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$pp \to t\bar{t}j + X$ matched to the Nagy-Soper parton shower at NLO QCD

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We briefly summarize the Nagy-Soper parton shower and the MC@NLO-like matching scheme. Results obtained using HELAC-NLO framework in conjunction with DEDUCTOR for top quark pair production in association with one hard jet at the LHC are presented. A comparison of our results with other matching schemes and other parton showers is also discussed for various observables.

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1. Introduction

High energy experiments like Tevatron or LHC study the Standard Model of particle physics and its possible extensions. At the core of these experimental studies are Monte Carlo (MC) generators that are based on factorization theorems. Their construction usually involves additional approximations and phenomenological models. However, this approach allows the simulation of particle scatterings starting from the hard interaction and then dressing the external legs with further radiation generated by the parton shower. This will evolve the hard state down to a low energy scale where non-perturbative effects are important. At that point hadronization models are employed.

In order to keep up with the increasing precision of experimental data, MC generators have to be improved. There are several options to achieve this. For fixed-order calculations the inclusion of next-to-leading order (NLO) corrections in quantum chromodynamics (QCD) are widely automated [1, 2]. Currently, efforts are ongoing in the automatization of electroweak corrections [3] while NNLO QCD corrections are only available for $2 \to 2$ processes.

Fixed-order calculations usually suffer from large logarithms, which can be resummed to all orders in perturbation theory using analytical resummation [4] or parton shower methods [5, 6, 7]. Matching of NLO fixed-order calculations to parton showers has the benefit of combining several features. Well separated partons are then correctly described by matrix elements in perturbative quantum field theory, whereas the soft and collinear parton splittings are generated by parton showers. There are several methods in the literature to do the matching, the most popular ones being MC@NLO [8] and POWHEG [9]. The current matching and merging schemes are all limited by the accuracy of the shower algorithms, that include only leading colour (LC) and leading logarithmic (LL) accuracies and no spin correlations. In order to go beyond these approximations one has to include soft-gluon interferences and other subleading effects. In Ref. [10] it has been shown that these subleading effects can be sizable for specific observables.

In this proceeding, we first briefly review the basics of the Nagy-Soper shower. In section 3 we explain the matching scheme for this shower and in section 4 we show first results for the $pp \to t\bar{t}j+X$ production at the LHC. Finally, we conclude and give an outlook for future improvements of this work in section 5.

2. Nagy-Soper parton shower

Here, we give a very brief summary of the Nagy-Soper parton shower introduced by Zoltan Nagy and Davison Soper [11, 12]. We only highlight the necessary concepts to understand the parton shower matching, while a more thorough discussion can be found in Ref. [13]. We start from the all-order expression of the expectation value of an observable F, for a $2 \to m$ process

$$\sigma[F] = \sum_m \frac{1}{m!} \int [d\{p,f,s',c',s,c\}_m] F(\{p,f\}_m) \langle \{s',c'\}_m | \{s,c\}_m \rangle \rho(\{p,f,s',c',s,c\}_m) \,, \quad (2.1)$$

where f_i, s_i, c_i and p_i represent the flavour, spin, colour and momentum of a particle. The generalized phase space integration measure, $[d\{p,f,s',c',s,c\}_m]$, includes the integration over the initial state momentum fractions η_a and η_b as well as the summation over spin and colour indices. The matrix element, $|\mathscr{M}(\{p,f\}_m)\rangle$, is a vector in colour and spin space and its square can be rewritten in the form of a quantum density matrix defined as

$$\rho(\{p,f,s',c',s,c\}_m) = \mathscr{M}^*(\{p,f,s',c',s,c\}_m)\mathscr{M}(\{p,f,s',c',s,c\}_m)\frac{f_a(\eta_a,\mu_F^2)f_b(\eta_b,\mu_F^2)}{4n_c(a)n_c(b)\times flux} . \tag{2.2}$$

The parton shower evolves this quantum density from the hard scale, t_0, of the scattering process down to the low scale, t_F, where non-perturbative physics models can be applied. The evolution of the system is described by a unitary operator $U(t_F,t_0)$, which satisfies

$$\frac{dU(t,t_0)}{dt} = [\mathscr{H}_I(t) - \mathscr{V}(t)]\,U(t,t_0) . \tag{2.3}$$

