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Top Quark Production and Decay in Herwig 7.1

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A summary of recent developments in the simulation of top quark production and decay in the Herwig Monte Carlo event generator.

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1 Introduction

We review recent developments in the simulation of top quarks in Herwig 7.0 [1, 2] and Herwig 7.1 [3]. We give an outline of relevant developments in the angular-ordered and dipole showers in Herwig, work on the choice of the shower-starting scale for next-to-leading order (NLO) matched $pp \to t\bar{t}$ events and a new multi-jet merging algorithm that has recently been implemented in Herwig.

2 Angular-Ordered Shower Developments

In the angular-ordered shower [4] each outgoing parton from the hard process, referred to as a shower progenitor, is selected and showered separately. First the values of the splitting variables are determined for each splitting in the shower from each progenitor. Using these values the kinematics of the partons in each splitting are reconstructed, starting from the final splitting in the shower from each progenitor and working towards the hard process. Through this process the partons in the hard process gain an unphysical off-shell mass and we must perform a reshuffling of the momenta of the particles in the event to restore energy-momentum conservation.

The default method for this reshuffling has changed between Herwig++, Herwig 7.0 and Herwig 7.1 such that we now make more use of the colour information from the hard process in our treatment of recoils in the procedure. The reader should refer to [5] for a detailed description of the changes. These developments in the reshuffling procedure have been driven by effects seen in distributions of top quark observables, in particular the invariant mass of the $t\bar{t}$-pair, obtained for PowhegBox [6, 7, 8] $pp \to t\bar{t}$ events showered with Herwig++. Improvements in these results between Herwig++ and Herwig 7.1 are primarily due to the changes in the shower reconstruction.

3 Dipole Shower Developments

The dipole shower [9, 10] has undergone significant developments between Herwig 7.0 and Herwig 7.1. The kinematics used to describe splittings off dipoles consisting of an initial-state emitter and a massive final-state spectator (massive IF dipoles) and a final-state emitter and a final-state spectator, including a massive parton before or after the splitting, (massive FF dipoles) have been completely reformulated. We have also revised the Jacobians required for the evaluation of the shower kernels and Sudakov form factors for dipole splittings involving massive partons. These changes were implemented in Herwig 7.1 and the reader should refer to [5] for full details.

While the changes to the massive IF dipole are particularly important in $t\bar{t}$-production, the improvements are most clearly seen in the prediction of the B-fragmentation distribution at LEP, shown in Figure 1, which is highly dependent upon the massive FF dipole. While this distribution was poorly described by the dipole shower in Herwig 7.0, the description is clearly improved in Herwig 7.1.

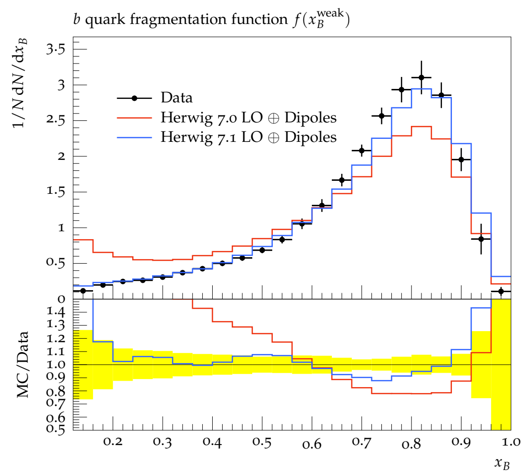


Figure 1: The B-fragmentation function as measured by SLD [11]. Predictions using the dipole shower in Herwig 7.0 and the improved treatment in Herwig 7.1 are shown.

In Herwig 7.1 the dipole shower has been extended to include the showering of top quarks in their decay. We treat top quark decays in the dipole shower in the narrow-width approximation and we require that the momentum of each top quark, set by the hard process and its showering, is conserved in its decay and subsequent showering. In addition, the NLO correction to the first emission off the top quark decay is available using the built-in Powheg decay correction in Herwig [12].

With these developments both parton showers in Herwig can shower top quarks in their production and decay at NLO in QCD. The production process can be matched at NLO using either the subtractive-type or multiplicative-type matching schemes available through the Matchbox module [10] in Herwig.

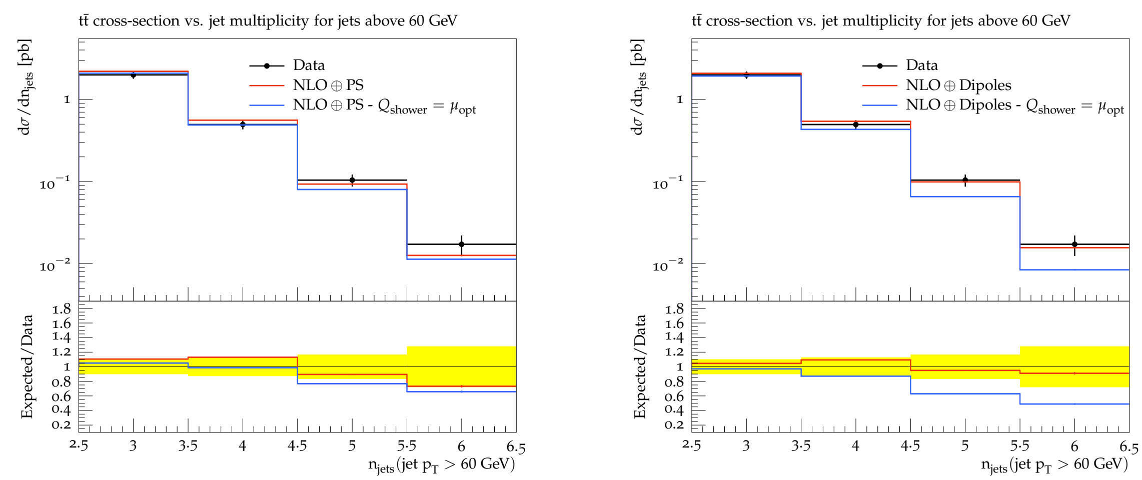
4 Shower Scale for NLO Matching in $pp \to t\bar{t}$

