region typically accessible in collider experiments, e.g. CMS [11], is shown in the lower set. The current model describes the threshold at low energies well but is not capable of describing the central, high energy data at the same time.

In order to allow for a meaningful extrapolation to high energies, instead of introducing an arbitrary energy dependent parametrization for $P_{\mathrm{q/qq}}$, one can couple the baryon production parameter to minijets whose energy dependence is at least partially given by QCD and use the inevitably occuring threshold effects due to the larger mass of baryons.

Furthermore minijets mostly produce particles in the central region which is exactly where the high energy data by CMS reveal a deficit of SIBYLL 2.1. This assumption is supported by the observation of the ratio of antiprotons to charged pions compared to the central charged multiplicity (see e.g. Fig.15 in Ref. [11]). It shows that the baryon production in jets is largely limited by the available phase space.

The simplest possible coupling of the diquark parameter to minijets is to choose a different but fixed value of $P_{\mathrm{q/diq}}$ in the fragmentation of minijets.

The resulting model describes the data much better (solid blue line in Fig. 2), especially in the central region.

Measurements of baryon production at LHC energies that cover the forward phase space, could test the assumptions made in this model.

2.3 Other updates

Other general and more technical aspects of the model that have been updated but are not discussed here are: kinematic distributions in hard scattering are now sampled according to the GRV pdf parametrization [13] with an effective scale $Q^2_{\mathrm{eff}} = 6\,\mathrm{GeV}^2$, the transverse momentum aquired in the scattering of valence quarks as well as in the string fragmentation is now sampled from an exponential transverse mass distribution rather than a Gaussian as in the

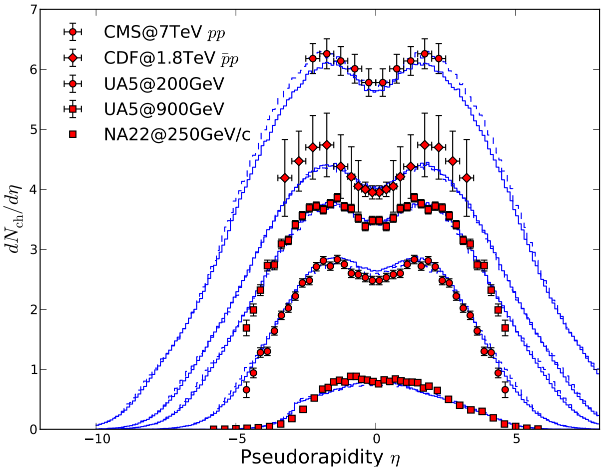

Figure 3: Pseudorapidity distribution of charged particles as a model test. The data are from NA22 [16],UA5 [17],CDF [18] and CMS [19]. The prediction by SIBYLL 2.1 is shown as the dashed histogram, the results of the updated model are shown by the solid histogram.

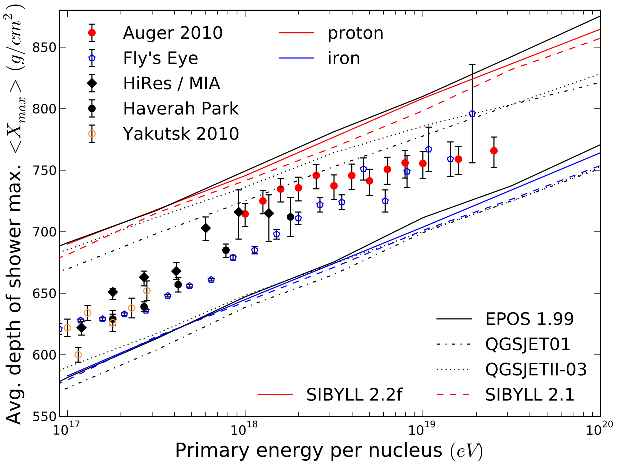

Figure 4: Prediction of the average depth of maximal shower development as a function of primary energy. The updated version of SIBYLL is shown by the solid black line. The interpretation of the data does not change much.

previous version. Also the production of charmed particles has been included.

A very specific aspect that has been updated is the preferred forward production of vector mesons over pions in meson nucleon interactions, that, especially in the neutral component, is suggested to have an influence on muon production in air showers [14].

Furthermore the calculation of the diffractive hadron-nucleus cross section has been extended to include screening effects [15].

We refer to the model including all these changes as SIBYLL 2.2f.

2.4 Comparison to data

In order to test whether the model gives a good description of data after introducing the changes mentioned above, we look at the charged particle *pseudorapidity distribution*. The advantage of this observable is that it is very sensitive to the details of the parton level interaction structure and kinematics (n_{jets}, x_i) as well as to the subsequent fragmentation process ($dN^{\mathrm{ch}}_{string}/d\eta$).

The changes introduced in the cross section are expected to increase the central multiplicity at energies beyond 1 TeV whereas the increased baryon production, due to the higher mass of baryonic particles, can be expected to lead to an overall decrease in the multiplicity. Fig. 3 shows that both effects approximately cancel one another at CMS energy and that SIBYLL 2.2f (solid blue histogram) describes the CMS data well.

3 Predictions for extensive air showers

The development of extensive air showers depends on many aspects of hadronic interactions. In the following we use the tuned model to make predictions for high energy air showers. Results for atmospheric lepton fluxes are shown in [6].

We will focus on those aspects where the above changes to the interaction model can be expected to manifest themselves the most, namely the average depth of shower maximum in case of the interaction cross section and the number of muons in case of the increased baryon production.