Here the evolution operator $U(t_F,t_0)$ is given by the real splitting operator, $\mathscr{H}_I(t)$, which describes the emission of resolved particles and the virtual operator, $\mathscr{V}(t)$, which describes unresolved emissions. The above differential equation is solved by the following operator

$$U(t_F,t_0) = N(t_F,t_0) + \int_{t_0}^{t_F} d\tau\,[\mathscr{H}_I(\tau) - \mathscr{V}_S(\tau)]\,U(\tau,t_0) , \tag{2.4}$$

with the normal Sudakov form factor

$$N(t_F,t_0) = \exp\left(-\int_{t_0}^{t_F} d\tau\, \mathscr{V}_E(\tau)\right) . \tag{2.5}$$

The virtual splitting operator is decomposed into $\mathscr{V}(t) = \mathscr{V}_E(t) + \mathscr{V}_S(t)$, where $\mathscr{V}_E(t)$ is the colour diagonal part and $\mathscr{V}_S(t)$ the colour off-diagonal part with subleading contributions. The colour diagonal part will be exponentiated while the off-diagonal contribution is treated as perturbation.

This shower concept differs in many ways from conventional showers and has been partly implemented in a MC program DEDUCTOR [14]. A main conceptual difference is that the splitting functions are derived using factorization on the amplitude level [11]. In addition, initial state charm and bottom quarks are treated as massive and PDFs used in the shower are evolved according to the shower splitting kernels [11, 15]. The shower is consistently able to include spin and colour correlations throughout the whole parton evolution [12, 16, 17]. The ordering parameter in the evolution is a virtuality based one and implements the validity of the on-shell approximation in each step of the evolution [18]

$$e^{-t_l} = \frac{\Lambda_l^2}{Q^2} , \qquad \Lambda_l^2 = \frac{|(\hat{p}_l \pm \hat{p}_{m+1})^2 - m^2(l)|}{2p_l\cdot Q} Q^2 . \tag{2.6}$$

Finally, the Nagy-Soper shower uses a global momentum mapping that improves resummation effects in Drell-Yan Z-production [19].

3. Parton shower matching

At next-to-leading order the quantum density matrix has to be extended by including the virtual and real matrix elements

$$|\rho) = \underbrace{|\rho_m^{(0)})}_{\text{Born, }\mathscr{O}(1)} + \underbrace{|\rho_m^{(1)})}_{\text{Virtual, }\mathscr{O}(\alpha_s)} + \underbrace{|\rho_{m+1}^{(0)})}_{\text{Real, }\mathscr{O}(\alpha_s)} + \mathscr{O}(\alpha_s^2) . \tag{3.1}$$

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Applying the shower evolution operator to this density generates a spurious non-zero contribution at $\mathscr{O}(\alpha_s)$, which can be easily seen by expanding the evolution operator

$$(F|U(t_F,t_0)|\rho) \approx (F|\rho) + \int_{t_0}^{t_F} d\tau \, (F|\,[\mathscr{H}_I(\tau) - \mathscr{V}(\tau)]\,|\rho_m^{(0)}) + \mathscr{O}(\alpha_s^2) \, . \tag{3.2}$$

As a consequence, the total cross section is changed and the first emission is double counted. In order to remove this additional contribution the MC@NLO approach has been applied. We will first focus on fully inclusive processes like $pp \to t\bar{t}$ and then we will explain the matching of exclusive processes which already suffer from divergences at the LO.

