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Update of the EvtGen decay models and branching ratios, together with mass tables for heavy flavour hadrons decay

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Summary. — Updated decay modes and models for heavy flavour hadrons are compared with the default ATLAS tables for the EVTGEN 1.7 Monte Carlo version using the Monte Carlo event generators: PYTHIA 8.244, HERWIG 7.2.1, POWHEG 04-05-01 and SHERPA 2.2.11. Heavy flavour hadron-related quantities such as production fractions, jet width and shape, multiplicities of stable and charged stable decay products, together with fragmentation functions are studied using inclusive $t\bar{t}$ samples generated for proton-proton collisions at $\sqrt{s} = 13$ TeV.

1. – Introduction

Final states that include heavy flavour (bottom and charm) hadrons are important for the study of many processes at the LHC [1]. Examples of these processes include top quark pair ($t\bar{t}$) production, Higgs production and searches for physics beyond the Standard Model (SM). To fully exploit the large data samples that have been collected during Run II at the LHC, a reduction in systematic uncertainties associated with the modelling of heavy flavour (HF) hadron production and decay will be needed. Although data-driven methods are likely to play a major part in the effort to reduce these uncertainties, improvements in the Monte Carlo (MC) models used to determine reconstruction efficiencies will also be necessary.

The BELLE II [2] Collaboration has provided new models and updated decay tables, with major updates pertaining to HF hadrons, therefore the focus of this work has been studying distributions that could give detailed info on how these changes affect Monte Carlo samples. These new models have been compiled into a modified version of EVTGEN 1.7 [3] and compared to the results obtained using the default ATLAS tables as well as other MC generators. The BELLE II Collaboration also provided updated mass tables with the most recent measurements from the PDG [4].

2. – Monte Carlo samples and Rivet routine

The versions of the generators studied here were Pythia 8.244 [5] and Pythia 8.3 [6], Herwig 7.2.1 [7], Powheg [8] and Sherpa 2.2.11 [9]. In all samples except Sherpa, EvtGen has been used to redecay the heavy flavour hadrons. All pp samples have been generated at the center-of-mass energy of $\sqrt{s} = 13$ TeV. The studied process is inclusive top-pair production, therefore no requirements are made for the W bosons decay channel.

The Rivet [10] routine, prepared to validate the new EvtGen decay tables from the BELLE II Collaboration, includes the following HF jets and hadrons related observables:

- Stable and charged stable particle multiplicities for B^+, B^0, B^0_s, Λ^0_b, D^0, D^+, D^+_s, Λ^+_c.
- Production fractions for HF hadrons.
- Stable charged particle multiplicity in b- and c-jets.
- Fragmentation functions (FFs) for HF jets, calculated as a function of

$$z \equiv \frac{\vec{p}_{\text{hadron}} \cdot \vec{p}_{\text{jet}}}{p^2_{\text{jet}}}, \tag{1}$$

  where $\vec{p}_{\text{hadron}}$ and $\vec{p}_{\text{jet}}$ are the 3-momentum of the HF hadron and of the reconstructed jet, respectively.

  In this study, z was measured for anti-k_t (R = 0.4) jets with rapidity $|\eta^{\text{jet}}| < 2.5$ and transverse momentum $p_T^{\text{jet}} > 25\,\text{GeV}$. Jets are defined to be heavy flavour jets if there is a HF hadron with momentum $p_T > 5\,\text{GeV}$ within $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} <\ 0.3$ of the jet direction.

  The following distributions were included in the routine:

- FFs for HF jets in the region $500\,\text{GeV} < p_T < 1000\,\text{GeV}$.
- FFs for HF jets with exactly 1 HF hadron.
- p_T and $p_{T_{\text{rel}}}$ distributions for leptons in b- and c-jets, where $p_{T_{\text{rel}}}$ is calculated as

$$p_{T_{\text{rel}}} \equiv \frac{|\vec{p}_{\text{lep}} \times \vec{p}_{\text{jet}}|}{|\vec{p}_{\text{jet}}|}. \tag{2}$$

  Here again $\vec{p}_{\text{jet}}$ is the 3-momentum of the considered jet, while $\vec{p}_{\text{lep}}$ is the one associated with the lepton.

