Simulating Muon-Proton DIS for the SHiP Experiment using PYTHIA 6 and PYTHIA 8

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Abstract
In this study, I simulated fixed target muon-proton DIS events at SHiP energies ($10-300$ GeV) using PYTHIA 6.4 and PYTHIA 8.3. For each event generator, I used two different configurations and compared event characteristics such as transverse momentum $p_\perp$, pseudorapidity η, outgoing energy, particle IDs, multiplicity per event, and momentum transfer Q^2. In general, both PYTHIA event generators agree reasonably well. In particular, the PYTHIA 8 setting `mHatMin=0.5` increases the agreement with the PYTHIA 6 event generator.

Keywords
SHiP, PYTHIA 6, PYTHIA 8, Muon-proton DIS

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Contents

1 Introduction

The SHiP experiment is a state-of-the-art programme designed to search for feebly interacting particles (FIPs) in a mass and coupling region that is solely accessible in a beam-dump setup. In order to detect FIPs, the SHiP experiment aims to be a low-background experiment, thus there is a need to characterise the background events particularly well. One of the main sources of background is the deep inelastic scattering (DIS) of incoming muons with nucleons in the experiment. Currently, in the SHiP software framework *FairShip*, these simulations are done using PYTHIA 6. However, the development of this version of PYTHIA has stopped in December 2012. But of recently, PYTHIA 8.3 introduced muon-nucleon DIS. This finally allows for the possibility to update. As PYTHIA 8 introduced a large number of new parameters and settings, making this transition is not completely trivial. In particular, to transition from PYTHIA 6 to 8 for rare or non-LHC processes, there is a need to compare and validate results. Muon-nucleon DIS events are considered such processes. Hence, the need arises for a more detailed study.

In this paper, we compare the performance of the event generators PYTHIA 6.4 and PYTHIA 8.3 for fixed target muon-proton DIS events by inspecting event characteristics such as transverse momentum $p_\perp$, pseudorapidity η, outgoing energy, particle IDs, multiplicity per event, and momentum transfer Q^2. In the rest of the *Introduction*, the SHiP experiment is explained in more detail. The next chapter, *Muon-nucleon DIS*, briefly outlines the theory of muon-nucleon DIS. Continuing to the chapter *PYTHIA event generator*, the event generator PYTHIA is introduced and the main differences between PYTHIA 6 and 8 are highlighted. Moreover, a setup guide for muon-nucleon in PYTHIA 8.3 is provided (in PyROOT). In the next chapter, *Results on event characteristics*, the main results of the study are presented and briefly discussed. Lastly, there is a chapter *Conclusion* where some concluding remarks are made. This chapter is followed by an *Appendix* where additional plots are located.

1.1 The SHiP experiment

The Search for Hidden Particles (SHiP) experiment is a recently approved experiment at CERN that aims at addressing some open questions in particle physics. SHiP is designed to search for FIPs predicted by extensions of the Standard Model, particularly those related to the so-called "hidden sector". This hidden sector is theorized to contain particles that have extremely weak interactions with ordinary matter, which could explain several beyond-the-standard-model questions, such as the nature of Light Dark Matter (LDM), the existence of Heavy Neutral Leptons (HNLs), neutrino masses, and the matter-antimatter asymmetry in the universe. By focusing on weakly interacting long-lived particles (LLPs), the SHiP experiment has the potential to detect particles that previous larger and higher-energy experiments were unable to discover.

To achieve these goals, SHiP will employ a 400 GeV, high-intensity proton beam from CERN's Super Proton Synchrotron (SPS), striking a fixed target to generate a large flux of secondary particles, including neutrinos, muons, and taons. Specifically, this beam-dump setup is set to give SHiP access to about $\approx 2 \times 10^{17}$ charmed hadrons, $\approx 1.4 \times 10^{13}$ beauty hadrons, $\approx 2 \times 10^{15}$ tauons *per year* [1]. From this production, there is a possibility of finding new, undiscovered particles from the hidden sector. These particles, particularly LLPs, are expected to travel a significant distance before decaying, making the experimental design of SHiP ideal for detecting such long-lived signals. SHiP will combine a complex detection system consisting of a Scattering and Neutrino (SND) detector and a Hidden Sector Decay Search (HSDS) detector to observe rare decay signatures while minimizing background interference.

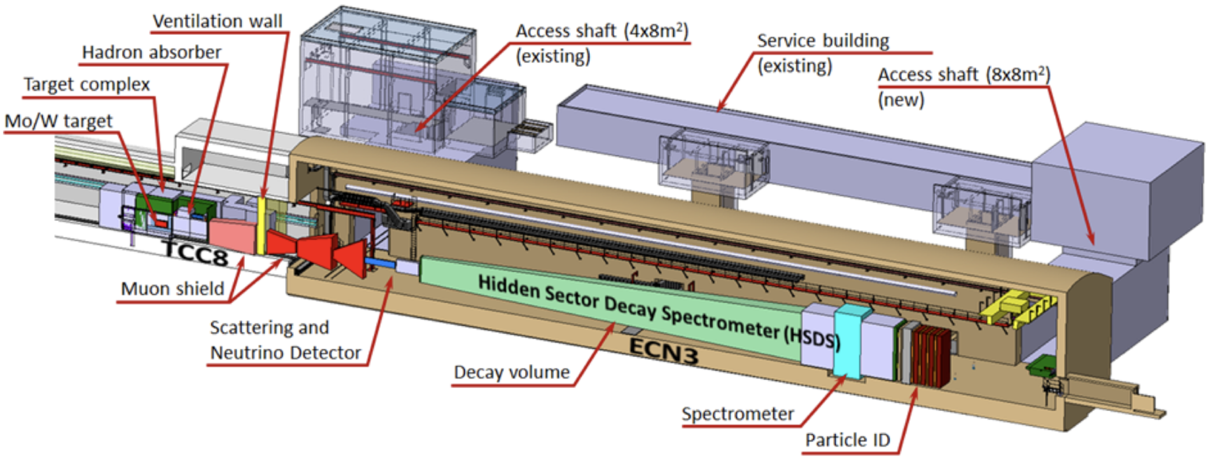

Figure 1: Overview of the SHiP experiment as presented in the 2023 proposal [1]. The SHiP experiment is to be housed in the ECN3 canvern in CERN's North Area.

In Figure 1, an overview of the current SHiP experimental setup is displayed. Below, I describe the main components of the SHiP experiment.

- Proton target and hadron absorber. The first stage in the SHiP experiment is a 400 GeV, high-intensity proton beam from CERN's Super Proton Synchrotron (SPS), which strikes a dense target with short interaction length to suppress weak decays of kaons and pions. This interaction produces a large number of secondary particles, including neutrinos, muons, and potentially LLPs. After the target, an absorber structure is used to stop hadrons and absorb most of the unwanted radiation and particles that could create backgrounds. This also helps to suppress the production of additional secondary particles that could interfere with signal detection.
- Muon shield. A key component in the SHiP detector is the active muon shield, a system of magnetic elements and absorbers designed to deflect and absorb the large flux of muons produced in the proton-target interactions. Since muons are highly penetrating and could contribute significantly to background events, the muon shield is essential in reducing the number of muons reaching

the sensitive detectors downstream. This is also the component that is highly dependent on the outcomes of the muon-nucleon DIS studies.

- SND detector. In addition to searching for hidden particles, SHiP also includes a neutrino detector, located before the HSDS detector. This detector is designed to study the interactions of tau neutrinos, which are difficult to detect and have been under-explored in other experiments. The neutrino detector will allow SHiP to make significant contributions to neutrino physics while also looking for LDM signatures. The neutrino detector consists of emulsion films interleaved with thin layers of lead or tungsten, forming a structure known as an emulsion cloud chamber. These emulsion detectors are highly precise and can capture the tracks of charged particles produced when neutrinos interact with nucleons in the lead. The system is complemented by electronic detectors for additional tracking and timing information. This allows for reconstructing the shower produced by the recoil electron in LDM scattering. Furthermore, the precision of the nuclear emulsion provides topological information that can be used to discriminate between LDM interactions and neurino-induced background events.
- HSDS detector. The hidden particle detection system is specifically optimized to detect the decays of long-lived particles produced at the target. It consists of a large decay volume, which is a vacuum or low-pressure vessel that provides a long, empty space for LLPs to decay. This volume is crucial for observing the decays of hidden particles into visible Standard Model particles, such as leptons or photons. Following the decay volume, there is a spectrometer consisting of several tracking detectors and a magnetic field. These components track the trajectories and record the momentum of charged particles produced in the decay of LLPs, allowing for precise reconstruction of the decay events. This data helps differentiate potential hidden particles from background processes.
- Electromagnetic calorimeter and hadronic calorimeter. Behind the spectrometer, the detector system also includes electromagnetic (EM) and hadronic calorimeters, which measure the energy of electrons, photons, and hadrons. These calorimeters provide key information for particle identification and help distinguish between different particle types based on their interaction with matter.
- Timing and veto detectors. Timing is used to improve tagging and thus reduce background. Additionally, veto detectors are positioned throughout the setup to identify and discard events that are associated with other background sources. These veto systems help reduce background in the dataset, increasing the overall sensitivity of the experiment.

