Air Shower Calculations With the New Version of SIBYLL

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Abstract

We discuss the main features of the new version of the SIBYLL Monte Carlo event generator and emphasize their impact on the simulation of air showers at ultra high energy. The inclusion of diffraction dissociation into the unitarization scheme and the use of new parton density functions improve the agreement with collider data. Predictions are given for typical quantities used to characterize EAS.

1 Introduction

Our knowledge of cosmic rays (CR) with energies above 10^{14} eV is based on extensive air shower (EAS) experiments. To extract the physical information about primary composition and energy spectrum, we need to interpret measurements of quantities such as depth of maximum $(X_{\max})$, muon number at detector level (N_μ) and shower size (S) as a function of energy over the entire range of EAS to beyond 10^{20} eV. The necessary simulations depend on extrapolation of models of hadronic and nuclear interactions to phase space and energy regions not explored by current accelerator experiments. On the other hand EAS data can give valuable information about some global features hadronic interactions at energies which cannot be reached at colliders or phase space regions which have not been measured in fixed target or collider experiments.

One interaction model in use for interpretation of EAS is SIBYLL (version 1.7, Fletcher *et al.* 1994, Engel *et al.* 1992). The minijet production in this model is based on EHLQ parton densities (Eichten *et al.* 1984). In the past few years new data from the HERA ep collider became available (Breitweg *et al.* 1997, Adloff *et al.* 1997) improving our knowledge on parton densities at low x (x is the momentum fraction carried by the parton relative to the proton). Parametrizations of parton densities taking HERA data into account predict a considerably steeper increase of the minijet cross section with the energy than that implemented in the EHLQ parton densities. In addition, data from air shower experiments such as KASCADE (Hörandel *et al.* 1997, Antoni *et al.* 1998) suggested that SIBYLL 1.7 does not describe hadronic interactions accurately enough at energies of about 10^{15} eV.

We have developed a new version of SIBYLL (version 2.0) which takes all new collider data into account. This version is expected to predict muon numbers and shower sizes which are compatible with KASCADE data. Although we do not discuss it here, we also expect that SIBYLL 2.0 should provide a more reliable extrapolation to the highest energies.

2 New version of the SIBYLL model

In general, recent models of hadron production in EAS consist of the following building blocks: (a) model for leading particle production in hh interactions ($h = \pi, K, p$), (b) model for central particle production in hh interactions, and (c) model for relating hh interactions to hA and AA collisions. Here, we concentrate on leading and central particle production. The model used to relate hh interactions to hA and AA interactions will be discussed elsewhere (Engel 1999).

The description of high-energy hadron production in SIBYLL is based on the minijet model (Durand & Pi 1987, Gaisser & Halzen 1987). The most important model assumptions are the following: (i) the rise of the total cross section is governed by the increase of the minijet cross section, (ii) there are multiple hard parton-parton interactions per hadron-hadron collision possible, and (iv) the change of the leading particle distribution with energy is driven by energy-momentum conservation effects (due to the increasing amount of energy entering central particle production). A detailed description of the model and it's predictions can be found in (Fletcher 1994).

There are several shortcomings of the old version of SIBYLL which were already discussed in (Fletcher 1994). First of all, it does not describe accurately enough the rise of the total $p\bar{p}$ cross section over the collider energy range. Secondly, the multiplicity fluctuations and the mean charged particle multiplicity are too small at high energy. These problems have been solved in SIBYLL 2.0.

In this new SIBYLL version, an energy-dependent soft cross section is introduced to accommodate for the rise of the total $p\bar{p}$ cross section in the center-of-mass energy range from $\sqrt{s}$ = 50 to 900 GeV. As a direct consequence multiple soft interactions of partonic constituents have to be considered. Previously, only one soft interaction per inelastic collision was generated.

The lack of large multiplicity fluctuations in SIBYLL 1.7 is mainly related to the model used for the unitarization of the soft and minijet cross section. The old unitarization model does not explicitly include diffraction dissociation. With the introduction of excited states of the projectile and target particles, which are produced in diffractive interactions, the description of the multiplicity distribution has improved considerably.

The average particle multiplicity predicted by SIBYLL 2.0 is higher at high energy than that of SIBYLL 1.7. The reason for this is mainly the introduction of multiple soft interactions and new parton densities which describe recent HERA data. The EHLQ parton densities used in the old version of the model correspond to an extrapolation of the gluon density of $g(x) \sim 1/x$ at low x. New parton density parametrizations (for example, (Glück, Reya & Vogt 1995, 1998)) implement a much steeper increase of the gluon number $g(x) \sim 1/x^{(1+\Delta)}$ with $\Delta = 0.3 \ldots 0.4$. Thus the change of the low-x extrapolation of the parton densities change the minijet cross section substantially at high energy. However, it is clear that the gluon density governing the minijet cross section at high energies, cannot rise without limit (Gribov, Levin & Ryskin 1983, Levin & Ryskin 1990). If the number of gluons times the transverse resolution scale of hard interactions ($\sim 1/p_\perp^2$) becomes comparable to the proton size, saturation effects cannot be neglected.

