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CORSIKA 8 with Pythia 8/Angantyr: Simulating Inclined Proton Showers

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The Muon Puzzle — an unresolved excess of muons in cosmic-ray air showers compared to theoretical predictions — remains at the forefront of air shower physics research. With the electromagnetic component rapidly attenuated in the atmosphere, inclined air showers provide a valuable tool to investigate this discrepancy by highlighting the hadronic processes that dominate muon production at ground level.
Recent advancements, particularly in the Angantyr model of Pythia 8, offer promising enhancements in describing hadron-nucleus interactions, thereby motivating its potential application in air shower simulations. The ongoing implementation of Pythia 8/Angantyr within the CORSIKA 8 framework reflects this potential.
Building on prior studies of vertical showers, this work shifts its focus on inclined shower geometries using Pythia 8/Angantyr to model hadronic interactions. We present CORSIKA 8 simulations results of inclined proton-induced air showers, with commonly used interaction models, EPOS-LHC, Sibyll 2.3d, QGSJet-II.04, as well as Pythia 8.312/Angantyr.

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Introduction

The hadronic interaction model Pythia 8 [1] has been making its first steps into the landscape of air shower simulations. One difference that Pythia brings to the table when compared to the commonly used models within this field, such as EPOS-LHC, Sibyll 2.3d and QGSJet-II.04 ([2–4]), is that Pythia 8 was not built with the requirements of air showers physics in mind. It was conceived as a general purpose particle interaction model, optimized for describing accelerator experiment measurements, i.e. e^+e^-, pp, $\bar{p}$p, pPb, PbPb interactions. The Angantyr model [5, 6] within Pythia 8 handles the nuclear interactions, providing a connection between high-energy particle physics and heavy-ion phenomenology.

An initial validation of Pythia 8/Angantyr in CORSIKA 8 [7–9] through vertical proton-induced showers at 10^{17} eV has been performed [10]. In this work, we present further results from the ongoing implementation of Pythia 8/Angantyr in CORSIKA 8 for inclined proton-induced air showers. At first, we discuss the cross-sections of the different high-energy hadronic interaction models available within CORSIKA 8. Secondly, we focus on the air shower simulation results including the longitudinal and energy loss shower profiles for all particles, as well as the lateral radial and energy distributions of the muons reaching sea level.

1. Cross-sections

In Figure 1, the inelastic cross-sections for proton-air interactions, from ~100 GeV to 100 EeV are displayed, for currently available high-energy interaction models within the CORSIKA 8 framework: Sibyll 2.3d, EPOS-LHC, QGSJet-II.04 and Pythia 8.312/Angantyr.

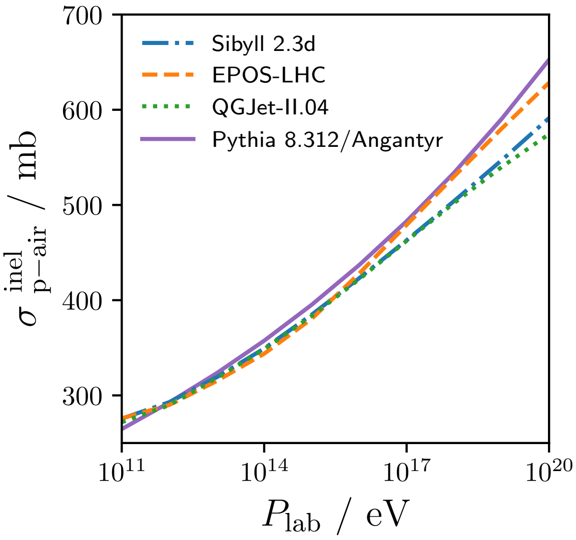

Figure 1: Inelastic cross-sections distributions as a function of the momentum in the laboratory frame of the projectile for proton-air collisions, predicted by the EPOS-LHC (dashed), QGSJet-II.04 (dotted) and Pythia 8.312/Angantyr (solid) interaction models assuming the composition of air as 78% nitrogen-14, 21% oxygen-16 to 1% argon-40 mix, and by Sibyll 2.3d (dash-dotted) for a simplified air composition of 80% nitrogen-14 to 20% oxygen-16 mix.