As of October 2024, the SHiP experiment is set be commissioned in 2031 in the ECN3 cavern in CERN's North Area.

2 Theory of muon-nucleon DIS

Deep inelastic scattering is a fundamental process often used to probe the internal structure of nucleons (protons and neutrons). DIS plays a central role in understanding quantum chromodynamics (QCD), the theory governing the strong interactions between quarks and gluons that make up nucleons. In muon-nucleon process, a high-energy muon scatters off a nucleon, and instead of interacting elastically (where the nucleon remains intact), it exchanges a virtual photon with one of the quarks inside the nucleon. The virtual photon transfers significant energy to the quark, breaking up the nucleon and creating a cascade of secondary particles, a phenomenon known as a jet. By analyzing these interactions, researchers gain insight into the behavior of quarks and gluons, including their distribution inside the nucleon, described by parton distribution functions (PDFs).

DIS involves a high-energy muon (or another charged lepton) scattering off a nucleon via the exchange of a virtual photon, γ^*, which probes the internal quark structure of the nucleon. The basic reaction can be written as:

$$\mu(k) + N(p) \to \mu'(k') + X,$$

where $\mu(k)$ is the incoming muon with momentum k, $N(p)$ is the target nucleon with momentum p, $\mu'(k')$ is the outgoing muon with momentum k', and X represents the final-state hadronic system resulting from the nucleon break-up. Key kinematic variables in the DIS process include:

- The four-momentum transfer squared Q^2: This is the momentum transferred by the virtual photon to the nucleon. It is given by:
  $$Q^2 = -q^2 = -(k - k')^2$$
  where $q = k - k'$ is the four-momentum of the virtual photon. High Q^2 values correspond to deep inelastic scattering, probing shorter distances inside the nucleon.
- Bjorken scaling variable x: Defined as the fraction of the nucleon's momentum carried by the struck quark, given by:
  $$x = \frac{Q^2}{2p \cdot q}$$
  In the parton model, x ranges from 0 to 1, where values close to 1 correspond to high-energy quarks and lower values of x represent sea quarks and gluons.
- Inelasticity y: Defined as the fraction of the muon's energy transferred to the hadronic system:
  $$y = \frac{p \cdot q}{p \cdot k}$$
  It ranges from 0 to 1, with higher values of y corresponding to larger energy transfers.

The differential cross-section for DIS in terms of these variables is given by:

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x\,\mathrm{d}Q^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1 - y + \frac{y^2}{2}\right) F_2(x, Q^2) - \frac{y^2}{2} F_L(x, Q^2)\right],$$

where $F_2(x, Q^2)$ and $F_L(x, Q^2)$ are the structure functions that encode information about the distribution of quarks and gluons inside the nucleon. F_2 is the dominant structure function in most regions of kinematic space, while F_L, the longitudinal structure function, becomes important at low Q^2.

In the context of the SHiP experiment, muon-nucleon DIS processes are a critical background that must be carefully understood and modeled. High-energy muons produced at the SHiP target can undergo DIS interactions with nucleons in the detector materials, creating secondary particles that may mimic the signatures of long-lived particles (LLPs) or other new physics phenomena. Accurately simulating muon-nucleon DIS is therefore essential for distinguishing these background events from genuine signals of hidden particles.

3 PYTHIA event generator

The PYTHIA program is generally referred to as a general-purpose Monte Carlo event generator. PYTHIA simulates high-energy hadron-hadron, hadron-lepton, and lepton-lepton collisions (events). The program utilizes physics derived from theoretical and phenomenological models and is subsequently calibrated with experimental data.

Event generation

Structurally, PYHTIA is composed of three principal parts: the process-level, the parton-level, and the hadron-level (see Figure 2). The process-level is concerned with the hard-scattering process and is generally described perturbatively. The parton-level covers initial-state radiation (ISR), final-state radiation (FSR), and multiparton interactions (MPIs). Starting from the hard-scattering, the ISR and FSR correspond to the backward and forward time-evolution of the parton showers, respectively. MPIs are secondary scattering processes, involving beam partons, that have a lower Q^2 than the hard-scattering process. Lastly, the hadron-level is responsible for converting the outgoing partons into colour-singlet hadrons (hadronisation/fragmentation). In PYTHIA, this non-perturbative process is described by the Lund string model [3].

The hardest sub-process determines the nature of the collision and is in PYTHIA determined by LO calculations. This hard-scattering process is dependent on the parton distribution functions (PDFs), which give the probability of a parton possessing a certain fraction of the total hadron momentum. The scale evolution of PDFs are described by the Dokshitzer–Gribov–Lipatov–Altarelli–Parisi (DGLAP) equations, which are subsequently fitted to experimental data from HERA and the LHC [4].

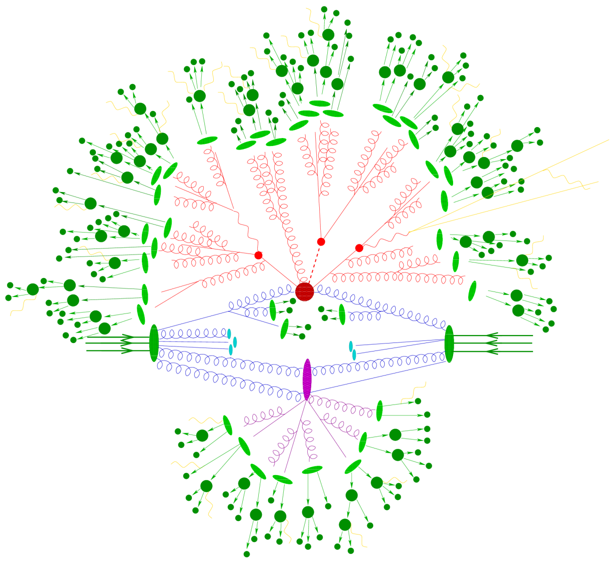

Figure 2: Schematic of a simulated hadron-hadron collision event. The centre blob (red) represents the hardest-scattering process from which the ISR (blue) and FSR (red) are generated. The purple oval indicates an MPI. The hadronisation process is represented by the light green ovals. Lastly, hadron decay is indicated by the dark green blobs [2].

PYTHIA 6 vs. PYTHIA 8

While both PYTHIA 6.4 [5] and PYTHIA 8.3 [4] share many of the same core functionalities, PYTHIA 8.3 is a newer version that introduces significant improvements and modernizations over PYTHIA 6.

PYTHIA 6 is written in Fortran and is based on an older codebase that has evolved over decades. It is less modular, making it harder to extend and modify in a modern computing environment. PYTHIA 8 is written in C++, which provides more flexibility and modularity. It is easier to integrate into contemporary analysis frameworks, offers better memory management, and is generally more user-friendly for new users. Furthermore, PYTHIA 8 introduces improved models for several processes, including more accurate handling of parton showers, hadronization, and MPI. For example, the evolution of parton showers in PYTHIA 8 is handled by a dipole-based approach, which better simulates color coherence effects in QCD. Meanwhile, PYTHIA 6 uses older parton shower models, which can still provide reasonably good approximations but lack some of the refinements found in PYTHIA 8, particularly when it comes to soft QCD processes and gluon radiation patterns.

Moreover, PYTHIA 8 features a more modern and flexible user interface, with improved event selection and analysis capabilities, while PYTHIA 6 uses a more rigid and less intuitive input/output system. In PYTHIA 8, the command structure is simplified, making it easier to configure simulations. Lastly, PYTHIA 8 benefits from improved tuning to a broader range of experimental data, incorporating insights from the LHC and other modern experiments. This results in more accurate simulations of processes across a wide range of energies. PYTHIA 6 was tuned mainly to data from pre-LHC experiments (like those at the Tevatron), which can make it less accurate for high-energy collisions compared to PYTHIA 8.

3.1 Muon-nucleon DIS in PYTHIA 6.4

To simulate muon-proton collisions in PYTHIA 6.4, I used two different configurations: a PYTHIA 6.4 setup with `mu` and a PYTHIA 6.4 setup with `gamma/mu`. Using the `mu` setting, PYTHIA focuses purely on processes involving muons as the incident particle without taking into account photon radiation from the incoming muon. In contrast, the `gamma/mu` setting introduces the simulation of initial-state photon radiation in addition to the processes available in the 'mu' setting. This mode allows for the inclusion of QED corrections, specifically through the emission of photons from the incoming muon before it interacts with the nucleon. Roughly, the `gamma/mu` setting gives a much more photon intense, and thus softer, interaction than the `mu` setting. Below, I describe the other, shared, settings.

