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The hadronic interaction model Sibyll 2.3c and muon production in extensive air-showers

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Abstract. One of the applications of the hadronic interaction model Sibyll is the simulation of extensive air showers of ultra-high energy cosmic rays. In recent years it has become more and more clear that simulations do not agree with measurements when it comes to observables related to muons in air showers. We discuss the processes in Sibyll that are directly related to muon production in extensive air showers and describe their relation to shower observables.

1 Introduction

Ultra-high energy cosmic rays (UHECR) can only be measured through the detection of extensive air showers (EAS). The extraction of the properties of the primary UHECR from observables relies on simulations of EAS. For the most part, the ingredients for air shower simulations are well understood and the principal physics is known. There are technical and performance problems with handling many particles and treating the large range of scales involved, but no fundamental issues. The exception are, of course, hadronic interactions. Here we are in the interesting situation where we have a precise theory of the microscopic nature of the interactions (QCD), which, once basic things have been measured at a given energy, can be used to make rather accurate predictions of the different aspects of hadronic particle production at this energy. We can predict the multiplicity of particles, angular and transverse momentum distributions etc. What we can not predict (accurately) is how these observables change when interactions in a new configuration, e.g. at higher energy or in a different phasespace region are considered.

Since hadronic interactions are essential for EAS simulations, everything that is known (and deemed important) about how hadrons interact, together with reasonable assumptions on how they should interact at high energy, is combined into hadronic interaction models. Although, the results obtained with these models are very encouraging [1], there are several observed discrepancies between EAS measurements and simulations [2–4], which are attributed to uncertainties or deficiencies in the hadronic interaction models.

One of the hadronic interaction models commonly used in air shower simulations is Sibyll. In this contribution we give a short overview of physics assumptions implemented in this model that are related to muon production in EAS.

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2 The interaction model

The interaction picture in Sibyll is inspired by the dual parton (DPM) [5] and minijet [6–9] models. The hadronization algorithm is based on the LUND model [10, 11], also known as string fragmentation. Details of the underlying model, amplitude calculations and cross section parameters can be found in [12]. The extension of Sibyll to charm production and the predictions for atmospheric fluxes of muons and neutrinos are discussed in [13]. The details of the current version Sibyll 2.3c will be published elsewhere [14]. Most modifications and intermediate results were discussed previously [15–18]. Here we focus on the predictions of the new model for muon production in extensive air showers.

2.1 Mechanisms of muon production in extensive air showers

When cosmic rays (CR) interact with nuclei in the atmosphere, they initiate extensive air showers (EAS). Air showers develop in two cascades: the hadronic and the electromagnetic (em.) cascades. Muons are produced by the decay of mesons in the hadronic cascade. Due to relativistic time dilation, decays are suppressed at high energies ($\gamma = E_{\rm Lab}/m$), so most muons are produced at comparatively low energies. For example, for muons produced in air showers with a primary energy of 10^{19} eV that can be detected at a distance of 1000 m from the axis of the shower, the energy of the mesons before the last interaction is between 10 to 100 GeV [19]. Between the primary particle and the decaying mesons lies the cascade of

hadronic interactions. In each interaction, the energy of the primary particle is converted into mass and distributed among secondary particles. From the perspective of the cascade, the secondary particles fall into two groups: those that decay into hadrons and those that decay into photons and/or electrons instead. The former enter the next stage of the hadronic cascade, while the latter will contribute to the em. cascade and will not produce muons. The final yield of muons depends strongly on the balance between these two groups. The currency of particle production is energy, so the important quantity for muon production is not only the multiplicity but the fraction of energy carried by the hadrons [20].

Mechanisms that increase the number of muons in EAS typically modify the balance between the em. and hadronic cascade. The two mechanisms that are important in Sibyll 2.3c and which will be discussed in the following are baryon-antibaryon pair production [21, 22] and leading ρ^0 production [23, 24].

2.2 ρ^0 production

Neutral pions have a very short lifetime. Within the energy range of cosmic ray observations they essentially always decay and never interact (re-interaction plays a role above 10^{20} eV). As lightest hadrons with a mass close to the muon mass, they can only decay to electrons or photons. The dominant channel ($\approx 99\%$) is the decay into two photons

