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# Pythia 8 as hadronic interaction model in air shower simulations

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**Abstract.** Hadronic interaction models are a core ingredient of simulations of extensive air showers and pose the major source of uncertainties of predictions of air shower observables. Recently, Pythia 8, a hadronic interaction model popular in accelerator-based high-energy physics, became usable in air shower simulations as well. We have integrated Pythia 8 with its new capabilities into the air shower simulation framework CORSIKA 8. First results show significantly shallower shower development, which we attribute to higher cross-section predictions by the new simplified nuclear model of Pythia.

## 1 Introduction

Large-scale experiments in modern ultra-high energy cosmic ray research rely heavily on simulations of extensive air showers to link air shower observables to properties of the primary cosmic ray. An important ingredient in these simulations are hadronic interaction models (also known as event generators) that govern the interactions of hadronic shower particles with air nuclei. Due to the nature of the strong interaction, the wealth of hadronic interactions and multiparticle production is difficult or impossible to calculate from first principles alone. Only hard processes, i.e. those involving a large momentum transfer, can be treated within the framework of perturbative quantum chromodynamics (pQCD). The bulk of soft interactions, however, relies mainly on phenomenological modelling in combination with theoretical constraints and pQCD [1]. The most widely used up-to-date models used in air shower simulations are EPOS-LHC [2], QGSJet-II.04 [3] and SIBYLL 2.3d [4]. While EPOS-LHC has its origins in heavy-ion physics, the other two are specifically tailored to the needs of air shower simulations and the features of hadronic interactions important in that context.

In accelerator-based high-energy physics (HEP), a very popular event generator is Pythia [5], currently at version 8.3 [6]. For a long time, Pythia was not suitable for air shower simulations, mainly due to entirely different setups employed in HEP and air shower simulations: While simulations for accelerators typically generate a large number of events with the same settings (beam particle IDs and momenta), air shower simulations require event generation with these settings randomly varying event by event. Recently, progress has been made in making Pythia 8 more suitable for that setup [7]. On the one hand, this pertains to an accelerated context switching between beam parameters. On the other hand, the number of valid beam particles has been extended and a simplified model of hadron-nucleus collisions has been developed, while the fully-fledged Angantyr module [8] for heavy-ion collisions is not yet usable in air shower simulations. Moreover, the range of valid beam energies has been extended down to $\sim 200\,\mathrm{MeV}$ (lab), which means that Pythia can be used without an additional low-energy hadronic interaction model or just as such together with another high-energy model.

In this contribution we describe and analyse first results obtained using Pythia 8 in a realistic air shower simulation. For this, we have integrated Pythia 8.307 into the air shower simulation framework CORSIKA 8 [9] (Note that Pythia 8 already has been used to handle particle decays in CORSIKA 8). This work represents a continuation of the study started in ref. [10].

## 2 Setup

We simulate air showers in a hybrid fashion: Hadronic interactions and propagation of hadron and muons are treated in a Monte Carlo manner in CORSIKA 8. Electromagnetic particles are passed to CONEX [11], which generates longitudinal profiles by solving the cascade equations numerically. Hadrons and muons stemming from photohadronic interactions are therefore missing in this setup. We consider showers at $10^{17.5}\,\mathrm{eV}$ with an inclination of 60° using Linsley's parameterization of the US Standard atmosphere (see e.g. ref. [12]). The observation level is set to sea level. We consider SIBYLL 2.3d, EPOS-LHC and Pythia 8.307 as high-energy interaction model above 63.1 GeV. In each case, Pythia is used as low-energy model down to the hadron/muon cut energy that is set to 1 GeV. For nuclear projectiles that cannot be treated directly in the simplified nuclear model, we employ the semi-superposition model implemented in SIBYLL that