- `MSEL(2)`: The MSEL parameter controls which class of processes are allowed in the simulation. By setting MSEL = 2, PYTHIA is configured to select hard QCD processes as well as include diffractive processes.
- `MSTP(14,10)`: This parameter is used to specify how hard scattering processes are chosen. Setting MSTP(14) = 10 ensures that the simulated events correspond to lepton-hadron DIS.
- `PARP(2,`Q^2`)`: This parameter controls the minimum invariant momentum transfer squared, denoted as Q^2, in hard scattering events. In deep inelastic scattering (DIS), this is a key variable that characterizes the energy scale of the interaction. Here, Q^2 is set to 2 GeV^2.
- `MSTP(33,1)`: This parameter governs the treatment of incoming leptons in hard scattering processes. By setting MSTP(33) = 1, the simulation explicitly ensures that the interaction involves lepton-hadron DIS.

To compare the two configurations, various event characteristics at different energies are presented in Figure 3 and Figure 4.

In Figure 3, we can see the comparison of outgoing energy, pseudorapidity, multiplicity, and momentum transfer at 300 GeV/c. The trends of these simulations also hold for lower energies. This is shown in Figure 4, where the transverse momentum of the outgoing particles is presented for various energies. Note that the `gamma/mu` interactions are generally of softer nature than the ones produces with `mu`. We can see this by looking at the momentum transfer, outgoing energy and multiplicity. Moreover, the pseudorapidity gives different outcomes as well. Furthermore, in Figure 4, we see that, in contrast to `gamma/mu`, the `mu` setting produces at bump around 1 GeV/c. Instead, the `gamma/mu` setting gives a bump around 0.1 GeV/c.

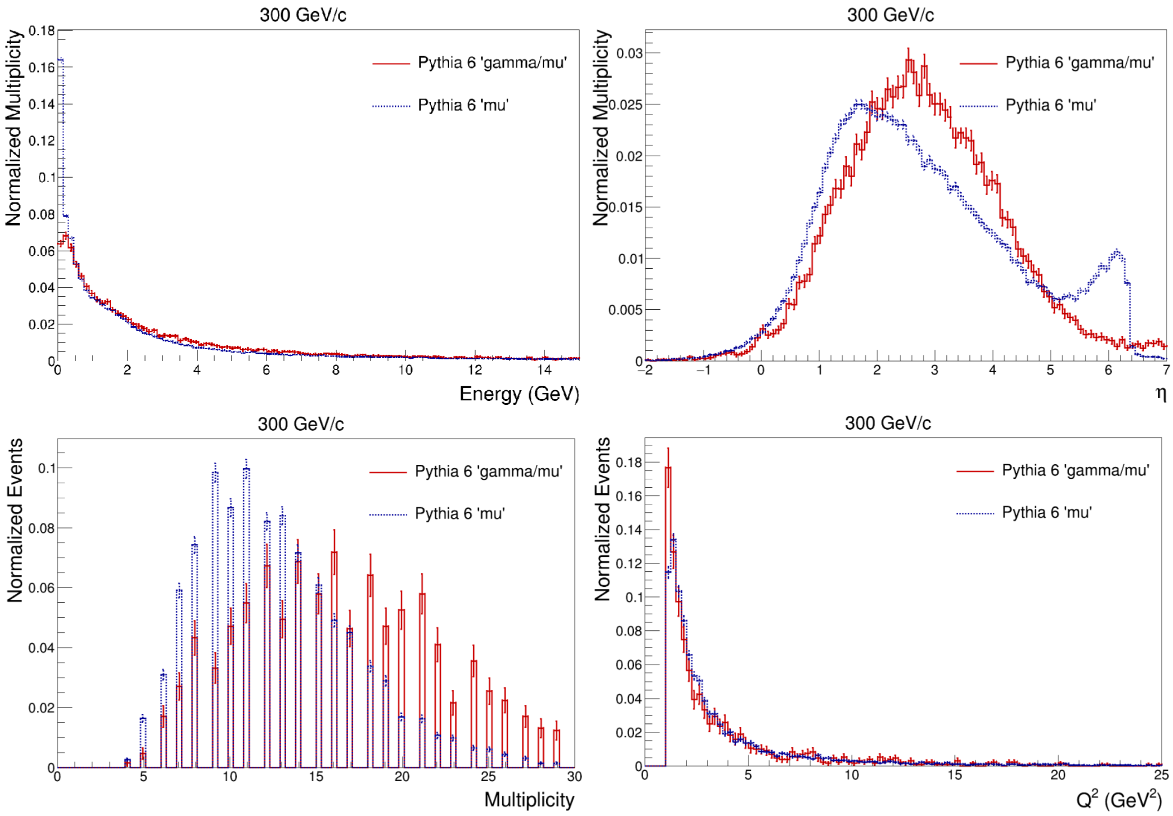

Figure 3: Various event characteristics of outgoing particles from 1000 (anti-)muon-proton collisions with incoming (anti-)muons with momentum 300 GeV/c. The vertical bars represent the statistical uncertainty per bin. Simulated using PYTHIA 6 `gamma/mu` (in red) and PYTHIA 6 `mu` (in blue).

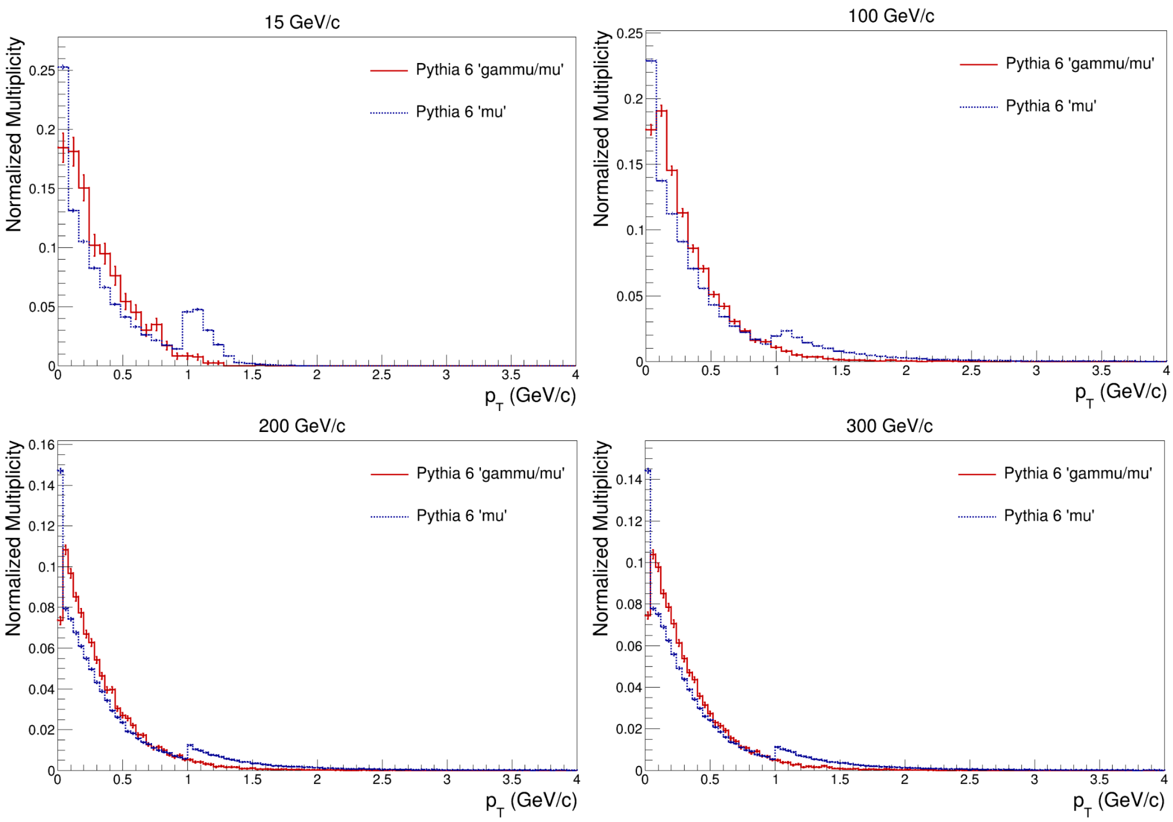

Figure 4: Transverse momentum in GeV/c of outgoing particles from 1000 (anti-)muon-proton collisions with incoming (anti-)muons with momenta of 15, 100, 200, and 300 GeV/c. The vertical bars represent the statistical uncertainty per bin. Simulated using PYTHIA 6 `gamma/mu` (in red) and PYTHIA 6 `mu` (in blue).

3.2 Muon-nucleon DIS in PYTHIA 8.3

As done for PYTHIA 6, to simulate muon-proton collisions in PYTHIA 8.3, I used two different configurations: a standard PYTHIA 8.3 setup and a specific PYTHIA 8.3 DIS setup. The main difference between the configurations is the addition of the `PhaseSpace:mHatMin = 0.5` setting for the PYTHIA 8.3 DIS setup. This sets the minimum invariant mass for the interaction. In the DIS setup, this is set to 0.5 GeV/c^2, allowing for events with smaller invariant masses, which can influence the phase space and kinematic properties of the generated events. The other settings, that are shared by both configurations, are described below.