$$\pi^0 \to \gamma\gamma\,. \tag{1}$$

As lightest hadrons, pions are also most abundantly produced in hadronic interactions. Approximating hadronic particle production with pion production, 1/3 of all particles produced are neutral pions. Assuming the energy is shared equally among the produced particles, at each step in the cascade (with each generation), 1/3 of the energy is transferred from the hadronic to the em. cascade by the neutral pions. The cascade continues until the energy per particle is too low to produce new particles, or until other processes become more likely. For pions (mesons) this is the decay, whereas for protons (baryons), which are stable, the cascade continues until they become non-relativistic. The energy per particle at which the cascade stops is called the critical energy, ϵ_c. Formally, using the approximations above, this gives for the final number of muons

$$N_\mu = \left(\frac{E_0}{\epsilon_c}\right)^\beta\,, \tag{2}$$

where $\beta = \ln n_{\text{charged}} / \ln n_{\text{total}}$ and n_{charged} and n_{total} are the charged and total multiplicities of pions [25]. While this definition of the exponent β and the value of the critical energy is only applicable under these approximations, more detailed MC studies show that the number of muons still obeys a power law relation as shown above [26, 27]. In a realistic scenario, energy is not equally distributed among the secondary particles. In fact, accelerator experiments have shown that a large part of the energy is carried by a leading particle which emerges from the debris of the projectile (in laboratory reference frame). These particles will play a more important role in the subsequent development of the shower and influence the effective value of β more than low energy particles.

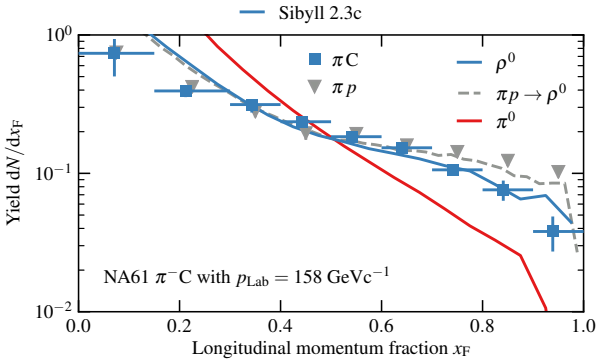

Figure 1. ρ^0 production in pion-proton and pion-carbon collisions.

A state with a higher mass in the spectrum of mesons similar to pions are the ρ mesons. The essential difference is ρ mesons are spin 1, which means the neutral state ρ^0 cannot decay into two photons, instead the dominant decay ($\approx 100\%$) is into two pions,

$$\rho^0 \to \pi^+\pi^-\,, \tag{3}$$

i.e., instead of feeding energy into the em. cascade like neutral pions, neutral ρ mesons keep energy in the hadronic cascade. Since ρ mesons are related to the pions, they will also benefit from the leading particle effect. Allowing one quark of the projectile pion to be exchanged, there are four options in pion air interactions:

$$\pi^\pm + \text{Air} \to \pi^\pm + X, \tag{4}$$
$$\pi^\pm + \text{Air} \to \pi^0 + X, \tag{5}$$
$$\pi^\pm + \text{Air} \to \rho^\pm + X \tag{6}$$
$$\pi^\pm + \text{Air} \to \rho^0 + X\,. \tag{7}$$

The expectation for the relation between these channels based on the parton model and fragmentation in Sibyll2.1 is that pion and ρ production share the same energy spectrum but that the rate of ρ production is lower, mostly due to the larger mass [17]. Experiments, on the other hand, find that the spectrum of ρ production is much harder than the pion spectrum and exceeds pion production at large x_F ($x_F = p_z/p_{z,\text{max}}$ in the center-of-mass frame) [28, 29]. To account for this effect in Sibyll2.3c, the fragmentation parameters for diffractive processes in meson interactions were adjusted to favor spin-1 states. Also the newly introduced remnant excitations were set to prefer the ρ excitation [24]. In Fig. 1 the recent measurement of the Feynman-x spectrum of neutral ρ mesons in pion-carbon interactions is shown [30]. There is good agreement between the measurement and the prediction by Sibyll 2.3c.

The model in Sibyll is entirely based on observations. So far the enhancement of leading ρ has only been observed in low energy interactions, so little is known about

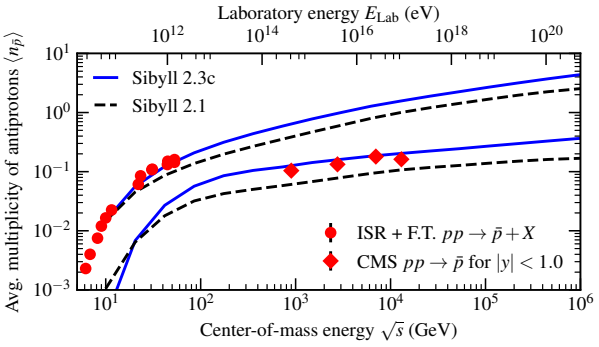

Figure 2. Average multiplicity of antiprotons as a function of center-fo-mass energy for proton-proton collisions.

