A new version of the event generator Sibyll

Felix Riehn
Karlsruher Institut für Technologie, Institut für Kernphysik, Postfach 3640, 76021 Karlsruhe, Germany
E-mail: felix.riehn@kit.edu

Ralph Engel[*]
Karlsruher Institut für Technologie, Institut für Kernphysik, Postfach 3640, 76021 Karlsruhe, Germany

Anatoli Fedynitch
Karlsruher Institut für Technologie, Institut für Kernphysik, Postfach 3640, 76021 Karlsruhe, Germany CERN EN-STI-EET, CH-1211 Geneva 23, Switzerland

Thomas K. Gaisser
Bartol Research Institute, Department of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA

Todor Stanev
Bartol Research Institute, Department of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA

The event generator Sibyll can be used for the simulation of hadronic multiparticle production up to the highest cosmic ray energies. It is optimized for providing an economic description of those aspects of the expected hadronic final states that are needed for the calculation of air showers and atmospheric lepton fluxes. New measurements from fixed target and collider experiments, in particular those at LHC, allow us to test the predictive power of the model version 2.1, which was released more than 10 years ago, and also to identify shortcomings. Based on a detailed comparison of the model predictions with the new data we revisit model assumptions and approximations to obtain an improved version of the interaction model. In addition a phenomenological model for the production of charm particles is implemented as needed for the calculation of prompt lepton fluxes in the energy range of the astrophysical neutrinos recently discovered by IceCube. After giving an overview of the new ideas implemented in Sibyll and discussing how they lead to an improved description of accelerator data, predictions for air showers and atmospheric lepton fluxes are presented.

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[*]Speaker.

1. Introduction

In the early years of studying cosmic ray showers, hadronic interactions were typically described by empirical parameterizations of the important features of hadron production at high energy, see, for example, [1] and references therein. These parameterizations of cross sections and distributions of inclusive particle production were tuned to reproduce accelerator data and extrapolated to high energy. The limitation to inclusive cross sections could only be overcome by developing microscopic models of hadronic interactions, generating individual hadronic interactions that satisfy quantum number and energy-momentum conservation.

Sibyll was one of the first of these microscopic event generators developed for describing hadronic interactions of high energy as needed for understanding extensive air showers (EAS) or the production of secondary lepton fluxes in the atmosphere. After having been used for several years already, version 1.7 was released in 1994 [2,3]. This first version of Sibyll was based entirely on the minijet model [4–7] combined with the Lund model of string fragmentation [8]. The key idea was that the increase of the total and inelastic cross sections as well as observed changes in the multiparticle final state could be traced back to one feature of high energy interactions, namely production of jets with low transverse momentum in multi-parton interactions [9].

Although Sibyll 1.7 has been very successful in describing many features of air showers, it had some shortcomings in reproducing the multiplicity distribution of secondaries and could not be used with modern parton densities that predict a faster growth of the number of partons at low momentum fraction x than those available before the HERA collider was turned on. These shortcomings were addressed in Sibyll version 2.1 [10], released in 2000, mainly by extending the multiple interaction and corresponding unitarization concepts to soft interactions [11], including diffraction dissociation, and by introducing an energy dependence of the transverse momentum cutoff used for calculating the minijet contribution. The model parameters of Sibyll 2.1 were tuned to data of fixed-target and collider experiments, with Tevatron ($\sqrt{s} = 1.8\,\text{TeV}$) being the highest energy collider available at this time. Tevatron data were of central importance for determining the increase of the secondary particle multiplicity. There was, however, a considerable uncertainty [12] in the extrapolation of the model predictions to higher energy due to the different cross section measurements indicating either a moderate [13,14] or a fast [15] rise of the total cross section.