Another complication is the limited applicability of the collinear factorization approximation which is usually applied to calculate minijet cross sections. Although the inclusive minijet rate is reasonably well described in this approximation, the relation $\sigma_{\rm hard} = \frac{1}{2}\sigma_{\rm incl.jet}$ does not hold at high energy (Kwieciński 1987). The reason is that in the collinear approximation only terms with large logarithms $\ln(p_\perp^2)$ are consistently summed. At large energy, additional contributions with $\ln(1/x)$ become large and have to be taken into account (Lipatov 1997).

In order to restrict the calculation of the minijet cross section to the phase space where the QCD improved parton model is expected to be reliable, we apply the following energy-dependent transverse momentum cutoff (Levin & Ryskin 1990)

$$p_\perp^{\rm cutoff} = p_\perp^0 + \Lambda \exp\left\{ c\sqrt{\ln(s/{\rm GeV}^2)} \right\}, \qquad (1)$$

with $p_\perp^0 = 1$ GeV, $\Lambda = 0.065$ GeV, and $c = 0.9$. Consequently, all partonic interactions leading to partonic final states with $p_\perp < p_\perp^{\rm cutoff}$ are considered as soft interactions and the soft interaction model is extended to higher transverse momenta.

3 Predictions for EAS

In the following we present results of a one-dimensional shower calculation. Electromagnetic cascades are treated with a simplified electromagnetic Monte Carlo in combination with Greisen's formula. The Monte Carlo includes photoproduction (Lipari 1997, Gaisser, Lipari & Stanev 1997). Hadronic particle interactions have been simulated down to the muon energy threshold of 1 GeV. Hadron-induced interactions with energies below $E_{\rm thr.} = 200$ GeV in lab. frame have been calculated with TARGET (Gaisser, Protheroe & Stanev 1983). All results refer to vertical showers with the detector being at sea level. The averages have been computed from 1000 simulated showers at each energy.

The calculations have been done with three models: SIBYLL 1.7, SIBYLL 2.0, and QGSjet (Kalmykov & Ostapchenko 1993 and Kalmykov, Ostapchenko & Pavlov 1997) as implemented in CORSIKA (Heck *et al.*

Table 1: Mean muon yields of proton induced air showers for different muon energy cutoffs at sea level.

	SIBYLL 1.7		SIBYLL 2.0		QGSjet	
$E_{\rm prim}$	1 GeV	1 TeV	1 GeV	1 TeV	1 GeV	1 TeV
10^{14} eV	960 (0.29)	0.54 (1.44)	1000 (0.27)	0.69 (1.29)	1040 (0.26)	0.55 (1.46)
10^{15} eV	7230 (0.25)	3.11 (0.68)	8030 (0.22)	3.70 (0.64)	8075 (0.24)	3.39 (0.69)
10^{16} eV	54900 (0.21)	18.6 (0.38)	62900 (0.20)	21.8 (0.41)	64050 (0.21)	20.6 (0.38)
10^{17} eV	410200 (0.21)	120 (0.28)	499000 (0.19)	140 (0.27)	520300 (0.18)	140 (0.29)

Table 2: Mean depth of maximum $X_{\rm max}$ (in g/cm^2) and shower size at depth of maximum $S_{\rm max}$. The relative width of the distributions is given in parenthesis.

	SIBYLL 1.7		SIBYLL 2.0		QGSjet	
$E_{\rm prim}$	$X_{\rm max}$	$S_{\rm max}$	$X_{\rm max}$	$S_{\rm max}$	$X_{\rm max}$	$S_{\rm max}$
10^{14} eV	528 (0.19)	6.95 10^4 (0.16)	485 (0.17)	6.94 10^4 (0.13)	510 (0.18)	6.90 10^4 (0.14)
10^{15} eV	592 (0.14)	7.18 10^5 (0.11)	550 (0.13)	7.25 10^5 (0.09)	575 (0.14)	7.22 10^5 (0.10)
10^{16} eV	650 (0.11)	7.26 10^6 (0.08)	612 (0.11)	7.37 10^6 (0.06)	630 (0.11)	7.31 10^6 (0.07)
10^{17} eV	708 (0.09)	7.28 10^7 (0.05)	675 (0.09)	7.31 10^7 (0.05)	690 (0.09)	7.19 10^7 (0.06)

1998). It is interesting to compare the SIBYLL predictions to those of QGSjet since the latter describes the KASCADE data reasonably well (Antoni *et al.* 1999).