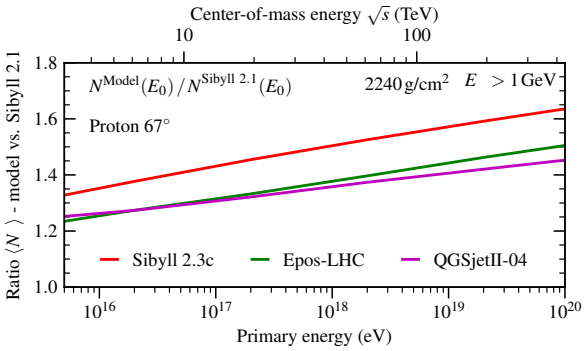

Figure 3. Predicted number of muons at the ground for the different post LHC interaction models relative to Sibyll 2.1.

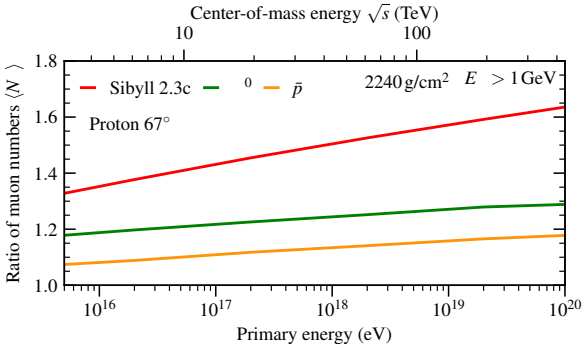

Figure 4. Contributions from different processes to the number of muons predicted by Sibyll 2.3c relative to Sibyll 2.1.

the energy dependence of the effect. For the implementation in Sibyll, no explicit energy dependence is built in. Implicitly, the effect loses importance at higher energies since both diffraction dissociation and the remnant excitation are suppressed at large energies.

2.3 $N\bar{N}$ production

Due to their high mass and the constraints from baryon number conservation, the rate of baryon-pair production in hadronic interactions is much lower than for mesons. Nevertheless, they play an important role in air showers. Due to baryon number conservation, baryons cannot leave the hadronic cascade through decay. They essentially transform all their kinetic energy into particles. In combination with the leading particle effect, baryons efficiently retain energy in the hadronic cascade and thereby increase the number of muons, when compared to a pion-only model.

In Sibyll 2.1, baryons are formed in the fragmentation process by the creation of diquark-antidiquark pairs. This is done universally for all fragmenting systems, whether it is hard-parton scattering or the dissociation of a diffractively excited state, the rate of baryon-pair production is determined by a global parameter $P_{\rm diq}$. Energy dependence in this approach is given by the growth of phase space and the minijet cross section. However, in comparison with experimental data, the production rate is underestimated at high energies [31–33] (see Fig. 2). In Sibyll 2.3c the diquark rate is therefore chosen to differ between diffractive, basic-inelastic (single color exchange) and hard-scattering processes (multiple exchanges).

3 Prediction for muon production in extensive air showers

Overall, the number of muons has increased between Sibyll 2.1 and Sibyll 2.3c. At the same time the shower development is shifted deeper (increase of average $X_{\rm max}$). We will discuss the changes in the muon production in more detail here. For a discussion of $X_{\rm max}$ we refer to the upcoming paper [14]. In the air-shower simulations shown here, muons are sampled at an observation level of 1400 m a.s.l. for inclined showers with a primary energy of 10^{19} eV. Simulations were done with CONEX [34] using FLUKA [35, 36] as low-energy interaction model. The energy threshold for muons is set to 1 GeV.

Relative to Sibyll 2.1, the change in the number of muons amounts to 30% to 60% in the energy range from 10^{16} eV to 10^{20} eV (see Fig. 3). Compared with other post LHC interaction models [37, 38], Sibyll 2.3c produces the highest number of muons in this particular configuration. As we will see, this ranking depends strongly on the muon energy threshold. The reason for the strong increase of the number of muons are the two mechanisms discussed in the previous section. Both mechanisms, baryon-pair and ρ production, shift the balance of energy towards the hadronic cascade. This corresponds to an increase in the slope β in Eq. (2) and means the effect should be larger at high primary energies (see Fig. 3). To be clear, this is not because these are effects of high-energy physics, but because as the primary energy increases, the number of low-energy interactions increases exponentially. In particular, baryon-pair production greatly enhances the number of low-energy particles. In Fig. 4 the contributions from baryon-pair and ρ production are shown relative to Sibyll 2.1. Enhanced baryon-pair production leads to an increase in the number of muons of around 10% to 20%, while the increase due to ρ production amounts to 20% to