LHC data (run I at $\sqrt{s} = 7$ and $8\,\text{TeV}$) give, for the first time, direct access to particle production at equivalent energies beyond the knee in the cosmic ray spectrum. The data of the LHC experiments are of outstanding importance not only because of the high interaction energy but also a change of the importance of the processes required to describe the interactions. For the first time hard multi-parton interactions are the dominant particle production process. It is very encouraging that the new LHC data were bracketed by the predictions of the hadronic interaction models commonly used in cosmic ray physics [16] and – up to collective effects, whose interpretation is still under investigation [17] – no qualitatively new features of hadron production were required to understand the data. Still work on re-tuning and improving the interaction models is needed to obtain a satisfactory description of the wealth of data published by the LHC experiments. In addition to new collider data, a number of important fixed-target measurements [18–22] became available since the release of Sibyll 2.1 and progress has been made in understanding uncertainties of importance to muon production in air showers [23,24].
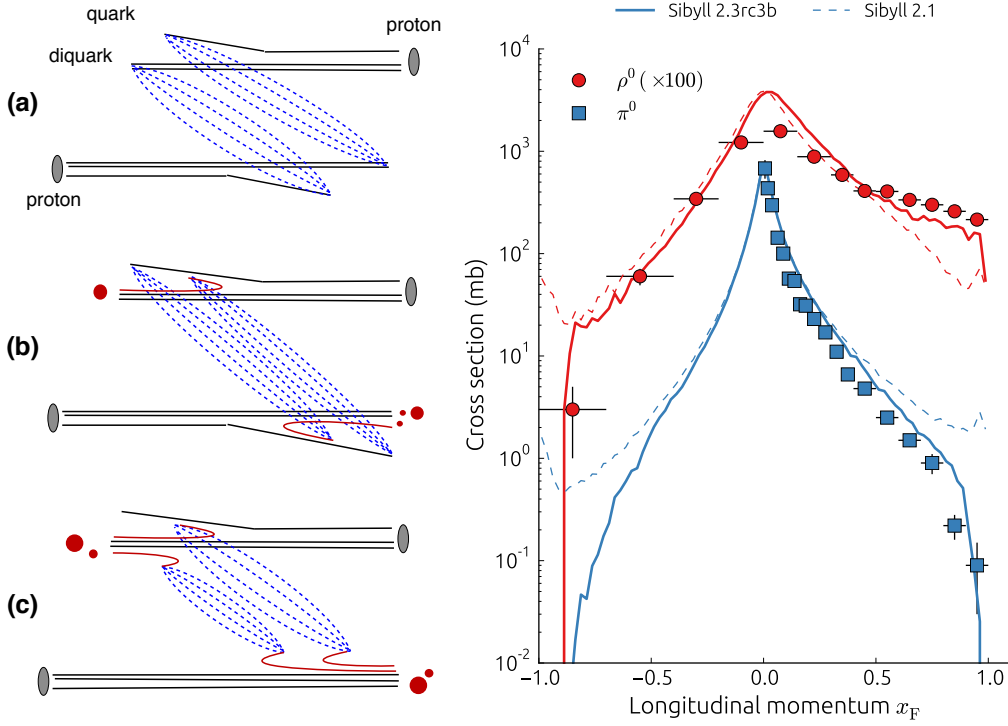
Figure 1: Left: Different configurations of color strings and valence/sea quarks (see text). Right: Feynman-x distributions of π^0 and ρ^0 in π^+-p interactions at 250 GeV/c lab. momentum. The model results are compared to NA22 data [27, 28]. Note that the ρ^0 cross section has been scaled up by 100 for clarity.

In this contribution we present a new version of Sibyll[1] that provides an improved description of multiparticle production with the aim of obtaining more accurate and reliable predictions for both EAS and inclusive lepton flux calculations. In Sec. 2 a summary of the model changes with respect to Sibyll 2.1 is given, focusing on those aspects that are not described in [25]. Predictions for EAS are discussed in Sec. 3 and the corresponding results for atmospheric muon and neutrino fluxes are given in [26].

2. Model improvements

Important modifications of the Sibyll model include, see [25],

- new fits to total and elastic cross sections for p-p, π-p and K-p interactions,
- the implementation of diffraction dissociation in interactions of hadrons with nuclei based on a two-component model (ground state and excited state of projectile and target hadrons), similar to the Good-Walker model of diffraction [29],
- the increase of the rate of baryon-antibaryon pair production in string fragmentation, including a higher production rate in minijet fragmentation than purely soft processes.

