NLO merging in $t\bar{t}$+jets

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In this talk the application of the recently introduced methods to merge NLO calculations of successive jet multiplicities to the production of top pairs in association with jets will be discussed, in particular a fresh look is taken at the top quark forward-backward asymmetries. Emphasis will be put on the achieved theoretical accuracy and the associated perturbative and non-perturbative error estimates.

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1. Introduction

The forward–backward asymmetry of an observable $O$ in top-quark pair production, as measured by the CDF and DØ experiments at the $p\bar{p}$ collider TEVATRON [1, 2, 3, 4, 5] is defined as

$$A_{FB}(O) = \frac{\frac{d\sigma}{dO}|_{\Delta y>0} - \frac{d\sigma}{dO}|_{\Delta y<0}}{\frac{d\sigma}{dO}|_{\Delta y>0} + \frac{d\sigma}{dO}|_{\Delta y<0}}$$

where $\Delta y = y_t - y_{\bar{t}}$ is the rapidity difference between the top and the antitop quark. In both inclusive and differential asymmetry measurements unexpectedly large deviations from the Standard Model predictions were found. Besides triggering substantial investigations of beyond-the-Standard-Model theories, higher order corrections in the Standard Model were calculated. Of particular importance is the influence of the parton shower, investigated in [6], as it captures effects indispensable for experimental measurements. Further, all Monte Carlo event generators which are currently being used by experiments provide at most the inclusive production of $t\bar{t}$-pairs at NLO accuracy. While NLOPS matched calculations of $t\bar{t}$+jet production have been available [7, 8] for a long time, they have not been combined with the inclusive simulation of $t\bar{t}$ production allowing improved predictions of $A_{FB}$. [9] remedied this situation, providing a merged simulation of $t\bar{t}$ and $t\bar{t}$+jet production at hadron colliders, which preserves both the NLO accuracy of the fixed-order prediction and the logarithmic accuracy of the parton shower. Thus, accurate predictions for both the transverse momentum dependent asymmetry above a certain threshold and the inclusive asymmetries can be made. Electroweak corrections, calculated in [10], are not included.

2. Results

In this study the SHERPA [11] event generator with its internal matrix element generators AMEGIC++ [12, 13] and COMIX [14], its Catani-Seymour/Catani-Dittmaier-Seymour-Trocsanyi [15, 16] dipole subtraction [17], and its CSS parton shower [18] has been used. The one-loop matrix element provided by the publicly available GoSAM package [19, 20] have been interfaced through the Binoth-Les-Houches accord (BLHA) [21, 22]. The MSTW2008 LO/NLO PDF sets [23] are employed for the leading order merged (MEPS@LO [24, 25]) and next-to-leading order merged (MEPS@NLO [26, 27]) calculations, respectively.

For the MEPS@NLO calculation the $p\bar{p} \rightarrow t\bar{t}$ and $p\bar{p} \rightarrow t\bar{t}j$ processes, calculated at next-to-leading order accuracy and matched to the parton shower individually using the variant of the Mc@NLO technique described in [28], have been merged as prescribed in [26, 27]. The scales in these calculations are set according to the prescription given therein, i.e.

$$\alpha_s^{n+k}(\mu_R) = \alpha_s^n(\mu_{\text{core}}) \prod_{i=1}^{k} \alpha_s(t_i),$$

where the $t_i$ are the emission scales identified in the backwards clustering, and $\mu_{\text{core}}$ is a freely chosen scale for the identified core process [24]. Two central scale choices have been investigated:

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1The applicability of this method to processes of most general colour structures was demonstrated in [29, 30, 31].
then highlights the importance of the inclusion of subleading colour terms in the resummation of the $t\bar{t}$-system as opposed to the $N_c \to \infty$ treatment utilised in conventional parton showers. While the effect on standard observables like the transverse momentum of the top quark pair production is almost fully covered by the scale uncertainty of the resummation, its impact

\begin{align*}
\mu_{\text{core}} &= m_{t\bar{t}} \\
\mu_{\text{core}} &= \mu_{\text{QCD}} = 2 |p_ip_j| (i, j \text{ large}-N_c \text{ colour partners}) \quad \text{Thus, } \mu_{\text{QCD}} \text{ is a scale inspired by the colour flow of the event.}
\end{align*}

Fig. 1 shows the predictions of both scale choices for a standard observable, such as the top quark transverse momentum. They lead to consistent results with overlapping scale uncertainties. The perturbative convergence is slightly better for $\mu_{\text{core}} = \mu_{\text{QCD}}$ as the NLO uncertainty band is contained in the LO uncertainty band.

Fig. 2 then highlights the importance of the inclusion of subleading colour terms in the resummation kernels of the Mc@NLO formulation of [28] as opposed to the $N_c \to \infty$ treatment utilised in conventional parton showers. While the effect on standard observables like the transverse momentum of the $t\bar{t}$-system is almost fully covered by the scale uncertainty of the resummation, its impact
Figure 3: The $t\bar{t}$ asymmetry at the TEVATRON in dependence on the transverse momentum (top), the rapidity separation (bottom left), and the invariant mass (bottom right) of the $t\bar{t}$-pair compared to CDF data [5].

Finally, Fig. 3 shows the forward-backward asymmetries wrt. to the transverse momentum, the rapidity difference and the invariant mass of the $t\bar{t}$-system for both core scale choices and the associated scale uncertainties. Data is well described for $A_{FB}(p_{T,t\bar{t}})$, while the description of $A_{FB}(\Delta y,t\bar{t})$ and $A_{FB}(m_{t\bar{t}})$ is still poor. More important, however, is the fact that the difference between the two central scale choices is much larger than each individual uncertainty band. This roots in the fact that i) the forward-backward asymmetry is a ratio of observables, thus the effect of scale variations largely cancels, and ii) both scales behave differently wrt. forward or backward $t\bar{t}$ production configurations. Such effects have to be born in mind when evaluating the true theoretical uncertainties on these and similar observables.

3. Conclusions

The top quark forward–backward asymmetry at the TEVATRON has been analysed using a $p\bar{p} \to t\bar{t} + 0$, 1jets next-to-leading order merged calculation. While this gives a good description of
the asymmetry in dependence on the $t\bar{t}$-pair transverse momentum, the asymmetry in dependence on the $t\bar{t}$-pair rapidity difference and invariant mass, even taking into account additional EW effects, remains poor. Nonetheless, a consistent description of both the Sudakov region of the $p_{t,\bar{t}}$ spectrum and the high $p_{t,\bar{t}}$ region has been achieved. Furthermore, the uncertainty of the theory predictions has been reduced owing to the use of a next-to-leading order merged calculation as opposed to a leading order merged one. However, the variation resulting from using two distinct scale choices outsizes the variation due to shifting the individual scales by factors of 2. This has been demonstrated explicitly by employing two scales with different functional form. Last but not least, sub-leading colour terms in the first emission of the $t\bar{t}$ production process have been shown to have a large impact on the asymmetries.

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