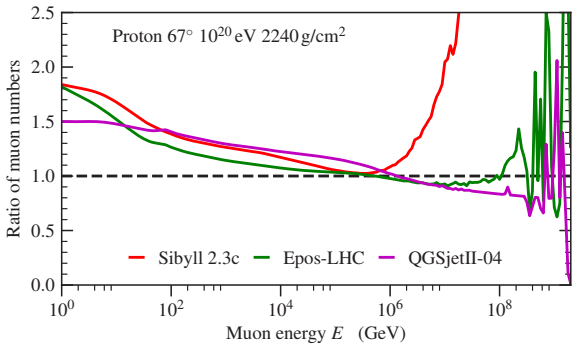

Figure 5. Predicted energy spectrum of muons at ground for the different post LHC interaction models relative to Sibyll 2.1. The primary energy is 2×10^{20} eV.

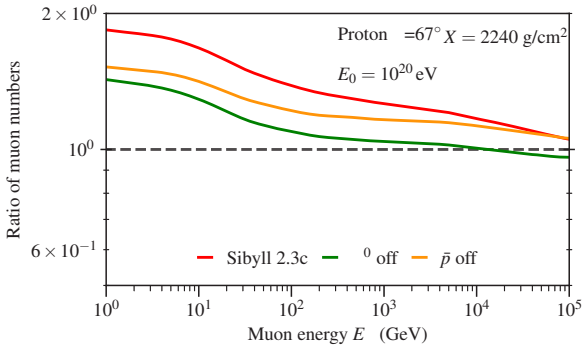

Figure 6. The muon energy spectrum predicted by Sibyll 2.3c and variants with extensions switched off relative to Sibyll 2.1.

30%. For both mechanisms the effect is stronger as the energy, and hence the number of generations in the shower, increases.

From the nature of the production mechanisms discussed in the first section, it was inferred that the additional muons present in Sibyll 2.3c are mostly of low energy. This is confirmed in Fig. 5 which shows the muon-energy spectra of post LHC interaction models relative to that of Sibyll 2.1. While N_μ is largest in Sibyll 2.3c for muon energies above 1 GeV, the figure shows that this is only the case in the range between 1 and 100 GeV. The strong increase in muons beyond 1 PeV in Sibyll 2.3c is due to charmed hadrons, which are not treated in the other models. At these energies, the parent pions and kaons of the muons have such long lifetimes that rare processes like charm production start to play a role [13]. The difference between baryon-pair and ρ production can be seen in Fig. 6. Here, the muon energy spectrum is again shown as a ratio with the energy spectrum in Sibyll 2.1. In addition to Sibyll 2.3c, two models where the extensions enhancing the production of ρ^0 and baryon-pairs have been switched off are also shown. By comparing these modified versions with the full model, the impact of the different mechanisms on the muon energy becomes visible. Both processes enhance muon production by preserving energy

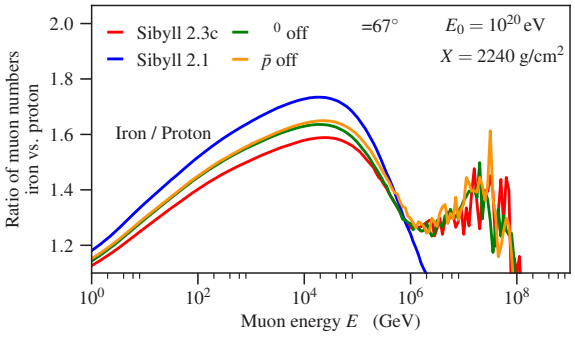

Figure 7. Contributions from different processes to the difference between the muon energy spectra of proton and iron primaries.

in the hadronic cascade. In case of ρ production the energy is kept in charged pions, which at any point (unless at extremely high energy) may decay, thus enhancing muons of all energies. Baryon-pair production, in combination with the leading particle effect, on the other hand, effectively locks the energy in the baryons, only to be gradually released among many interactions producing many low-energy pions.

A side effect of the baryon-pair and ρ production is that the difference between primaries decreases. Starting from Eq. (2), the superposition ansatz suggests that the number of muons for primaries with nucleon number A is $A^{1-\beta}$ times higher. As β approaches unity, the difference between primaries of different A is diminished. The effect can be seen in Fig. 7 in which the ratio of the muon energy spectra between iron and proton primaries are shown for different versions of Sibyll.

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