In proton-air interactions, all hadronic interaction models yield an extremely similar description until a divergence starting at the TeV scale, establishing Pythia 8 as the model with the highest cross-sections in the energy range of ultra-high energy cosmic-rays. Further collisions systems of interest for air shower physics, such as πp and π-air were discussed in previous studies [11].

2. CORSIKA 8 air shower simulations

2.1 Pythia 8/Angantyr implementation

The implementation of Pythia in CORSIKA 8 follows in the footsteps of previous studies [12, 13], with a recent shift to using the Angantyr machinery within Pythia 8.312 for nuclear interactions [10, 11] instead of PythiaCascade. A new feature allows for a single instance of Pythia to run, from which the beam system can be switched and the collision energy can vary on an event-by-event basis. In the existing framework, Angantyr treats collisions with nuclear targets, while Pythia is responsible for all other collision systems. The integration of nuclear projectiles handling within Angantyr in CORSIKA 8 is still a work-in-progress.

A comprehensive set of total and partial cross-sections for collisions with the atmosphere was tabulated to simulate interactions using Pythia within CORSIKA 8, as displayed for proton-air interactions in Figure 1. This database includes pions, kaons, protons, neutrons, other long-lived mesons and baryons as projectiles, as well as protons, ^{12}C, ^{14}N, ^{16}O and ^{40}Ar as targets. Another approach to handle nuclear interactions using the PythiaCascade approach is discussed in [14].

For this work, 1000 inclined air showers that were induced by protons with a primary energy of $10^{17.5}$ eV and a zenith angle of 60° were simulated using four different high-energy interaction models. The following energy thresholds for particle tracking were used: $e^{\pm}/\gamma$ particles at 10 MeV, hadrons and muons at 300 MeV. Electromagnetic particles with an energy below 10^{-6} times the primary energy were combined statistically to reduce runtime; this thinning is detailed in [8]. The energy threshold to transition from the lower energy model FLUKA [15] to Pythia 8/Angantyr is set at 100 GeV, while the CORSIKA 8 default value is ~80 GeV when using the other high energy models. The results discussed in this proceeding are still at a preliminary stage.

2.2 Shower development

When a cosmic ray interacts with the atmosphere, it creates a cascade of secondary particles, leading to an air shower. This shower develops as these particles undergo successive interactions and energy losses, forming distinct profiles that can be analyzed. Key observables include the longitudinal profile, which tracks the number of particles as a function of atmospheric depth and provides insight into the shower's evolution, and the lateral distribution function, which describes the spatial spread of particles at ground level. Additionally, energy loss profiles and particle spectra help characterize the shower maximum ($X_{\max}$) and the overall energy deposition in the atmosphere.

The average longitudinal shower profiles for several particle types including photons, electrons/positrons, hadrons and muons, are displayed in Figure 2. At first glance, a clear trend emerges across all particle species: Pythia 8/Angantyr produces more particles in the early stages of shower development, whereas fewer particles persist beyond $\sim 800\,\mathrm{g\,cm^{-2}}$ compared to the other models.

