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

Marek Schönherr*

Institute for Particle Physics Phenomenology, Durham University, Durham DH1 3LE, UK

Stefan Höche

SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA

Junwu Huang

SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA

Gionata Luisoni

Max-Planck Institut für Physik, Föhringer Ring 6, 80805 München, Germany

Jan Winter

Max-Planck Institut für Physik, Föhringer Ring 6, 80805 München, Germany

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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*Speaker.

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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

$$A_{\rm FB}(O) \;=\; \frac{\left.\frac{{\rm d}\sigma_{t\bar{t}}}{{\rm d}O}\right|_{\Delta y>0}-\left.\frac{{\rm d}\sigma_{t\bar{t}}}{{\rm d}O}\right|_{\Delta y<0}}{\left.\frac{{\rm d}\sigma_{t\bar{t}}}{{\rm d}O}\right|_{\Delta y>0}+\left.\frac{{\rm d}\sigma_{t\bar{t}}}{{\rm d}O}\right|_{\Delta y<0}} \tag{1.1}$$

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 NLOPS 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 $A_{\rm FB}$. [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 $p\bar{p}\to t\bar{t}$ and $p\bar{p}\to t\bar{t}j$ 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],[1] have been merged as prescribed in [26, 27]. The scales in these calculations are set according to the prescription given therein, i.e.

$$\alpha_s^{n+k}(\mu_R) \;=\; \alpha_s^n(\mu_{\rm core})\prod_{i=1}^{k}\alpha_s(t_i)\;, \tag{2.1}$$

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

[1] The applicability of this method to processes of most general colour structures was demonstrated in [29, 30, 31].

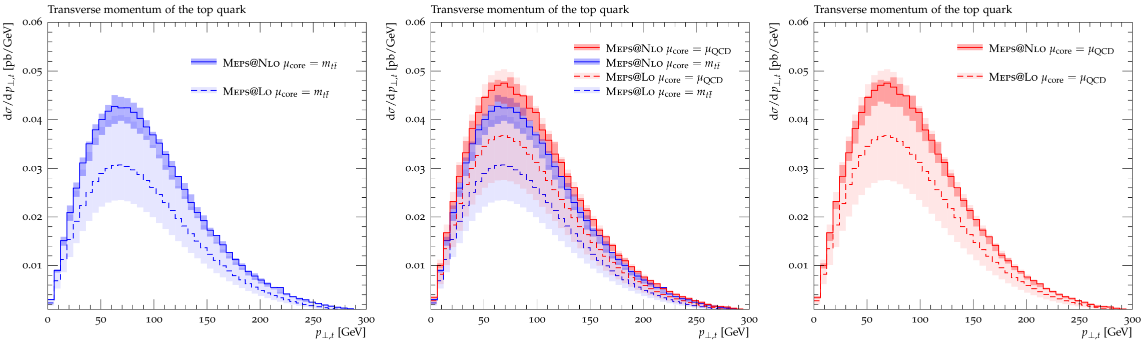

Figure 1: The scale dependence of the transverse momentum of the top quark in top quark pair production at the TEVATRON for two different choices of core scales, $\mu_{\text{core}} = m_{t\bar{t}}$ (left) and $\mu_{\text{core}} = \mu_{\text{QCD}}$ (right). The customary scale uncertainties are indicated by the dark (NLO) and light (LO) coloured bands, respectively. The central figure combines the two outer figures for easy comparison.