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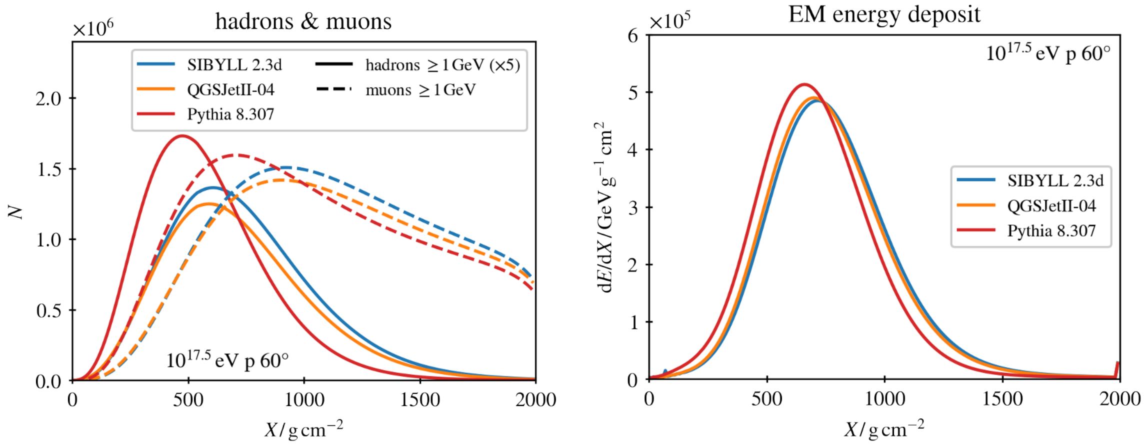


**Figure 1.** Longitudinal profiles. Left: hadrons and muons. Right: electromagnetic energy deposit.

breaks down $A - A$ collisions into multiple $p/n - A$ collisions [13].

## 3 Results

Figure 1 shows the average longitudinal profiles of proton-induced showers. We observe that Pythia produces some 30 % more hadrons than the traditional models in its maximum, which occurs 120 g cm$^{-2}$ to 140 g cm$^{-2}$ earlier than with the other models. Regarding the muon profile, the maximum with Pythia is more than 200 g cm$^{-2}$ shallower and the number of muons at the maximum is $\sim$ 6 % higher than with QGSJet-II.04. At ground, however, the number of muons $N_\mu$ is smaller with Pythia due to the longer propagated distance causing higher energy losses and a higher probablity of in-flight decay. The electromagnetic (EM) longitudinal profiles differ less severly as the EM cascade quickly decouples from the hadronic one, so that deviations in the hadronic interactions cannot accumulate that much.

Figure 2 displays the results in the $X_{\max}$-$N_\mu$ plane also for heavier primaries. We note a significant shift of the Pythia line by $\sim$ 40 g cm$^{-2}$ to 50 g cm$^{-2}$ towards lower $X_{\max}$ values w.r.t. the other models.

It has been shown by Ulrich et al. [14] that a variation of the inelastic hadron-air cross-sections has a large impact on $X_{\max}$ while leaving $N_\mu$ almost unchanged. For that reason, we show the model predictions of the inelastic cross-sections in fig. 3. Due to the wealth of precise data on $pp$ collisions from accelerator measurements up to LHC energies ($\sim$ $10^{17}$ eV in lab frame) to which the models have been tuned, the predictions differ only slightly. Precise data on $\pi^\pm p$ collisions, however, exist only up a few 100 GeV, so that predictions diverge especially above $10^{14}$ eV, with Pythia yielding the lowest values. At present, it is unknown whether the $\pi p$ cross-sections eventually converge to the $pp$ ones, which is expected assuming a universal saturation of low-$x$ gluons, or stay below as expected from a Pomeron-style rise.

When considering oxygen targets, the picture is different. Pythia predicts cross-sections significantly higher