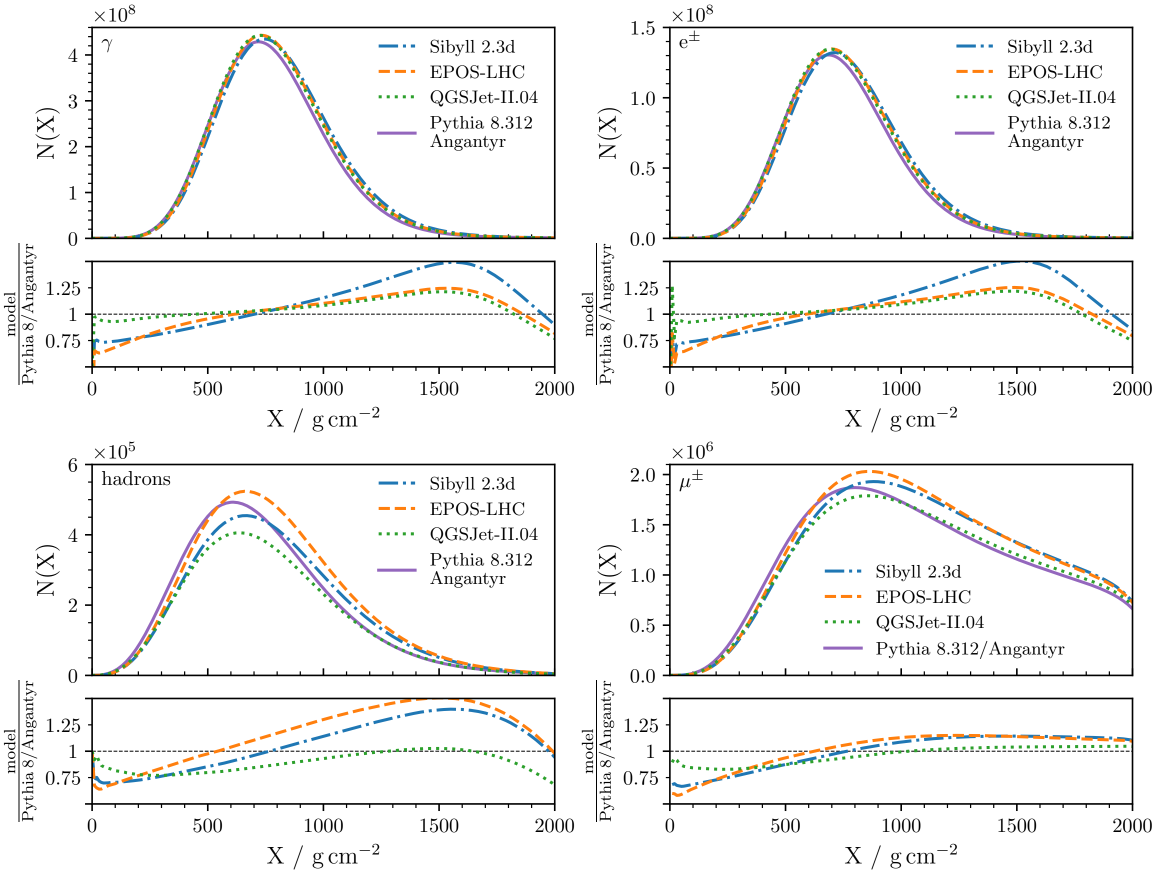

Figure 2: Average longitudinal shower profiles for inclined (θ = 60°) proton-induced $10^{17.5}$ eV air showers for various particle types: photons (upper left), electrons/positrons (upper right), hadrons (lower left) and muons (lower right); using FLUKA as low-energy interaction model, and Sibyll 2.3d (dash-dotted), EPOS-LHC (dashed), QGSJet-II.04 (dotted) or Pythia 8.312/Angantyr (solid) as high-energy interaction models.