In MC@NLO-type [13] events, referred to as subtractive-type matching, $\oplus$, in our Matchbox-specific terminology, we must choose the scale, Q_{shower}, from which we begin showering the hard process. In general the effects of the choice of Q_{shower} are of a higher-order than the formal accuracy of the calculation, therefore it should be considered as a shower uncertainty. The default setting in Herwig is $Q_{\mathrm{shower}} = \mu_{\mathrm{F}}$, where μ_{F} is the factorisation scale. In Herwig 7.1 we have introduced a new optional choice for the shower-starting scale for use in $pp \to t\bar{t}$. We have introduced this scale to allow the developers and users of Herwig to investigate the effects of using an alternative functional form for this scale. The new scale option, μ_{opt}, is,

$$\mu_{\mathrm{opt}}^2 = \frac{1}{n_{\mathrm{out}}} \sum_{i=1}^{n_{\mathrm{out}}} m_{\mathrm{T},i}^2 \ , \tag{1}$$

where n_{out} is the number of particles outgoing from the hard process and the transverse mass, $m_{\mathrm{T},i}$, of the ith outgoing particle is given in terms of the mass, m_i, and transverse momentum, $p_{\mathrm{T},i}$, of the particle by $m_{\mathrm{T},i} = \sqrt{m_i^2 + p_{\mathrm{T},i}^2}$.

In Figure 2 we show the jet multiplicity, n_{jets}, distribution in 7 TeV $pp \to t\bar{t}$ events for jets with transverse momentum greater than 60 GeV. The predictions have been produced with the factorisation scale chosen to be the invariant mass of the $t\bar{t}$-pair. Results from both showers, with and without the alternative shower-starting scale, are presented. We see that the new scale choice produces a decrease in all multiplicity bins, however the effects are more pronounced in the dipole shower prediction. The reader should refer to [14] for a more detailed discussion of this topic.



(a) (b)

Figure 2: The jet-multiplicity in $pp \to t\bar{t}$ at 7 TeV as measured by ATLAS [15] and predictions using the angular-ordered (PS) and dipole showers, with and without the new optional shower-starting scale choice.

5 NLO Multi-jet Merging

A new NLO multi-jet merging algorithm based on the unitarised merging paradigm has been introduced in Herwig 7.1 [16, 17]. This new implementation builds upon the existing Matchbox infrastructure in Herwig and is currently available for merging with the dipole shower. For a given process one can merge the leading order matrix elements (MEs) for additional jet multiplicities and apply the NLO corrections to these MEs as required. In principle it is possible to merge an abitrary number of jets, however in practice the multiplicity is limited by the availability of the required MEs from external libraries and by the computation time required to merge large numbers of additional jets.

Several observables of interest in $pp \to t\bar{t}$ are not expected to be well-described by NLO-matched samples. An example, shown in Figure 3, is the H_{T} distribution, where H_{T} is the scalar sum of the transverse momentum of all outgoing jets from each event. It is evident that the NLO-matched result does a poor job of describing the data across much of the distribution. The results from two merged samples are also given. The $t\bar{t}(0,1,2)$ sample merges tree-level MEs for $t\bar{t}$-production with 0-, 1- and 2-additional parton emissions, while the $t\bar{t}(0^*,1^*,2)$ sample also includes the one-loop MEs for 0- and 1-additional parton emissions. The results from the merged samples display an evident improvement over the NLO-matched result.

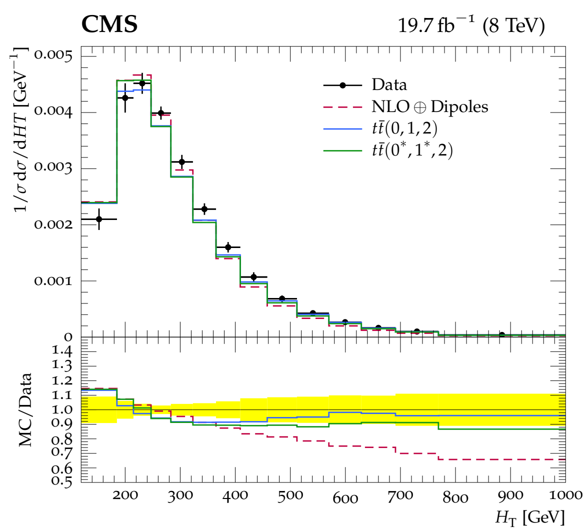


Figure 3: The distribution of H_{T} in $pp \to t\bar{t}$ at 8 TeV as measured by CMS [18] and predictions of the dipole shower in a NLO-matched sample and two multi-jet merged samples.

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