- `WeakBosonExchange:ff2ff(t:gmZ) = on`: Enables neutral current interactions involving photon and Z-boson interference.
- `WeakBosonExchange:ff2ff(t:W) = on`: Activates charged current interactions mediated by the W-boson.
- `SoftQCD:elastic = on`: Allows elastic scattering in soft QCD processes.
- `SoftQCD:nonDiffractive = on`: Enables non-diffractive scattering, which includes inelastic interactions where the proton remains intact.
- `PDF:lepton = on`: Activates parton distribution functions (PDFs) for the lepton, allowing QED radiation to be taken into account.

To highlight the main differences between the two configurations, some figures are presented below. The differences are most pronounced at lower momenta. This can be seen in Figure 5. Here, the energy of the outgoing particles is presented for 15 and 100 GeV/c for both PYTHIA 8 and PYTHIA 8 DIS. For the 15 GeV/c plots, there are clear bumps in multiplicity around 1.6 and 14 GeV for the non-DIS configuration. These bumps are assumed to be protons and muons, respectively, that interacted softly. These bumps mostly disappear for the DIS configuration and also for the non-DIS configuration at higher energies.

These observations are strengthened by indications from the plots in Figure 6. Here, we see that the pseudorapidity, number of protons and neutrons (PDG code of 2212 and 2112, respectively), multiplicity, and momentum transfer all indicate that the interactions in the non-DIS configurations are of a softer nature than those of the DIS configuration. Again, this effect disappears at higher energies (see Figure 13 in Appendix).

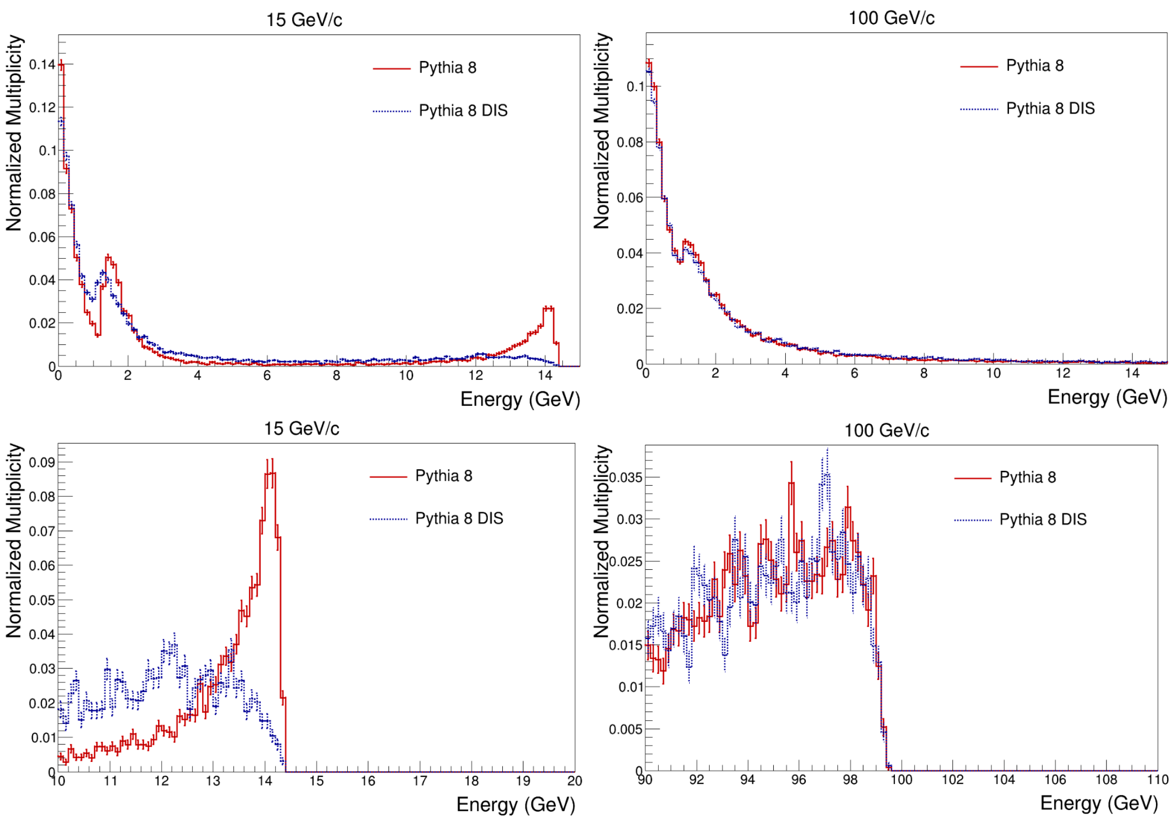

Figure 5: Energy in GeV of outgoing particles from 1000 (anti-)muon-proton collisions with incoming (anti-)muons with momenta of 15 (left) and 100 (right) GeV/c. The vertical bars represent the statistical uncertainty per bin. Simulated using PYTHIA 8 (in red) and PYTHIA 8 DIS (in blue).

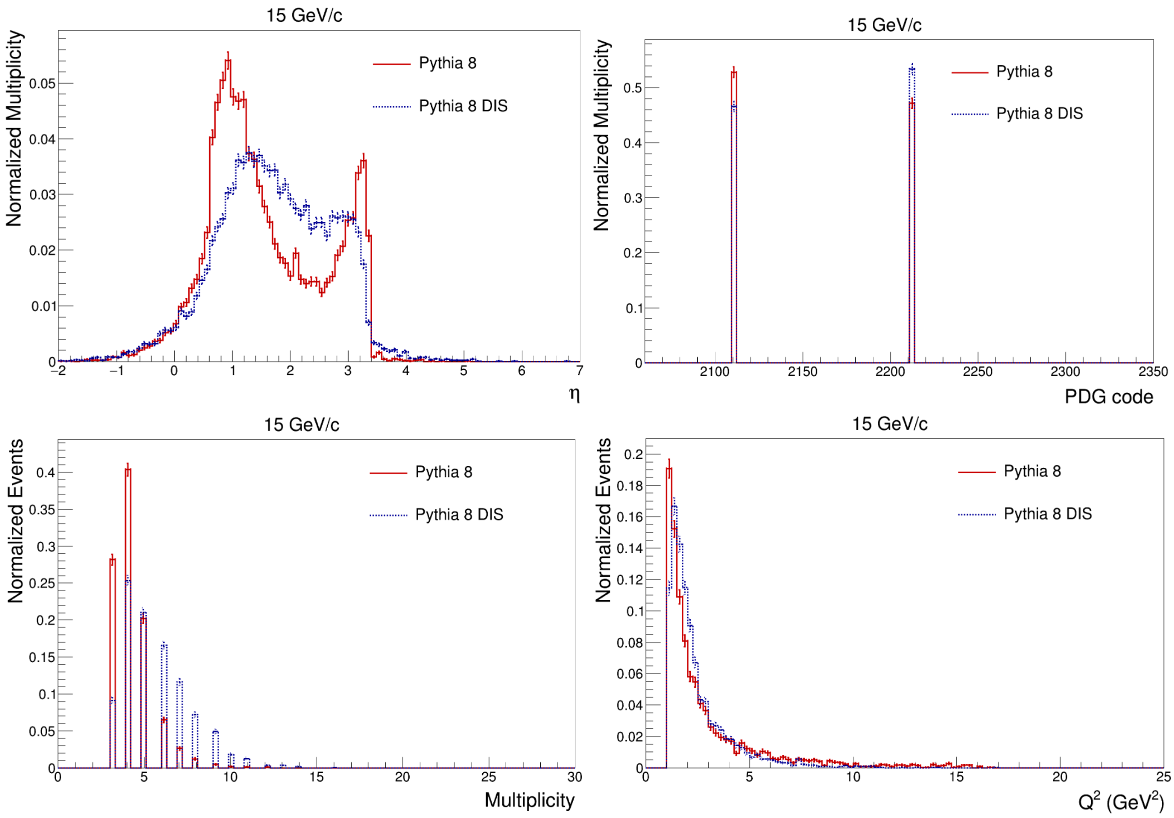

Figure 6: Various event characteristics of outgoing particles from 1000 (anti-)muon-proton collisions with incoming (anti-)muons with momentum of 15 GeV/c. The vertical bars represent the statistical uncertainty per bin. Simulated using PYTHIA 8 (in red) and PYTHIA 8 DIS (in blue). In the top right plot, I zoom in on the PDG codes of protons and neutrons. There are many other types of particles created.