3.1 Longitudinal shower development

The influence of the interaction cross section on air showers is obvious. As a measure of the probability of interaction the cross section defines the interaction length. The consequence of a smaller cross section is a larger interaction length which means the showers will develop deeper into the atmosphere.

The most direct experimental observable for this *longitudinal* development of air showers is the average depth of the shower maximum ($< X_{\mathrm{max}} >$). From the deeper showers due to the smaller cross section in the updated SIBYLL we would expect to see an increase in the average X_{max}.

However there are multiple factors which dilute the effect. One is that the primary energy is dispersed very quickly among the particles in the cascade so that only the first interaction is affected by the new high energy cross section.

Another factor is that the $\pi - p$ and $K - p$ cross sections have actually been increased at energies below 1 TeV, so the secondary hadronic cascades will develop more rapidly in terms of depth, undoing the delay due to the first interaction being deeper in the atmosphere.

In Fig. 4 the $< X_{\mathrm{max}} >$ as a function of primary energy is shown. 1000 air showers for each primary were simulated using CORSIKA 7.3500 [20]. Hadronic interactions below 80 GeV in the laboratory were treated with FLUKA 2011 [21].

As expected the difference between the updated version (solid black line) of SIBYLL and version 2.1 (colored dotted line) is an overall small increase of the average X_{max}.

3.2 Number of muons

In case of baryon production the influence on hadronic cascades is more subtle than for the interaction cross section.

Despite the lower multiplicity in the baryonic component compared to the mesonic component, baryons still can have a large influence on the development of an air shower. The fact that baryon number is conserved, along with the higher mass, is what causes the low multiplicity (see the

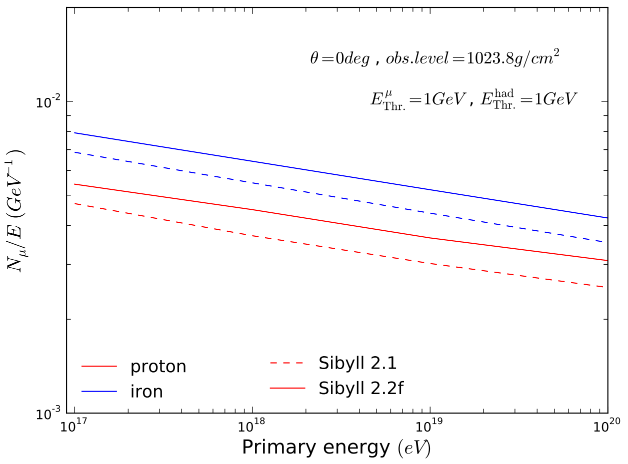

Figure 5: Muon number as a function of the primary energy in simulated air showers.

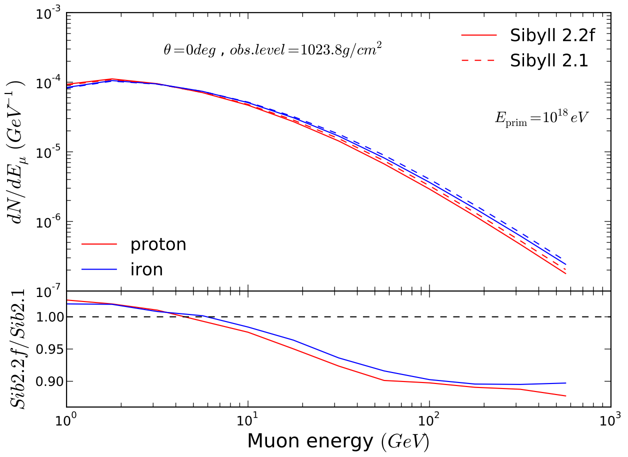

Figure 6: Energy spectrum of muons in simulated air showers at $E_0 = 10^{18}$ eV.

delayed threshold in the $\bar{p}$ multiplicity in Fig. 2) but it also means that baryons only drop out of the cascade when they reach non-relativistic energies. The usual trade off between interaction length and decay length that defines the *critical energy* for mesons does not apply since protons, the baryons with the lowest mass, do not decay.

At the end of a hadronic cascade, before becoming non-relativistic, an initial high energy proton, for example, will produce low energy pions with energies close to or below the critical energy that will decay into low energy muons.

In Fig. 5 the average number of muons per primary energy in the simulations is shown. Version 2.2f is shown as solid lines, 2.1 as dashed lines. Proton (red) and iron (blue) primaries were simulated, both with vertical incidence.

The equal increase of the muon number for the different primary particles is a consequence of the superposition model.

Fig. 6 shows the energy spectrum of the muons at ground for a 10^{18} eV primary as well as the ratio of the muon spectra in the old and new model. As expected the additional muons appear at the low energies, although it is not possible to say that they were necessarily produced by the baryons since all changes in version 2.2f were included in the simulations.

4 Conclusions and future developments

An improved version (2.2f) of the hadronic interaction model SIBYLL has been presented. The update of the *pp* cross section and the extension of the fragmentation model to describe increased baryon production have been discussed in more detail. It was shown that the interpretation of the average depth of the shower maximum in the atmosphere is not affected much by using the new model. The average number of muons on the other hand exhibits a $\sim 20\,\%$ increase.

In the future we plan to implement a parton level saturation model to improve the description of multiplicity distributions and replace the semi-superposition model by a full Glauber model to give a more accurate description of nucleus-nucleus collisions.

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