- Differential and integrated jet shapes. The differential jet shape $\rho(r)$ in an annulus of inner radius $r - \Delta r/2$ and outer radius $r + \Delta r/2$ from the axis of a given jet([1]) is defined as

$$\rho(r) \equiv \frac{1}{\Delta r}\frac{p_T(r - \Delta r/2, r + \Delta r/2)}{p_T(0, R)}, \tag{3}$$

([1]) The jet axis is defined to be the direction of the momentum of the jet from the anti-k_t ($R = 0.4$) algorithm.

where $p_T(a,b)$ is the total p_T of the particles found in an annulus of inner radius a and outer radius b. In a similar way, the integrated jet shape is defined to be:

$$\Psi(r) \equiv \frac{p_T(0,\ r)}{p_T(0,R)},\ 0 \leq r \leq R. \tag{4}$$

- Jet width W, obtained as a distribution of the distance ΔR from the center of the jet weighted by the jet constituent (stable) particles' p_T in the following way:

$$W \equiv \frac{\sum_i p_{T_i} \Delta R_i}{\sum_i p_{T_i}}. \tag{5}$$

- Jet p_T and p_T^{had}. Here p_T is the transverse momentum of the jet, while p_T^{hadron} is the transverse momentum of the HF included in the jet.

The routine also includes the distributions of the following observables:

- differential jet shape,
- lepton $p_{T_{\text{rel}}}$ for b- and c-jets,
- stable charged particle multiplicity in HF jets,

divided in the following jet p_T bins:

$$\{25,\ 30,\ 50,\ 70,\ 100,\ 150,\ 300,\ 500,\ 1000\}\,\text{GeV}.$$

In this study, only jets with a $p_T > 25\,\text{GeV}$ were considered. The routine has been added to the Rivet repository under the name MC_HFDECAYS.

3. – Results

A good agreement was found between the new BELLE II models/decay tables and the standard ATLAS ones. Herwig and Sherpa, on the other hand, while in reasonable agreement in the b-jet fragmentation function and in the core of the c-jet one ($0.2 < z < 0.9$), showed a difference of ∼40% in the low- and high-z regions. The b-jet width distribution showed a good agreement between all generators, while in the c-jet case the low- and high-width bins differed by ∼25% for Sherpa, while the mid/high-width range ($0.12 < W < 0.26$) is where Herwig differed the most (∼20%). The $p_{T_{\text{rel}}}$ distribution of the leptons contained in the HF jets again showed a good overall agreement between different generators, except for Sherpa 2.2.11, which differed from the others by more than 40% in most of the bins. As for the differential jet shape, for both b- and c-jets the agreement was very good between all the considered MC samples, reaching differences not bigger than ∼10% in all the bins.

Comparing the results obtained with different generators for distributions divided into p_T bins (*e.g.*, the $p_{T_{\text{rel}}}$ of the leptons in the HF jet), all the generators were in good agreement, even in low-statistics bins considering the large uncertainties. Sherpa was the only one which differed by more than 40% in most of the $p_{T_{\text{rel}}}$ bins. However, in the high-p_T bins ($p_T > 300\,\text{GeV}$), this difference became smaller and disappeared in the last one, where $500\,\text{GeV} < p_T < 1000\,\text{GeV}$.

Since the biggest changes in the EvtGen tables were made in the HF hadrons decays, part of the study has been dedicated to investigate how these changes affect the production fractions and multiplicities of neutral stable and stable charged decay products of these hadrons. Comparing the production fractions for all the weakly decaying hadrons, they showed a complete agreement between the results obtained with the default ATLAS tables and the updated ones from the BELLE II Collaboration.

Charged multiplicities and decay multiplicities showed quite clearly the differences between the default and updated tables, together with some differences with other generators. In particular, Sherpa, which however has not been interfaced with EvtGen, differed by $\sim$40% with respect to other generators in the low-multiplicity bins of the charged multiplicity distribution when looking at b-jets, while Herwig differed by $\sim$50% in the high-multiplicities region both for b- and c-jets.

4. – Conclusion

The differences between the standard ATLAS decay tables used by EvtGen and their updated version made available by the BELLE II Collaboration were studied, together with new decay models. Since the changes were mostly important in heavy flavour hadrons decays, the studied distributions refer to either b- or c-jets. No major change was observed in fragmentation functions, jet width/shape, nor $p_{T_{\mathrm{rel}}}$ distributions, while it was clear (and expected) that the updated tables affect the neutral stable and charged stable decay products multiplicities for HF hadrons.

Some differences have been observed between Herwig, Sherpa and Pythia, in particular in distributions like fragmentation functions, where differences ranged from 10 to 40% for both Sherpa and Herwig, and $p_{T_{\mathrm{rel}}}$ distributions where Sherpa differed from the other generators by as much as 50%. Large differences were also observed in the production fractions of heavy flavour hadrons.

To investigate the difference between different generators and versions of both decay models and tables, a Rivet routine was prepared, which contained most of the distributions shown in a previous work [11]. Additional distributions were also added.

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