3.3 Start-up guide for muon-nucleon DIS in PYTHIA 8.3

In this section, I will briefly outline how to simulate muon-nucleon DIS in PYTHIA 8.3. For the SHiP case, i.e. using *FairShip*, PYTHIA is used in the PyROOT environment. This means these commands differ slightly from the ordinary PYTHIA commands. I highlight the importance to explicitly set a seed. The default seed setting did not work in the version I used.

```python
# initialise PYTHIA 8 generator
myPythia = ROOT.Pythia8.Pythia()

# set a seed
seed = 0
myPythia.readString("Random:setSeed = on")
myPythia.readString(f"Random:seed = {seed}")

# primary settings PYTHIA 8
myPythia.settings.mode("Beams:idA", int(particle_id))  # anti-muon/muon beam
myPythia.settings.mode("Beams:idB",2212)  # proton target
myPythia.settings.mode("Beams:frameType", 2)  # fixed-target configuration
myPythia.settings.parm("Beams:eA", p) # initial momentum
myPythia.settings.parm("Beams:eB", 0.938) #proton mass

# secondary (DIS) settings PYTHIA 8
myPythia.readString("WeakBosonExchange:ff2ff(t:gmZ) = on")
myPythia.readString("WeakBosonExchange:ff2ff(t:W) = on")
myPythia.readString("SoftQCD:elastic = on")
myPythia.readString("SoftQCD:nonDiffractive = on")
myPythia.readString("PDF:lepton = on")
myPythia.readString("PhaseSpace:mHatMin = 0.5")

# start generator
myPythia.init()

# in events loop
if not myPythia.next(): continue
```

4 Results on event characteristics

In this section, I present the results of simulating fixed target collisions of 500 muons and 500 anti-muons with a proton at various energies in PYTHIA 6.4 and PYTHIA 8.3. Additionally, for every collision we produce 10 events. In general, events from PYTHIA 6.4 *mu* and PYTHIA 8.3 DIS are compared as these have the most similar results. Furthermore, the event characteristics that are compared are transverse momentum $p_\perp$, pseudorapidity η, outgoing energy, multiplicity per event, and momentum transfer Q^2.

4.1 Transverse momentum, outgoing energy, and pseudorapidity

In Figure 7, the transverse momentum plots for the momenta 15, 100, 200, and 300 GeV/c for both PYTHIA 6 `mu` and PYTHIA 8 DIS are presented. We see that, in general, there is substantial agreement. However, for PYTHIA 6 `mu` the initial peak (0-0.1 GeV/c) is significantly more pronounced than for PYTHIA 8 DIS. This holds for all momenta.

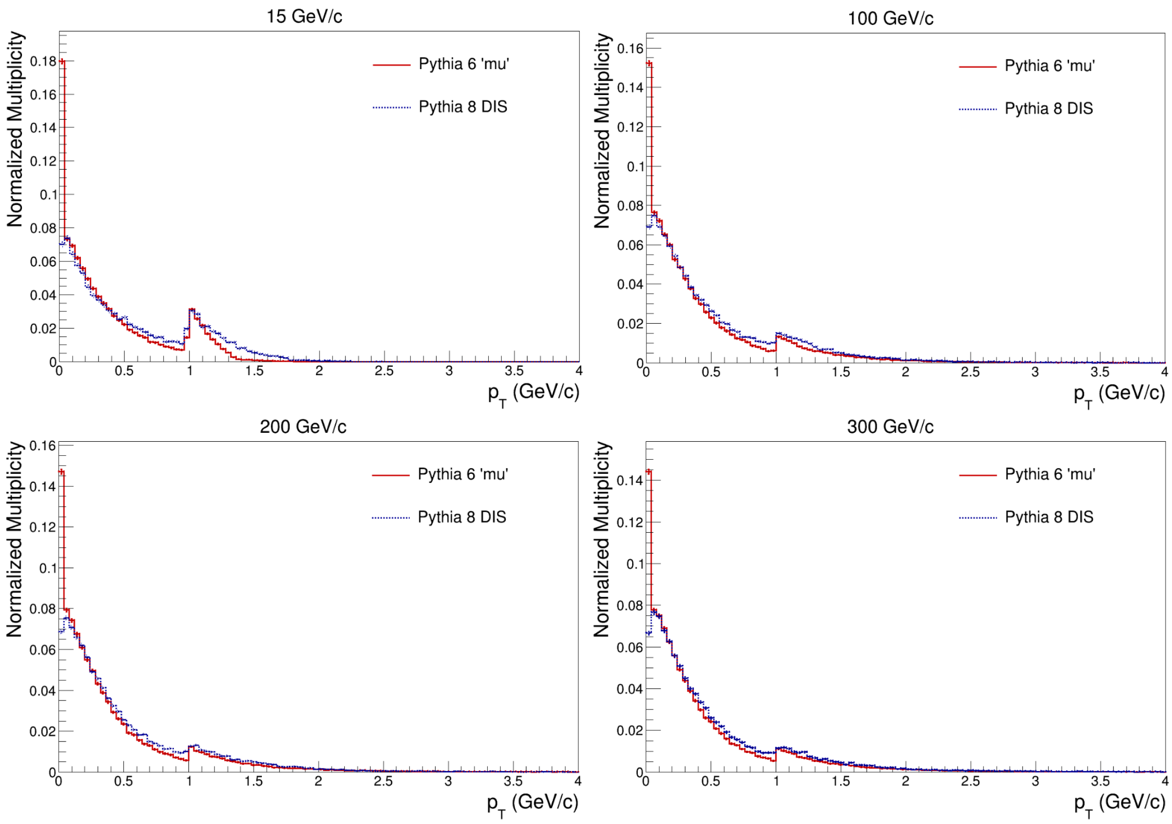

Figure 7: Transverse momentum in GeV/c of outgoing particles from 1000 (anti-)muon-proton collisions with incoming (anti-)muons with momenta of 15, 100, 200, and 300 GeV/c. The vertical bars represent the statistical uncertainty per bin. Simulated using PYTHIA 6 `mu` (in red) and PYTHIA 8 DIS (in blue).

In Figure 8, the outgoing energy plots for the momenta 15, 100, 200, and 300 GeV/c for both PYTHIA 6 `mu` and PYTHIA 8 DIS are presented. Here, we see that bump around 1.5 GeV is present in PYTHIA 8 DIS but not in PYTHIA 6 `mu`. As initail momentum increases, the presence of this bump decreases. Furtermore, as for the transverse momentum, the initaial peak (0-0.1 GeV) is much more pronounced for PYTHIA 6 `mu`. Lastly, by zooming in on the highest energy bit of each momenta, we can see that PYTHIA 6 `mu` the maximum energy is about 2 GeV lower than for PYTHIA 8 DIS. This trend holds for all momenta.