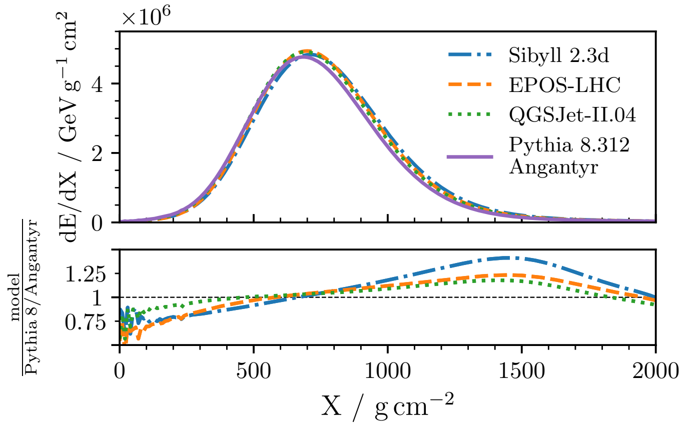

Figure 3: Average total energy loss distributions for inclined (θ = 60°) proton-induced $10^{17.5}$ eV air showers, using FLUKA as low-energy interaction model, and Sibyll 2.3d (dash-dotted), EPOS-LHC (dashed), QGSJet-II.04 (dotted) or Pythia 8.312/Angantyr (solid) as high-energy interaction models.

QGSJet-II.04 and Pythia show close agreement in the shower profiles of electromagnetic particles prior to $\sim 700\,\mathrm{g\,cm^{-2}}$, while for muons, this agreement between the two models emerges at a later stage of the shower development after $\sim 900\,\mathrm{g\,cm^{-2}}$. It is interesting to observe the crossover region between Pythia and the other models, especially for the hadrons: on the one hand, it occurs around $600\,\mathrm{g\,cm^{-2}}$ for EPOS-LHC, yet on the other hand, Pythia consistently predicts an equal or higher number of hadrons than QGSJet-II.04 on average throughout the entire shower development.

Figure 3 showcases the total energy loss profile, from which the depth of the shower maximum, X_{max}, is inferred and visualized in Figure 4. The shift between the models is clearly visible in Figure 3, where Pythia shows earlier contributions to the total energy loss on average compared to the other interaction models.

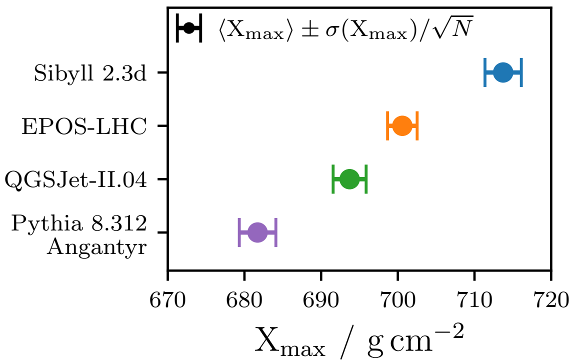

Figure 4: Average depth of the shower maximum for 1000 inclined ($\theta = 60°$) proton-induced $10^{17.5}$ eV air showers, using FLUKA as low-energy interaction model, and Sibyll 2.3d, EPOS-LHC, QGSJet-II.04 or Pythia 8.312/Angantyr as high-energy interaction models.

While there appears to be no agreement between the predictions for the average depth of shower maximum across all models, the results from the established models show a similar trend as from previous studies [16]. Pythia 8/Angantyr predicts steeper showers, characterized by a more rapid and earlier development, which is further corroborated by Figure 2. This emphasizes model-dependent differences in hadronic interactions at ultra-high energies. The inclusion of Pythia 8/Angantyr alongside established models increases ΔX_{max} to $\sim 30\,\mathrm{g\,cm^{-2}}$. However, since these predictions are based on preliminary work, their reliability remains an open question. This spread could have profound implications, introducing a key systematic uncertainty in mass composition studies, such as those conducted at the Pierre Auger Observatory.

2.3 Particles at sea level

At the observer level, the lateral distribution function describes the spatial spread of particles from the shower core, providing insight into the shower footprint. The energy spectra of charged particles at observer level help characterize energy deposition and the particle composition, offering insights into the energy profile of the shower. The observation level for all simulations discussed in this work is set at sea level, therefore not projected into the shower plane. No corrections were applied for the asymmetry effects resulting in the choice of this observer plane.

The average lateral distribution for muons can be found in Figure 5 (left), where Pythia 8/Angantyr exhibits a lower muon yield near the shower core than other models but produces up to 20% more muons at a distance of roughly 10 km from the shower axis.