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[1]At the time of writing the new version of Sibyll is still a beta-test version, referred to as version 2.3 release candidate 3b (2.3rc3b).
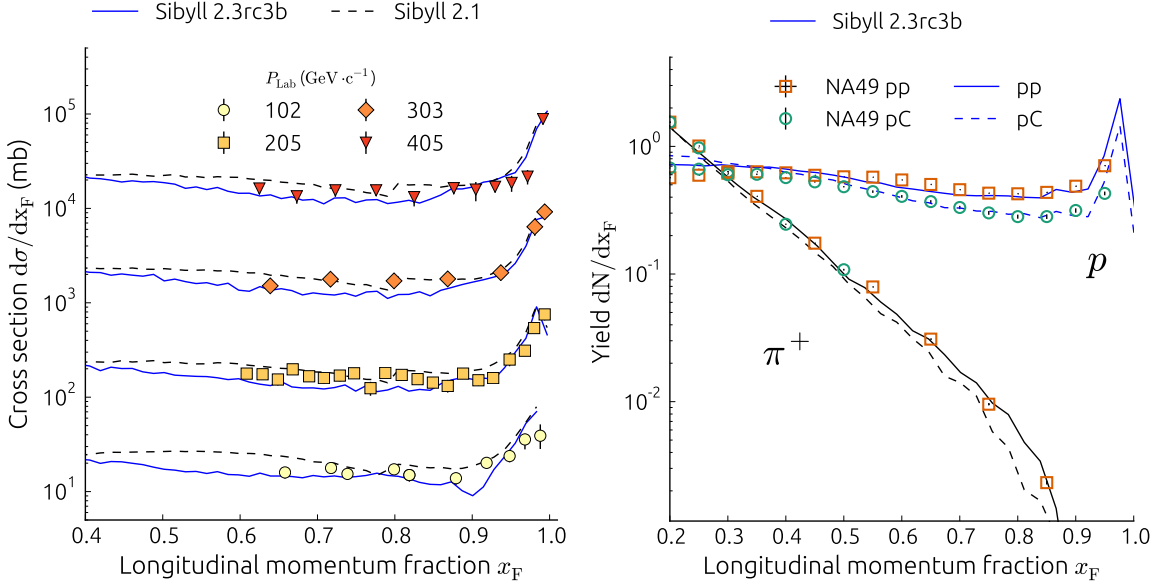
Figure 2: Left: Sibyll predictions for leading protons produced in proton-proton interactions at different energies. Right: Comparison of pion and proton production in proton-proton and proton-carbon interactions. Shown are the predictions of Sibyll 2.3 and NA49 data [18, 19, 22].

- and the implementation of a phenomenological model for describing the production of charm particles.

In addition to these improvements we have changed the way leading particles can be produced in Sibyll.

At low energy, at which hadronic interactions are only soft processes, the typical string configuration for a non-diffractive *p-p* interaction is shown in Fig. 1 (left, a). The exchange of a soft gluon leads to color transfer and two QCD strings are formed. The leading particles of such interactions are formed by the fragmentation of the strings. In the new version of Sibyll we also include the possibility that the soft gluon is exchanged between sea quarks, see Fig. 1 (left, b), or sea and valence quarks. Then a hadronic remnant with an excitation mass is formed. Often this remnant forms a proton, neutron or strange baryon, but higher-mass resonances can also be produced. If the system has a mass higher than $M - m_{\text{beam}} > 0.2\,\text{GeV}$ the remnant is set to fragment. A similar treatment of remnants is implemented in QGSJet [30]. For completeness we also show the remnant model of EPOS [31] in Fig. 1 (left, c), in which gluons are exchanged between sea quarks and, depending on the number of elementary interactions (cut pomerons), hadronic remnants with different numbers of quarks can be produced.