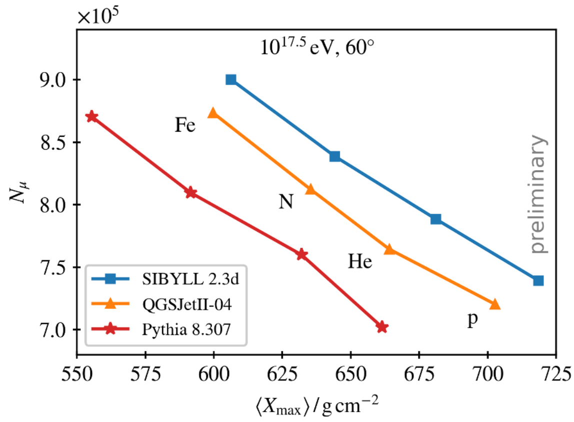


**Figure 2.** Number of muons at ground $N_\mu$ vs. shower maximum $X_{\max}$

than the other models. The simplified nuclear model of ref. [5] considers only total cross-sections $\sigma_{\mathrm{tot}}$ by employing the relation $\sigma^{(hA)}_{\mathrm{tot}} = A\sigma^{(hp)}_{\mathrm{tot}}/\langle n_{\mathrm{subcoll}}\rangle$, with the mean number of subcollisions $\langle n_{\mathrm{subcoll}}\rangle$ parameterized from full Angantyr events. Therefore, we estimate the inelastic cross-section by scaling $\sigma_{\mathrm{tot}}$ with the ratio $f_{\mathrm{inel}}$ of inelastic events, which we determined to be approx. 92 % in case of $\pi O$ and 90 % in case of $pO$ events with negligible energy dependence. It is noteworthy that Pythia yields the smallest cross-sections among the considered models in case of $\pi p$ but the largest in case of $\pi O$ and $pO$.

## 4 Conclusions and outlook

We have integrated the latest version of Pythia 8 into CORSIKA 8 to be used as hadronic interaction model for realistic air shower simulations for the first time. The results presented demonstrate that Pythia is capable to meet the higher demands (more projectile/target configurations, extrapolations to beyond-LHC energies) of such simulations compared to its original use-case in accelerator-

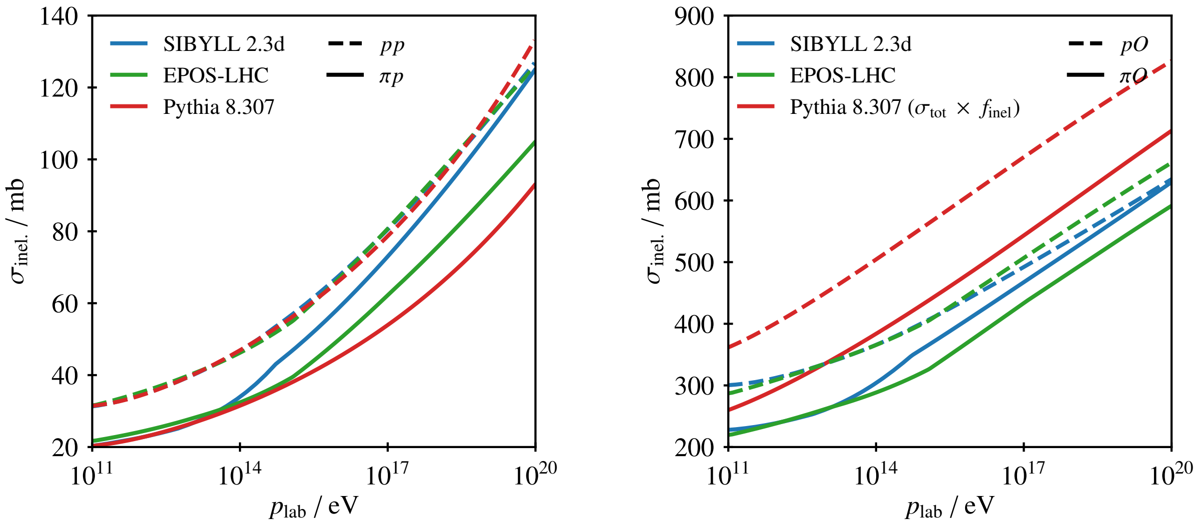


**Figure 3.** Inelastic cross-section predictions. Left: proton target, right: Oxygen target

based high-energy physics. The observed differences in the longitudinal development can be attributed to cross-section predictions significantly higher than those of the other models – an issue that requires further investigation and improved modelling. Further refinements and improvements, also regarding the use of Angantyr directly, are ongoing and expected in upcoming releases.

The availability of Pythia 8 in air shower simulations does not only provide yet another interaction model but also interesting opportunities: The possibility of tuning the model by the users themselves may offer new insights into the production of muons and its uncertainties by systematically studying the impact on air shower observables and accelerator measurements at the same time. Moreover, Pythia 8 is the only model treating the production of all quark flavors. Until now, only SIBYLL models charm production. Finally, the advent of Pythia 8, being an object-oriented C++ code, marks an important step towards enabling parallelization of CORSIKA 8 simulations by multithreading.

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