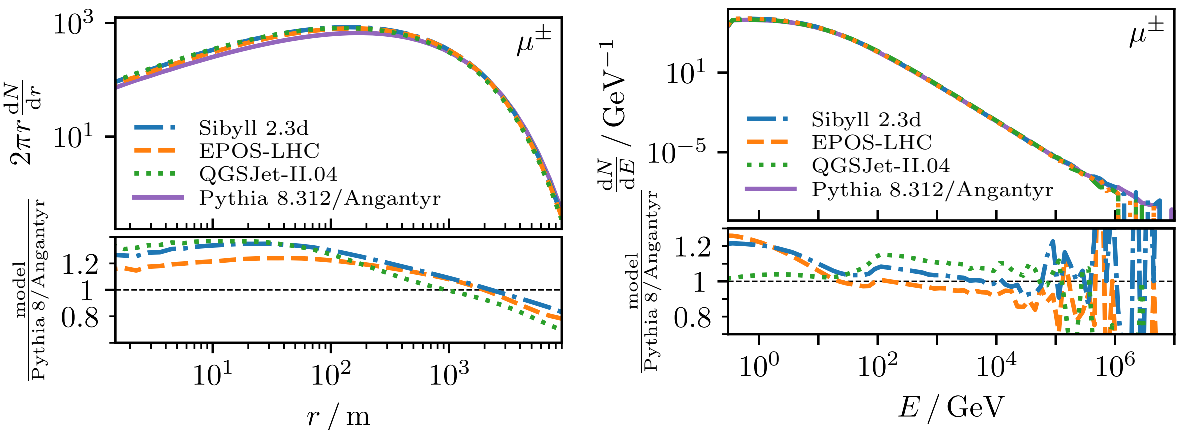

Figure 5: Average lateral distributions (left) and average energy spectra (right) of muons at sea level for inclined ($\theta = 60°$) proton-induced $10^{17.5}$ eV air showers, using FLUKA as low-energy interaction model, and Sibyll 2.3d (dash-dotted), EPOS-LHC (dashed), QGSJet-II.04 (dotted) or Pythia 8.312/Angantyr (solid) as high-energy interaction models. These results are preliminary.

The average energy spectrum of muons at ground is shown in Figure 5 (right). It is worth noting that in simulations using Pythia 8/Angantyr, all hadronic interactions below 100 GeV are handled by FLUKA, whereas for the other high-energy interaction models, this transition occurs at approximately 80 GeV. Pythia 8 and EPOS-LHC show agreement in their muon predictions for energies from 100 GeV to 10 TeV at sea level, while other models suggest a higher number of muons in this range. Beyond ~10 TeV, statistical uncertainties arising from the limited number of showers take precedence in all models.

Conclusion

The current implementation of Pythia 8/Angantyr within CORSIKA 8 is advancing step-by-step. The hadronic interactions in vertical and inclined proton-induced air showers can now be simulated with Pythia, and testing has been carried out for the energy range associated with the second knee. It is technically feasible to run Pythia at higher energies, given that cross-section look-up tables were computed up to 10^{20} eV, with further validation to be performed for ultra-high energy cosmic rays. Expanded validation studies at higher energies and for varying shower geometries will be undertaken to thoroughly evaluate the predictions of Pythia 8/Angantyr. In addition, the CORSIKA 8 development team is actively working on supporting nuclear projectiles with Pythia 8/Angantyr.

As discussed in a study by the Pierre Auger Collaboration [17], a deeper $X_{\max}$ would result in more muons at ground, suggesting that Pythia 8/Angantyr cannot solve the Muon Puzzle on its own. Thus, this underscores the need for a dedicated tuning study for air shower physics once the Pythia 8/Angantyr implementation in CORSIKA 8 is finalized. Pythia is particularly well-suited for such studies, as its structured and user-friendly tuning framework allows for systematic modifications of internal parameters, which can significantly impact air shower observables. Previous work has explored a forward physics tune of Pythia [18], and ongoing efforts aim to develop a tune specifically for fixed-target measurements [11].

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