The new remnant treatment in Sibyll allows us to modify particle production in forward direction without having to change the string fragmentation parameters. The additional degree of freedom is used for reproducing the NA22 data on leading π^0 and ρ^0 production on π^+-p interactions, see Fig. 1 (right). By construction, there is a constant ratio between the production rate of vector and scalar mesons in string fragmentation, see predictions of Sibyll 2.1. In contrast to this expectation, production of π^0 in remnants has to be suppressed strongly to obtain a reasonable

agreement with data (results for Sibyll 2.3). The more forward a leading particle is produced in π-p interactions the more likely it is a vector meson. Although this observation is not really understood within current hadronic interaction models, it is very important for muon production in air showers [24].

The NA49 Collaboration has published data on pion and kaon production in p-p interactions at $E_{\mathrm{lab}} = 158$ GeV that reach in Feynman-x up to $0.6 - 0.8$. These data sets have been used extensively for tuning Sibyll at low energy. Thanks to the very good approximate scaling of the secondary particle distributions in forward direction the NA49 data also provide guidance for higher energies.

In Sibyll, the probability of generating excited remnant states similar to those shown in Fig. 1 (left, b) does depend on the number of multiple interactions and becomes as such dependent on the interaction energy and the number of participating nucleons in interactions with nuclei. This allows us to describe both the forward nucleon distribution in p-p interactions, see Fig. 2 (left) and also the softer leading nucleon distribution in p-C interactions – Fig. 2 (right). It is interesting to note that the distributions of pions produced in p-p and p-C interactions are almost identical in the range covered by NA49 data. This similarity is a characteristic feature of the new version of Sibyll.

3. Air shower predictions

The rate at which energy is transferred from the hadronic shower core to the electromagnetic shower component is closely related to the number of muons produced in showers [32]. The smaller the energy fraction that is given to neutral pions, the larger is the number of muons produced by the other hadronic particles.

In general, the details of the particle types generated for the remnants are very important [24]. The production of ρ^0 mesons instead of leading π^0 in charged pion interactions[2] is one key feature of the new model. While neutral pions feed the electromagnetic shower component, $\pi^0 \to \gamma\gamma$, the decay of ρ^0 mesons keeps the energy in the hadronic component, $\rho^0 \to \pi^+ \pi^-$. This change increases the production of muons of all energies in air showers.

In addition, the increased rate of baryon pair production in string fragmentation leads to a larger number of muons at low energy: due to baryon number conservation baryons produce secondary particles in many consecutive interactions until their energy falls below the particle production threshold [23]. Increased baryon production in the new version of Sibyll adds mainly low-energy muons, making the muon energy spectrum softer.

Predictions for the number of muons produced in air showers are shown in Fig. 3. The results obtained with LHC-tuned versions of QGSJet [34, 35] and EPOS [31, 36] are compared with those of Sibyll. The Sibyll predictions on the muon number have increased and are now very similar to QGSJet II.04.

The modifications of the model have also changed the predictions on the depth of shower maximum, X_{max}, see Fig. 4. Showers simulated with Sibyll 2.3 develop deeper in the atmosphere, and existing data are interpreted with a mass composition heavier than before. This change is expected to ease the tension between the shower-to-shower fluctuations and the mean X_{max} measured by the Auger Collaboration, see [38, 39].