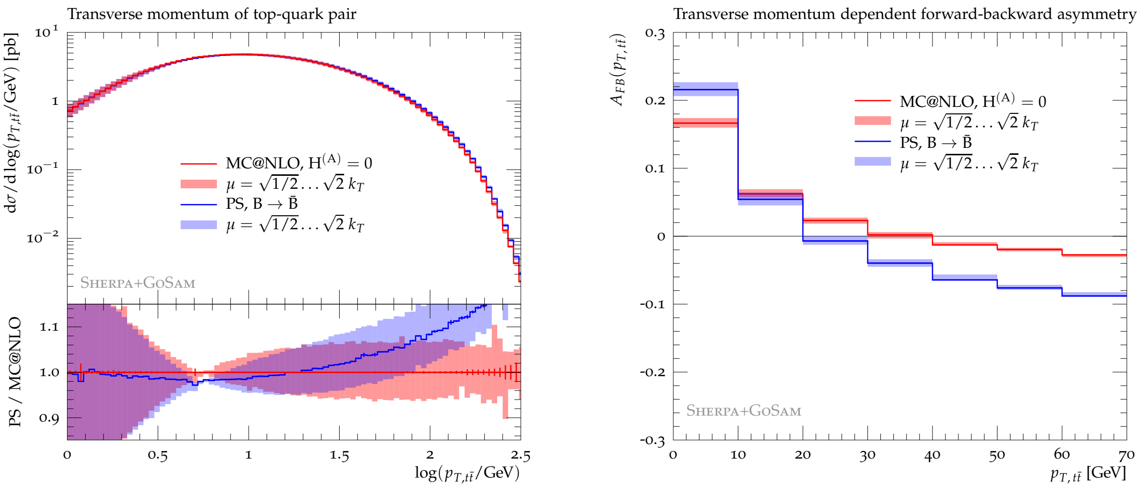

Figure 2: The importance of $N_c = 3$ soft-gluon colour-coherence on the transverse momentum of the $t\bar{t}$-pair (left) and the associated forward-backward asymmetry (right). The uncertainties are shown, stemming from a variation of the renormalisation scale in the resummation kernels of either the parton shower kernels (blue) or the subleading-colour improved MC@NLO kernels (blue). The parton shower is supplied with a local K-factor to compensate for the different normalisations. Likewise, the MC@NLO calculation is deprived of the fixed-order real emission correction, thus the resulting predictions differ only in subleading colour terms.

$\mu_{\text{core}} = m_{t\bar{t}}$ and $\mu_{\text{core}} = \mu_{\text{QCD}} = 2\,|p_i p_j|$ (i, j large-N_c colour partners). Thus, μ_{QCD} is a scale inspired by the colour flow of the event.

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

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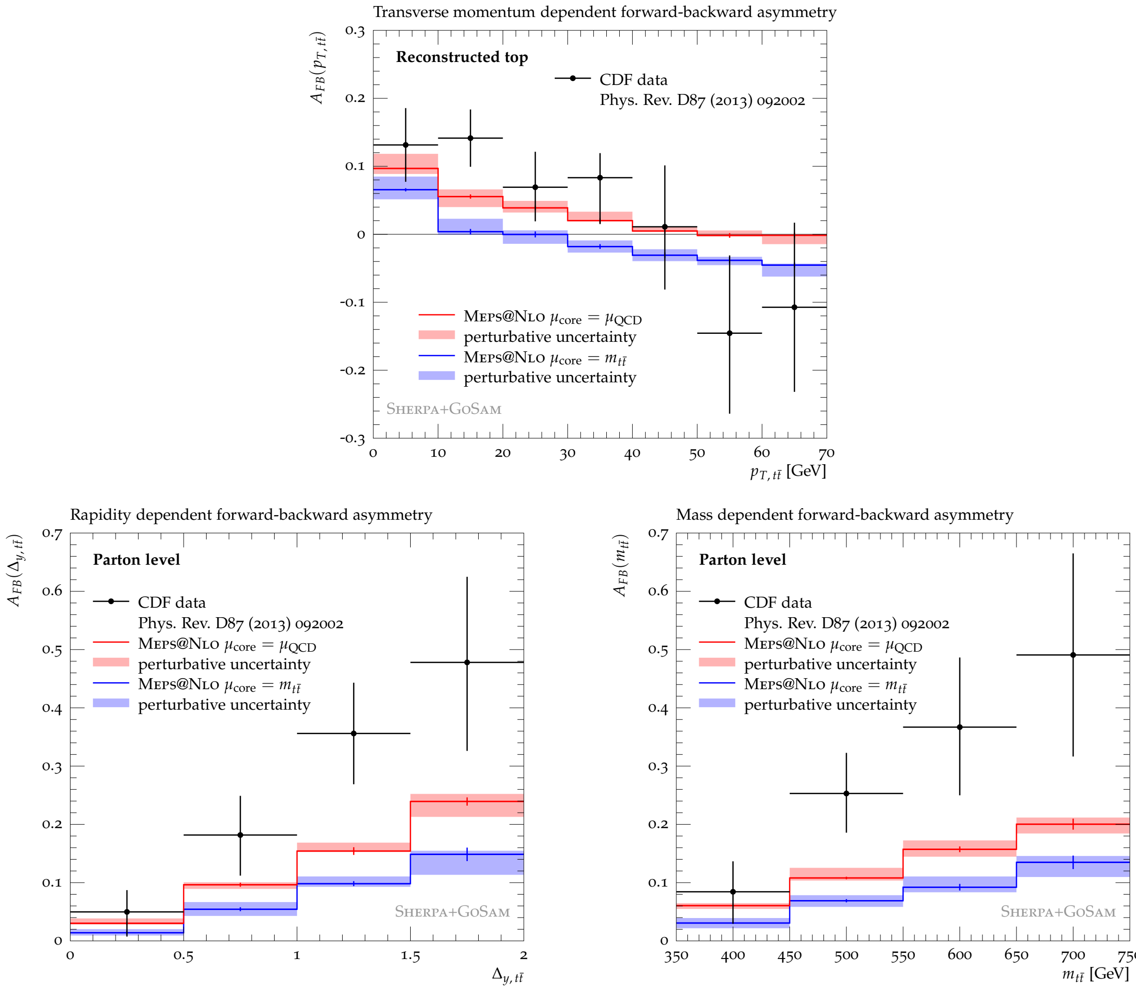