In Table 1 the mean values for muon yields for different energy thresholds are given. For each mean value the relative width of the distribution is given in parentheses. The comparison shows that the number of muons predicted by SIBYLL has increased from version 1.7 to 2.0 by about 10%. Furthermore, the new SIBYLL version results in muon yields which are comparable to the QGSjet results. The number of very high-energy muons predicted by SIBYLL 2.0 is the largest of all compared models, however, it should be noted that these values are subject to very large fluctuations.

The muon numbers given for the energies 10^{14} and 10^{15} eV can be directly compared to the results obtained with the CORSIKA code using the old SIBYLL version and QGSjet (Knapp *et al.* 1996). Whereas in the case of QGSjet the multiplicities we obtain are in good agreement with those of Knapp *et al.*, this is not the case for the old SIBYLL model; we find consistently larger low-energy muon multiplicities with SIBYLL than Knapp *et al.*. The origin of this technical discrepancy needs to be investigated, but we can imagine two possible sources. We used the the proton- and pion-air cross sections as predicted by each model, whereas model-independent hadronic cross sections were used in the CORSIKA simulations (Knapp *et al.* 1996). In addition, different low-energy models were used in combination with different energy thresholds between the high- and low-energy models (CORSIKA: GEISHA with $E_{\rm thr.} = 80$ GeV; here TARGET with $E_{\rm thr.} = 200$ GeV lab energy).

In Tab. 2 we show the predictions of the models for the average depth of maximum $\langle X_{\rm max}\rangle$ and the shower size. As expected, the total shower size at $X_{\rm max}$ reflects rather well the primary particle energy and is almost independent of the model used for the calculation. By contrast, the depth of maximum depends strongly on the model. The new SIBYLL model predicts shallower depths of the shower maximum than both old SIBYLL and QGSjet. The change in the SIBYLL prediction is mainly related to the change of the hadronic cross sections and an increase of the inelasticity at high energy. It should be emphasized that the part of the model describing forward particle production was not explicitly altered between versions 1.7 and 2.0. The increased inelasticity is mainly due to increased particle production in the central region coupled to the fragmentation region by energy-momentum conservation.

In the studied energy range, the elongation rate $\Lambda = dX_{\max}/d\log_{10}(E_{\text{prim}})$ predicted by the old SIBYLL version is the smallest of the three models. Assuming an constant elongation one gets about 60 g/cm^2 for SIBYLL 1.7 and 63 g/cm^2 for SIBYLL 2.0. In the case of QGSjet it is not possible to approximate the elongation rate by a constant.

Finally we show the correlation of the electron and muon number at sea level in Fig. 1. The contour lines correspond to about half the maximum for each model and energy. In contrast to the results reported by Knapp *et al.* 1996 we find similar muon distributions for all models considered here. The different number of electrons are directly correlated to the mean depth of maximum of the models given in Tab. 2.

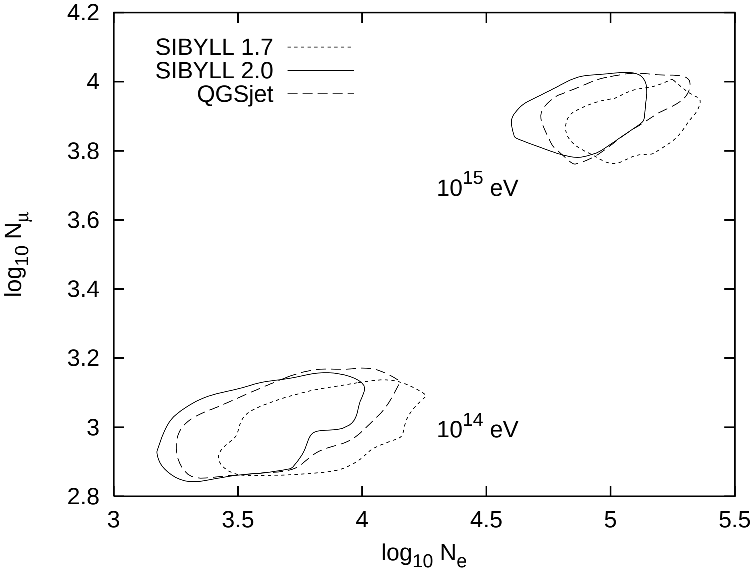

Figure 1: Electron-muon number correlation in proton induced EAS.

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