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[2]There is about a 30% chance to have a π^0 as leading particle in a $\pi^{\pm}$-air interaction.
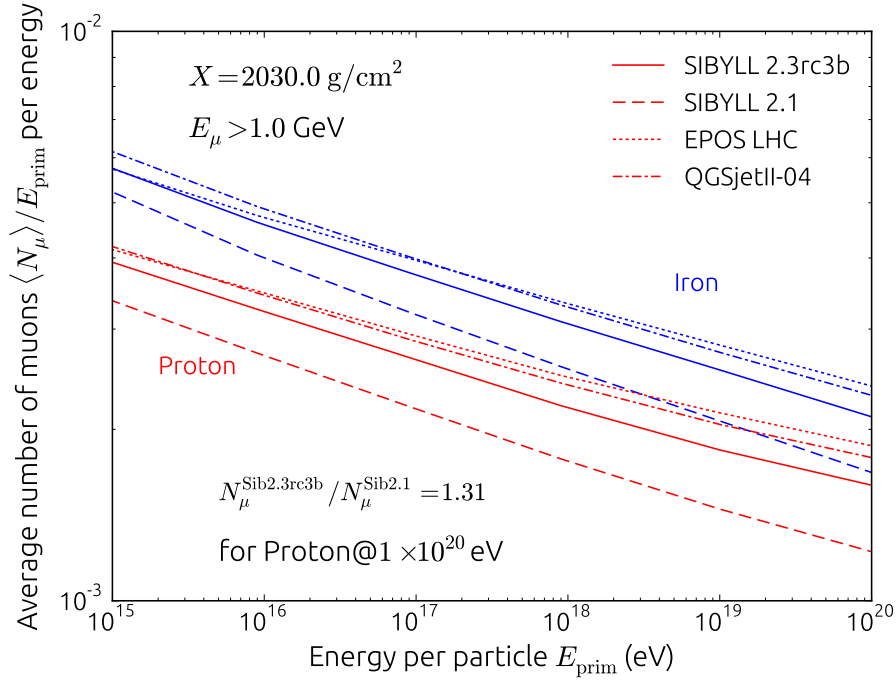
Figure 3: Comparison of model predictions on the mean number of muons in air showers at the depth of 1000 g/cm². The calculations have been done with CONEX [33].

4. Conclusions and outlook

A new version of the Sibyll interaction model has been presented that is tuned to LHC and fixed target data that became available after the release of version 2.1. Particular attention has been paid to reproduce leading particle distributions measured by the NA49 and NA22 collaborations. The introduction of the production of leading vector mesons in pion-air interactions and an increased rate of baryon-antibaryon pair production has lead to a $\sim 20\%$ increase of the number of muons in high-energy showers. The depth of shower maximum is shifted deeper into the atmosphere by ~ 25 g/cm². Another remarkable feature of the new version of Sibyll is the very good Feynman scaling found for pion and kaon production at $|x_F| > 0.1$.

The version of the model presented here is still being tested. The code will be released for public use by the end of 2015.

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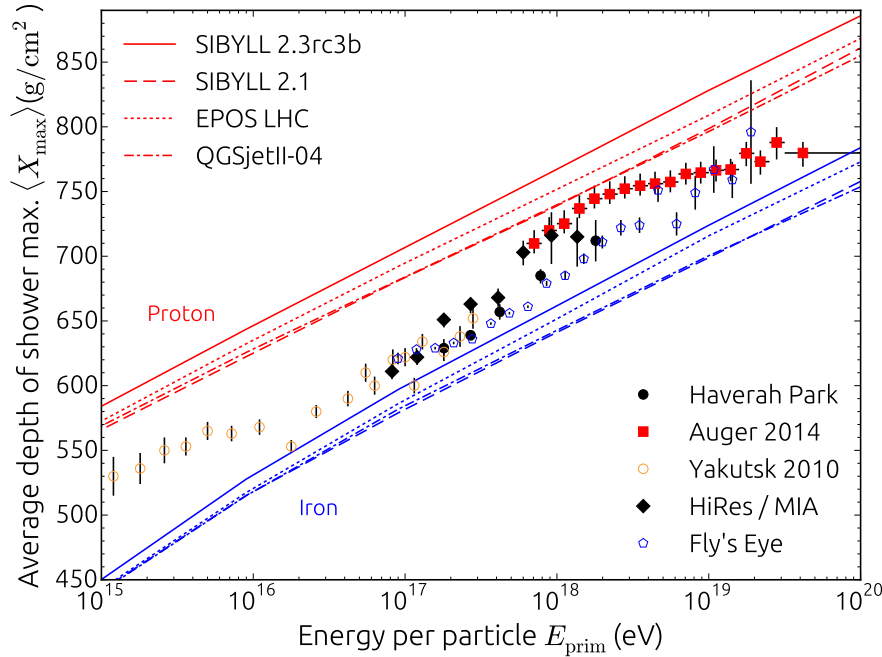
Figure 4: Comparison of model predictions for the mean depth of shower maximum, X_{max}. The model results are shown together with measurements from different experiments, see [37] for references to the data and [38]. The calculations have been done with CONEX [33].

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