Figure 3: The $t\bar{t}$ asymmetry at the TEVATRON in dependence on the transverse momentum (top), the rapidity separation (bottom left), and the invariant mass (bottom right) of the $t\bar{t}$-pair compared to CDF data [5].

on its associated forward-backward asymmetry is profound.

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 $A_{\text{FB}}(p_{\perp,t\bar{t}})$, while the description of $A_{\text{FB}}(\Delta_{y,t\bar{t}})$ and $A_{\text{FB}}(m_{t\bar{t}})$ 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 $p\bar{p} \to t\bar{t}+0,1$jets 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 $p_{\perp,t\bar{t}}$ spectrum and the high $p_{\perp,t\bar{t}}$ 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.

References

[1] V. Abazov et al., D0 Collaboration collaboration, *First measurement of the forward-backward charge asymmetry in top quark pair production*, Phys.Rev.Lett. **100** (2008), 142002, [arXiv:0712.0851 [hep-ex]].

[2] T. Aaltonen et al., CDF Collaboration collaboration, *Forward-Backward Asymmetry in Top Quark Production in $p\bar{p}$ Collisions at sqrts* $= 1.96$ *TeV*, Phys.Rev.Lett. **101** (2008), 202001, [arXiv:0806.2472 [hep-ex]].

[3] T. Aaltonen et al., CDF Collaboration collaboration, *Evidence for a Mass Dependent Forward-Backward Asymmetry in Top Quark Pair Production*, Phys.Rev. **D83** (2011), 112003, [arXiv:1101.0034 [hep-ex]].

[4] V. M. Abazov et al., D0 Collaboration collaboration, *Forward-backward asymmetry in top quark-antiquark production*, Phys.Rev. **D84** (2011), 112005, [arXiv:1107.4995 [hep-ex]].

[5] T. Aaltonen et al., CDF collaboration, *Measurement of the top quark forward-backward production asymmetry and its dependence on event kinematic properties*, Phys.Rev. **D87** (2013), 092002, [arXiv:1211.1003 [hep-ex]].

[6] P. Skands, B. Webber and J. Winter, *QCD Coherence and the Top Quark Asymmetry*, JHEP **1207** (2012), 151, [arXiv:1205.1466 [hep-ph]].

[7] S. Alioli, S.-O. Moch and P. Uwer, *Hadronic top-quark pair-production with one jet and parton showering*, JHEP **1201** (2012), 137, [arXiv:1110.5251 [hep-ph]].

[8] A. Kardos, C. Papadopoulos and Z. Trocsanyi, *Top quark pair production in association with a jet with NLO parton showering*, Phys.Lett. **B705** (2011), 76–81, [arXiv:1101.2672 [hep-ph]].

[9] S. Höche, J. Huang, G. Luisoni, M. Schönherr and J. Winter, *Zero and one jet combined NLO analysis of the top quark forward-backward asymmetry*, Phys.Rev. **D88** (2013), 014040, [arXiv:1306.2703 [hep-ph]].

[10] W. Hollik and D. Pagani, *The electroweak contribution to the top quark forward-backward asymmetry at the Tevatron*, Phys.Rev. **D84** (2011), 093003, [arXiv:1107.2606 [hep-ph]].

[11] T. Gleisberg, S. Höche, F. Krauss, M. Schönherr, S. Schumann, F. Siegert and J. Winter, *Event generation with* S*HERPA* *1.1*, JHEP **02** (2009), 007, [arXiv:0811.4622 [hep-ph]].

[12] F. Krauss, R. Kuhn and G. Soff, *AMEGIC++ 1.0: A Matrix Element Generator In C++*, JHEP **02** (2002), 044, [hep-ph/0109036].