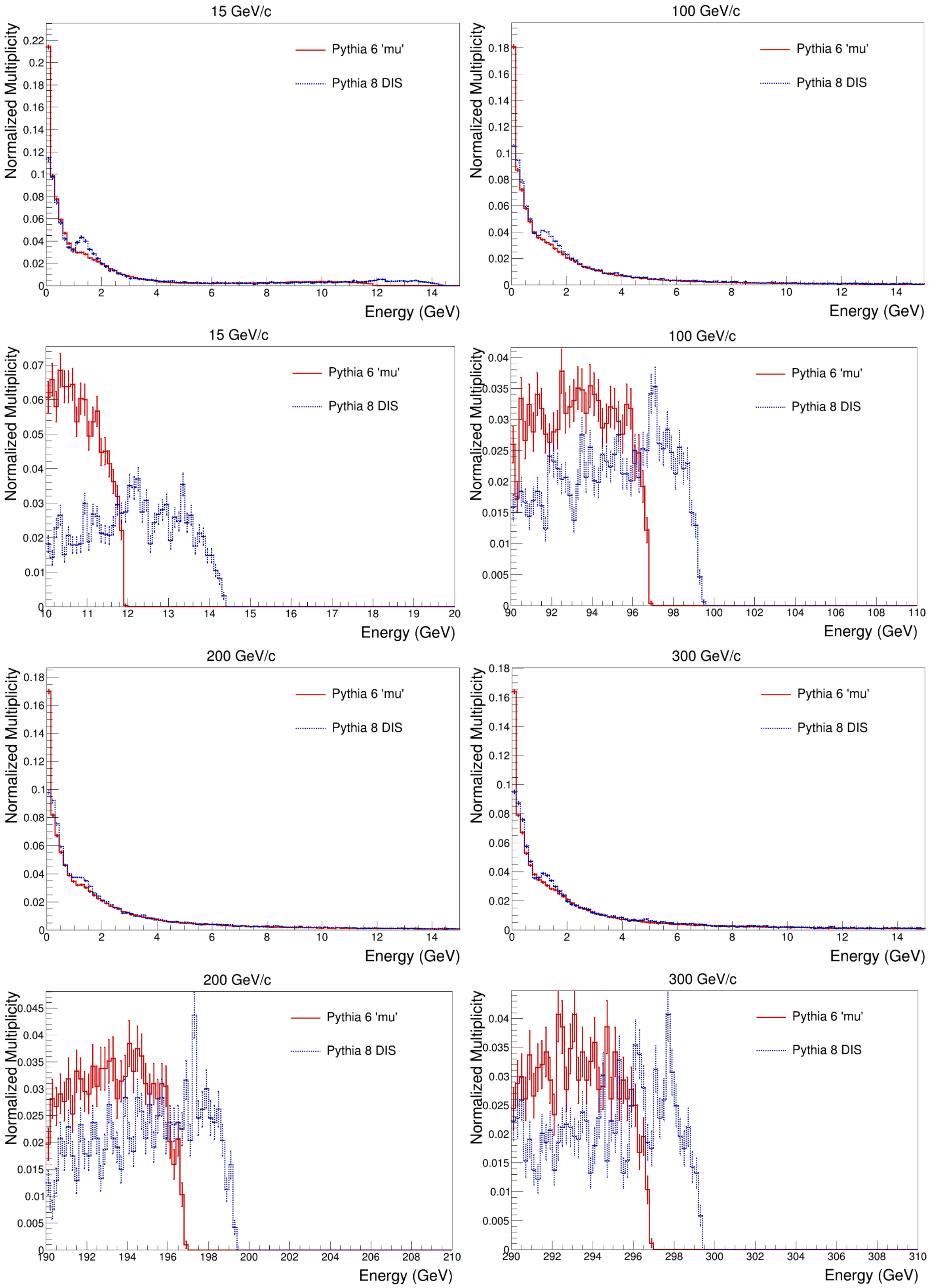

Figure 8: Energy in GeV of outgoing particles from 1000 (anti-)muon-proton collisions with incoming (anti-)muons with momenta of 15, 100, 200, and 300 GeV/c. The vertical bars represent the statistical uncertainty per bin. Simulated using PYTHIA 6 `mu` (in red) and PYTHIA 8 DIS (in blue).

Lastly, in Figure 9, the pseudorapidity distribution plots for the momenta 15, 100, 200, and 300 GeV/c for both PYTHIA 6 `mu` and PYTHIA 8 DIS are presented. For each momentum, PYTHIA 6 `mu` and PYTHIA DIS agree for the most part.

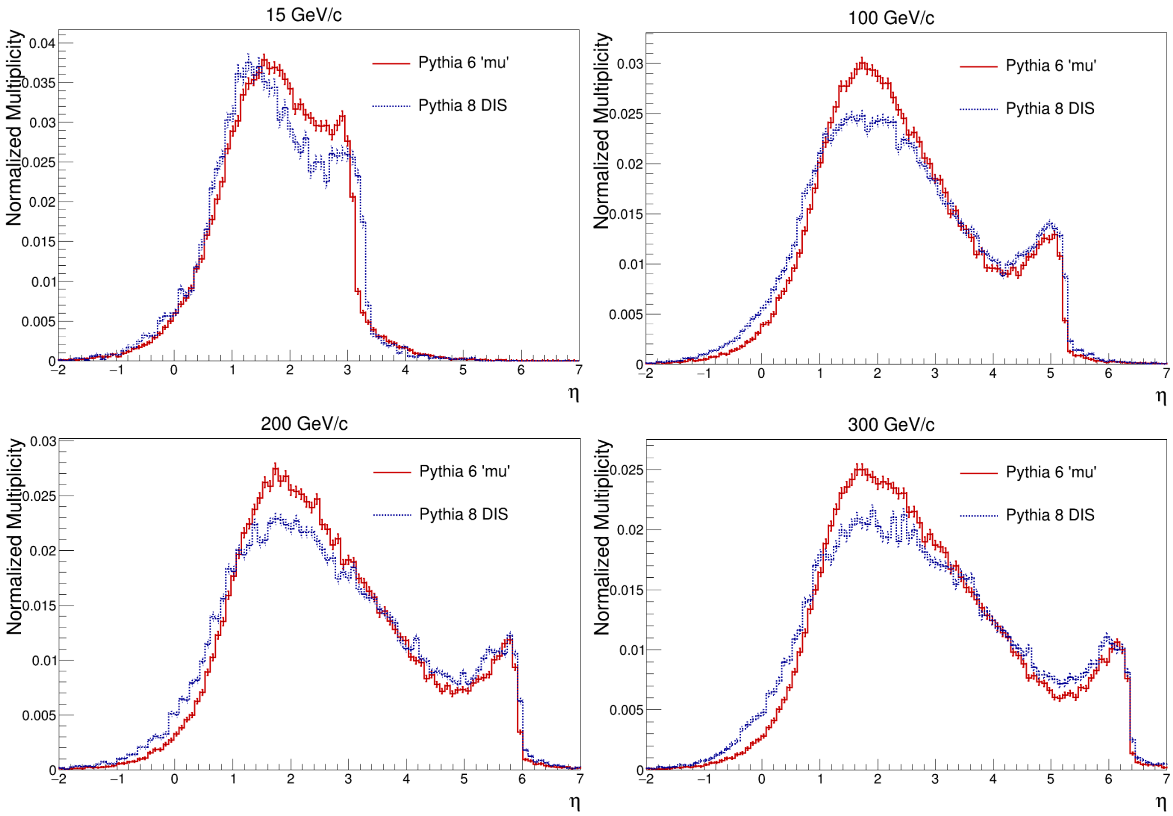

Figure 9: Pseudorapidity distribution of outgoing particles from 1000 (anti-)muon-proton collisions with incoming (anti-)muons with momenta of 15, 100, 200, and 300 GeV/c. The vertical bars represent the statistical uncertainty per bin. Simulated using PYTHIA 6 `mu` (in red) and PYTHIA 8 DIS (in blue).

4.2 Momentum transfer and multiplicity per event

In Figure 10, the momentum transfer per event is shown for momenta of 15, 100, 200, and 300 GeV/c. From this figure we can see that the momentum transfer in PYTHIA 6 `mu` and PYTHIA 8 DIS is quite similar. This indicates that the hardness of interaction is similar. Therefore it is somewhat surprising that the multiplicity per event (Figure 11) is substantially higher at each momentum for PYTHIA 6 `mu`. A likely explanation is that PYTHIA 6 `mu` includes the incoming particles in the multiplicity count of the event. This would explain why the PYTHIA 8 DIS trend seems to be shifted to the left by two. However, to confirm this, additional studies are needed.

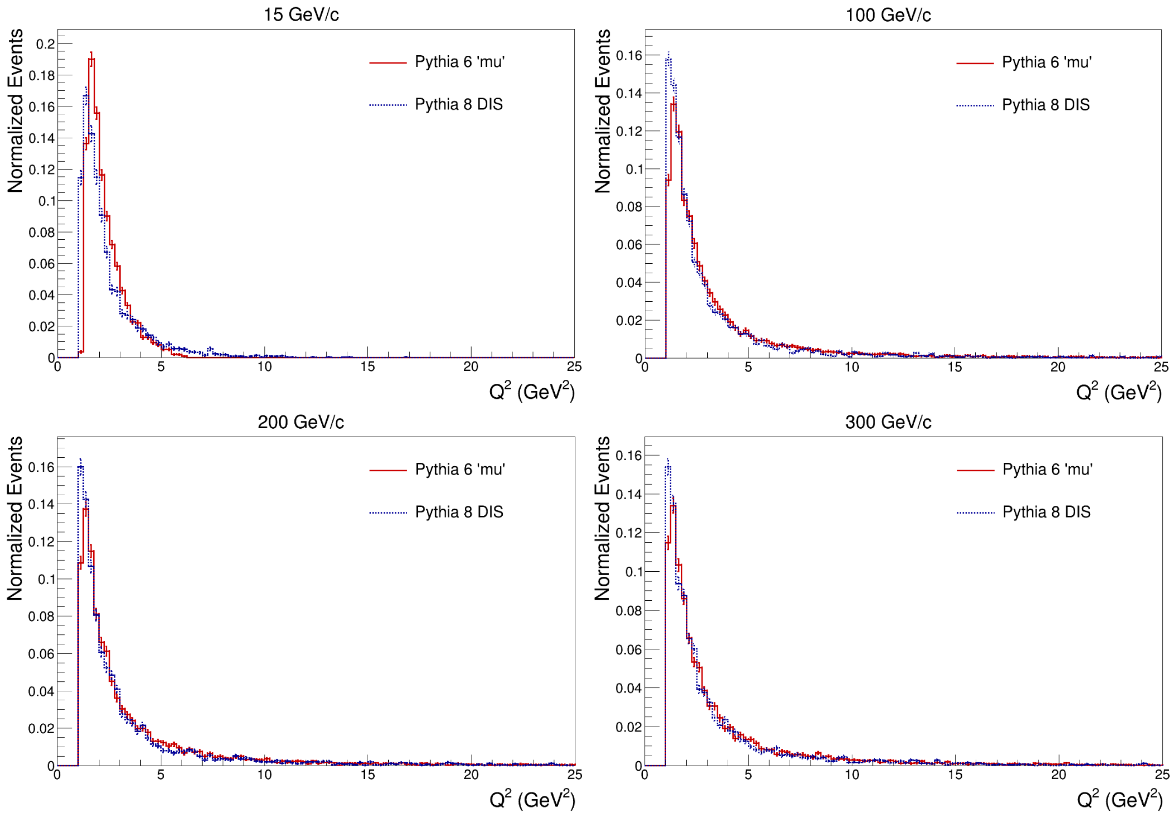

Figure 10: Momentum transfer per event in GeV^2 for 1000 (anti-)muon-proton collisions with incoming (anti-)muons with momenta of 15, 100, 200, and 300 GeV/c. The vertical bars represent the statistical uncertainty per bin. Simulated using PYTHIA 6 `mu` (in red) and PYTHIA 8 DIS (in blue).