[13] T. Gleisberg, F. Krauss, K. T. Matchev, A. Schälicke, S. Schumann and G. Soff, *Helicity formalism for spin-2 particles*, JHEP **09** (2003), 001, [hep-ph/0306182].

[14] T. Gleisberg and S. Höche, *Comix, a new matrix element generator*, JHEP **12** (2008), 039, [arXiv:0808.3674 [hep-ph]].

[15] S. Catani and M. H. Seymour, *A general algorithm for calculating jet cross sections in NLO QCD*, Nucl. Phys. **B485** (1997), 291–419, [hep-ph/9605323].

[16] S. Catani, S. Dittmaier, M. H. Seymour and Z. Trocsanyi, *The dipole formalism for next-to-leading order QCD calculations with massive partons*, Nucl. Phys. **B627** (2002), 189–265, [hep-ph/0201036].

[17] T. Gleisberg and F. Krauss, *Automating dipole subtraction for QCD NLO calculations*, Eur. Phys. J. **C53** (2008), 501–523, [arXiv:0709.2881 [hep-ph]].

[18] S. Schumann and F. Krauss, *A parton shower algorithm based on Catani-Seymour dipole factorisation*, JHEP **03** (2008), 038, [arXiv:0709.1027 [hep-ph]].

[19] G. Cullen, N. Greiner, G. Heinrich, G. Luisoni, P. Mastrolia, G. Ossola, T. Reiter and F. Tramontano, *Automated One-Loop Calculations with GoSam*, Eur.Phys.J. **C72** (2012), 1889, [arXiv:1111.2034 [hep-ph]].

[20] P. Mastrolia, G. Ossola, T. Reiter and F. Tramontano, *Scattering AMplitudes from Unitarity-based Reduction Algorithm at the Integrand-level*, JHEP **1008** (2010), 080, [arXiv:1006.0710 [hep-ph]].

[21] T. Binoth et al., *A proposal for a standard interface between Monte Carlo tools and one-loop programs*, Comput. Phys. Commun. **181** (2010), 1612–1622, [arXiv:1001.1307 [hep-ph]].

[22] S.~Alioli et~al., *Update of the Binoth Les Houches Accord for a standard interface between Monte Carlo tools and one-loop programs*, arXiv:1308.3462 [hep-ph].

[23] A. D. Martin, W. J. Stirling, R. S. Thorne and G. Watt, *Parton distributions for the LHC*, Eur. Phys. J. **C63** (2009), 189–295, [arXiv:0901.0002 [hep-ph]].

[24] S. Höche, F. Krauss, S. Schumann and F. Siegert, *QCD matrix elements and truncated showers*, JHEP **05** (2009), 053, [arXiv:0903.1219 [hep-ph]].

[25] S. Höche, F. Krauss, M. Schönherr and F. Siegert, *NLO matrix elements and truncated showers*, JHEP **08** (2011), 123, [arXiv:1009.1127 [hep-ph]].

[26] S. Höche, F. Krauss, M. Schönherr and F. Siegert, *QCD matrix elements + parton showers: The NLO case*, JHEP **1304** (2013), 027, [arXiv:1207.5030 [hep-ph]].

[27] T. Gehrmann, S. Höche, F. Krauss, M. Schönherr and F. Siegert, *NLO QCD matrix elements + parton showers in $e^+e^- \to$hadrons*, JHEP **1301** (2013), 144, [arXiv:1207.5031 [hep-ph]].

[28] S. Höche, F. Krauss, M. Schönherr and F. Siegert, *A critical appraisal of NLO+PS matching methods*, JHEP **09** (2012), 049, [arXiv:1111.1220 [hep-ph]].

[29] S. Höche, F. Krauss, M. Schönherr and F. Siegert, *W+n-jet predictions with MC@NLO in Sherpa*, Phys.Rev.Lett. **110** (2013), 052001, [arXiv:1201.5882 [hep-ph]].

[30] S. Höche and M. Schönherr, *Uncertainties in next-to-leading order plus parton shower matched simulations of inclusive jet and dijet production*, Phys.Rev. **D86** (2012), 094042, [arXiv:1208.2815 [hep-ph]].

[31] F.~Cascioli, P.~Maierhoefer, N.~Moretti, S.~Pozzorini and F.~Siegert, *NLO matching for $t\bar{t}b\bar{b}$ production with massive b-quarks*, arXiv:1309.5912 [hep-ph].