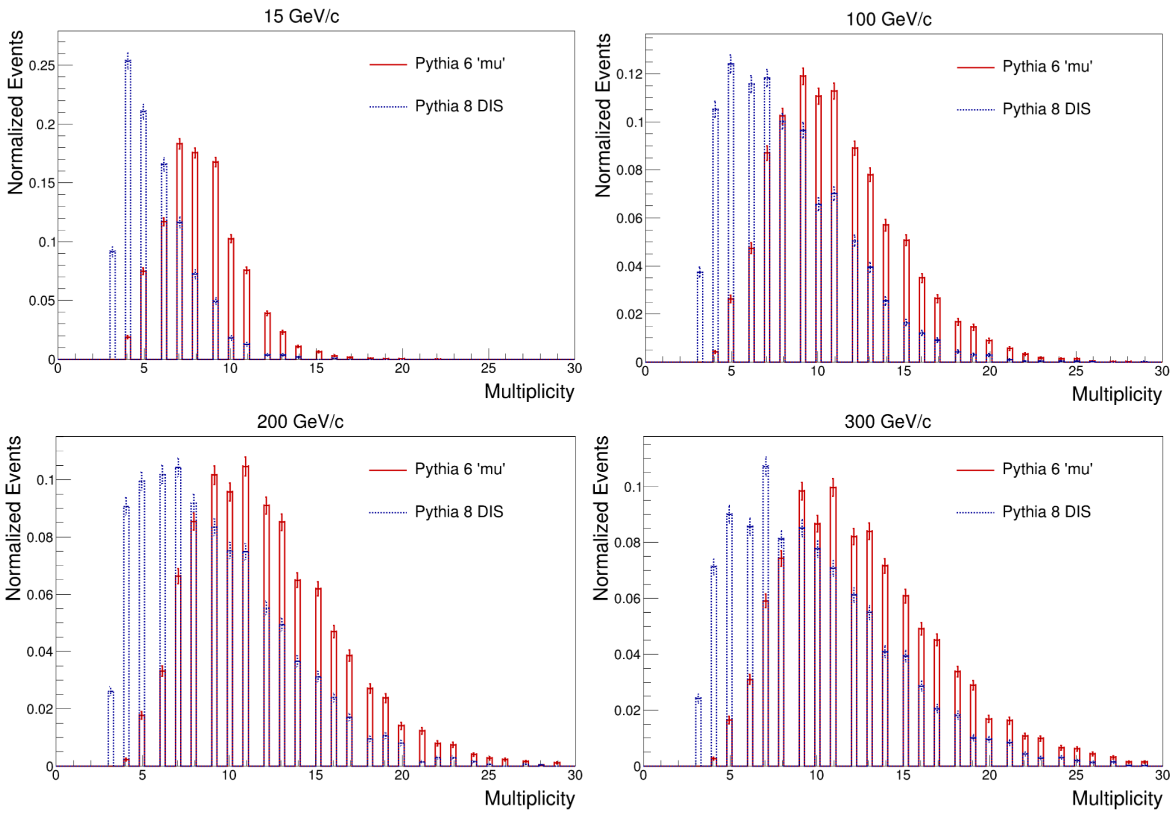

Figure 11: Multiplicity per event for 1000 (anti-)muon-proton collisions with incoming (anti-)muons with momenta of 15, 100, 200, and 300 GeV/c. The vertical bars represent the statistical uncertainty per bin. Simulated using PYTHIA 6 `mu` (in red) and PYTHIA 8 DIS (in blue).

4.3 Low energy (10 GeV)

At energies lower than 15 GeV, PYTHIA 6 `mu` and PYTHIA 8 non-DIS do not run anymore. Therefore, the only comparisons that can be made are those between PYTHIA 6 `gamma/mu` and PYTHIA 8 DIS. For 10 GeV/c, some event characteristics are shown in Figure 12.

We can see that the differences are quite substantial. In particular, the characteristics bumps in energy (around 1.5 GeV) and transverse momentum (around 1.2 GeV/c) for PYTHIA 8 DIS are missing, or at least greatly shifted towards 0, in PYTHIA 6 `gamma/mu`. Furthermore, by looking at the momentum transfer, we see that the PYTHIA 6 `gamma/mu` interactions are much softer than those of PYTHIA 8 DIS.

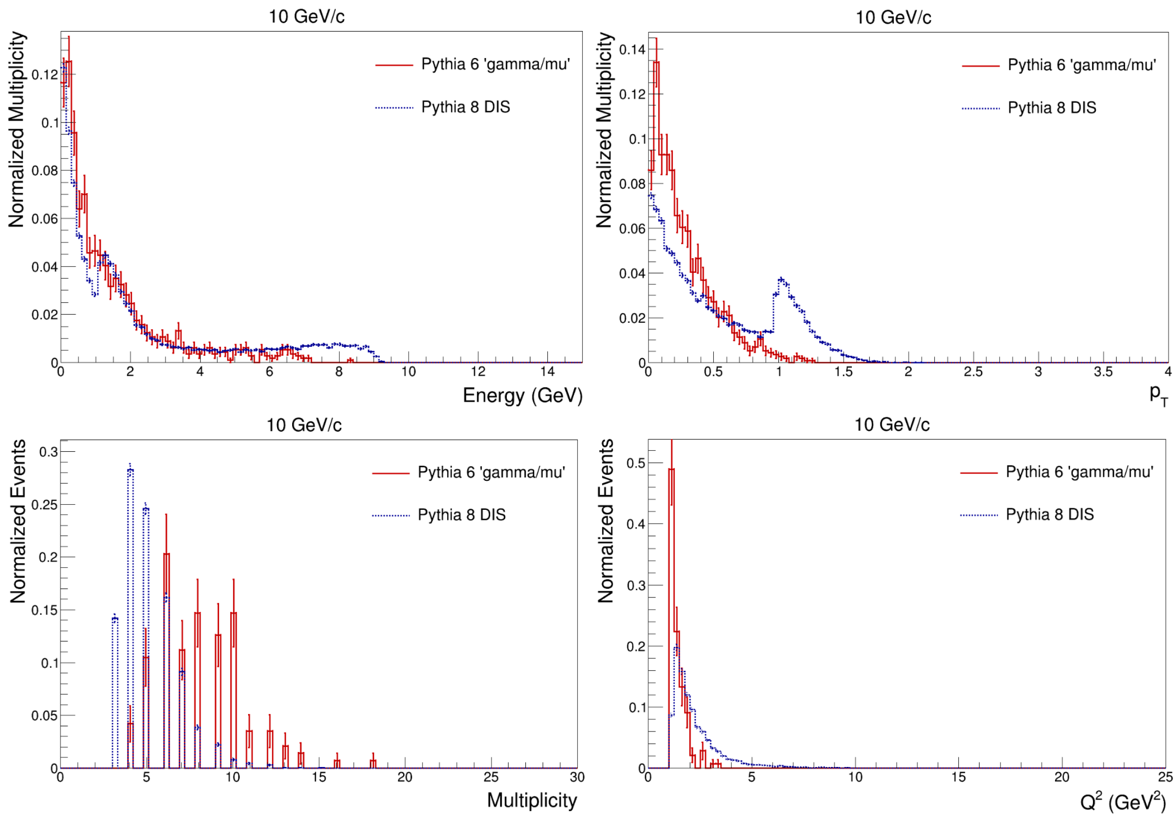

Figure 12: Various event characteristics for 1000 (anti-)muon-proton collisions with incoming (anti-)muons with momentum of 10 GeV/c. The vertical bars represent the statistical uncertainty per bin. Simulated using PYTHIA 6 `gamma/mu` (in red) and PYTHIA 8 DIS (in blue).

5 Conclusion

In this study, I have looked exclusively at uniform muon-proton DIS collisions for two configurations of PYTHIA 6.4 and PYTHIA 8.3 in the energy range $10 - 300$ GeV. I found that, for most energies and event characteristics, the PYTHIA 6 `mu` and PYTHIA 8 DIS configurations generally agree well. This is mostly due to the PYTHIA 8 setting `mHatMin=0.5`. The main issues that were found are concerned with low energy (<15 GeV) and initial (0-0.1 GeV) transverse momentum and outgoing energy peaks. However, the first steps, enabling muon-nucleon collisions and comparing the basic event characteristics using PYTHIA 8.3 were accomplished.

Regarding the SHiP application of muon-nucleon DIS studies, the next steps are clear. Firstly, it is crucial that simulations and subsequent comparisons of muon-neutron with non-uniform initial conditions in PYTHIA 8.3 are performed. This will shed light on the robustness of the muon-nucleon DIS framework of PYTHIA 8.3. Secondly, to come closer to real-world SHiP simulations in PYTHIA, a study regarding the cascade must be done. This will provide an actual quantification of the expected background due to muon-nucleon DIS. Thirdly, from a theoretical and systematic uncertainty perspective, it is recommended that PYTHIA 8 results are compared to other event generators such as Geant4 and GENIE. Lastly, to step out of the simulation world, tuning to experimental data would be recommended.

6 Appendix

In this appendix some further figures are presented. Figure 13, shows some event characteristics for 100 GeV/c using two configurations of PYTHIA 8. Figure 14, shows the particle IDs (PDG codes) for 15, 100, 200, and 300 GeV/c initial muon momenta. This is done using PYTHIA 6 `mu` and PYTHIA 8 DIS. Next to additional plots, the final simulation and analysis codes are available on request.

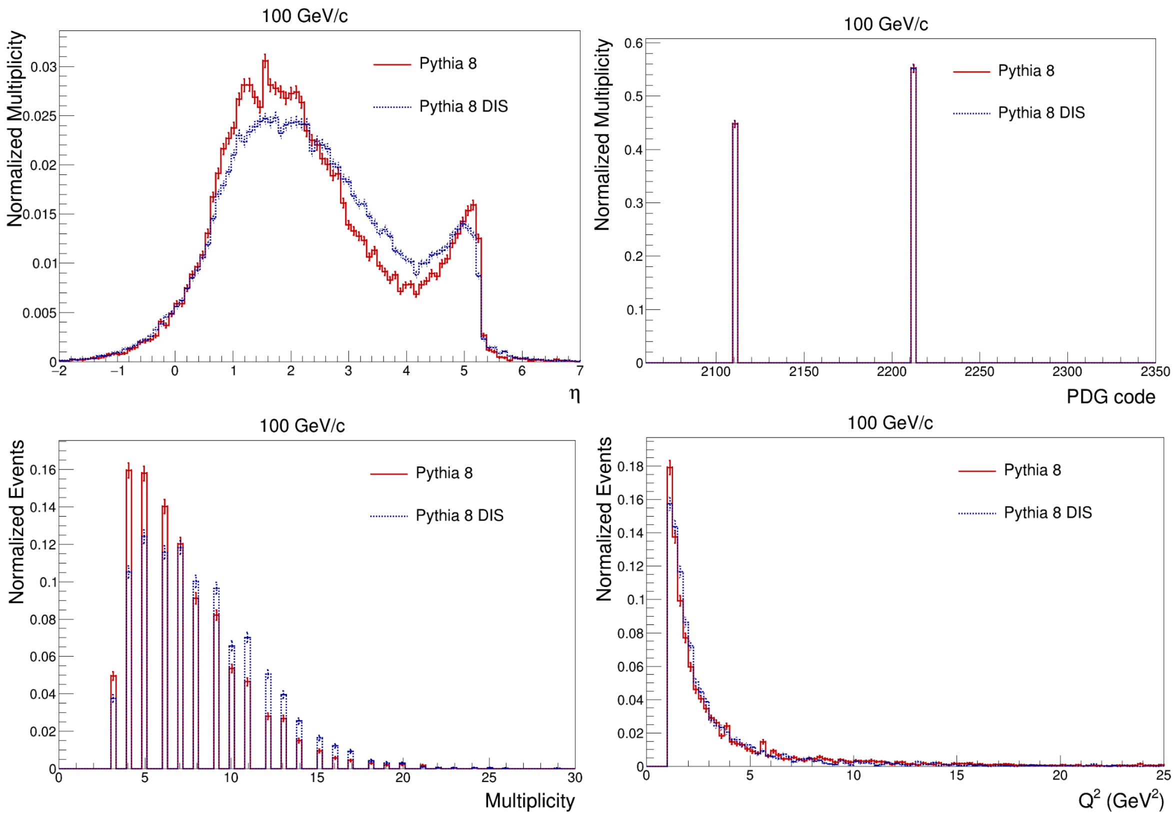

Figure 13: Various event characteristics of outgoing particles from 1000 (anti-)muon-proton collisions with incoming (anti-)muons with momentum of 100 GeV/c. The vertical bars represent the statistical uncertainty. Simulated using PYTHIA 8 (in red) and PYTHIA 8 DIS (in blue). In the plot top right, I zoom in on the PDG codes of protons and neutrons. There are many other particles created.

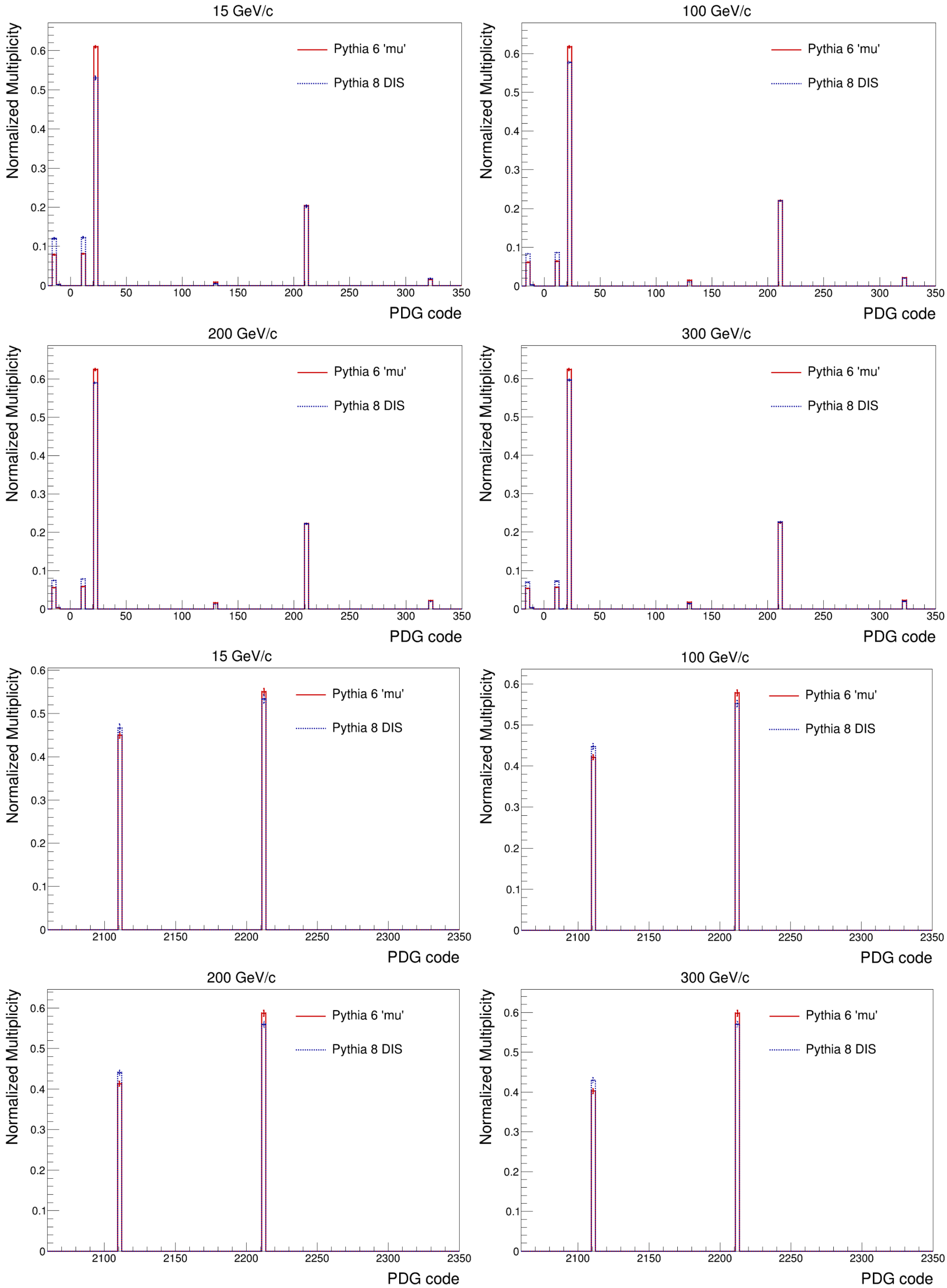

Figure 14: Particle IDs (PDG codes) of outgoing particles from 1000 (anti-)muon-proton collisions with incoming (anti-)muons with momenta of 15, 100, 200, and 300 GeV/c. The vertical bars represent the statistical uncertainty per bin. Simulated using PYTHIA 6 `mu` (in red) and PYTHIA 8 DIS (in blue).

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