3.1 Fully inclusive processes

The idea is to redefine the quantum density matrix by providing suitable counterterms for the shower contribution

$$|\bar{\rho}) \equiv |\rho) - \int_{t_0}^{t_F} d\tau \, [\mathscr{H}_I(\tau) - \mathscr{V}(\tau)]\,|\rho_m^{(0)}) + \mathscr{O}(\alpha_s^2) \, . \tag{3.3}$$

By dropping the infrared cutoff ($t_F \to \infty$) we observe that the shower naturally incorporates the NLO subtraction scheme

$$\begin{aligned} \int_{t_0}^{\infty} d\tau \, \mathscr{H}_I(\tau) &= \sum_l \mathbf{S}_l \int_{t_0}^{\infty} d\tau \delta(\tau - t_l)\Theta(\tau - t_0) = \sum_l \mathbf{S}_l \Theta(t_l - t_0) \, , \\ \int_{t_0}^{\infty} d\tau \, \mathscr{V}(\tau) &= \sum_l \int d\Gamma_l \mathbf{S}_l \Theta(t_l - t_0) \equiv \mathbf{I}(t_0) + \mathbf{K}(t_0) \, . \end{aligned} \tag{3.4}$$

Thus, we see that matching is a two-step procedure

$$\begin{aligned} \bar{\sigma}[F] = \frac{1}{m!} &\int [d\Phi_m](F|U(t_F,t_0)|\Phi_m)(\Phi_m|S) \\ &+ \frac{1}{(m+1)!} \int [d\Phi_{m+1}](F|U(t_F,t_0)|\Phi_{m+1})(\Phi_{m+1}|H) \, , \end{aligned} \tag{3.5}$$

where $\Phi_m = \{p, f, \hat{c}, \hat{s}, c, s\}_m$. First we have to generate the samples

$$\begin{aligned} (\Phi_m|S) &\equiv (\Phi_m|\rho_m^{(0)}) + (\Phi_m|\rho_m^{(1)}) + (\Phi_m|\mathbf{I}(t_0) + \mathbf{K}(t_0) + \mathbf{P}|\rho_m^{(0)}) \, , \\ (\Phi_{m+1}|H) &\equiv (\Phi_{m+1}|\rho_{m+1}^{(0)}) - \sum_l (\Phi_{m+1}|\mathbf{S}_l|\rho_m^{(0)})\Theta(t_l - t_0) \, , \end{aligned} \tag{3.6}$$

and then apply the shower evolution operator $U(t_F, t_0)$.

3.2 Exclusive processes

The situation is more complex for exclusive processes. In order to avoid double counting, we have to add inclusive jet functions F_I and we have to modify the subtraction terms

$$\begin{aligned} \bar{\sigma}[F] = \frac{1}{m!} &\int [d\Phi_m](F|U(t_F,t_0)|\Phi_m)(\Phi_m|S)F_I(\{\hat{p},\hat{f}\}_m) \\ &+ \frac{1}{(m+1)!} \int [d\Phi_{m+1}](F|U(t_F,t_0)|\Phi_{m+1})(\Phi_{m+1}|\tilde{H})F_I(\{p,f\}_{m+1}) \, , \end{aligned} \tag{3.7}$$

with

$$(\Phi_{m+1}|\tilde{H}) \equiv (\Phi_{m+1}|\rho^{(0)}_{(m+1)}) - \sum_l (\Phi_{m+1}|\mathbf{S}_l|\rho^{(0)}_m)\Theta(t_l - t_0)F_I(Q_l(\{p,f\}_{m+1})) , \tag{3.8}$$

where the jet function $F_I(Q_l(\{p,f\}_{m+1})) = F_I(\{\hat{p},\hat{f}\}_m)$ acts on the underlying Born kinematics. Expanding the evolution operator now gives

$$\begin{aligned}\bar{\sigma}[F] \approx \sigma^{NLO} + \int \frac{[d\Phi_m]}{m!}\frac{[d\Phi_{m+1}]}{(m+1)!}\int_{t_0}^{t_F} d\tau (F|\Phi_{m+1})(\Phi_{m+1}|\mathscr{H}_I(\tau)|\Phi_m) \\ \times (\Phi_m|\rho^{(0)}_m)\,[1 - F_I(\{p,f\}_{m+1})]\,F_I(\{\hat{p},\hat{f}\}_m) + \mathscr{O}(\alpha_s^2) .\end{aligned} \tag{3.9}$$

Thus, double counting is removed if $F_I(\{p,f\}_{m+1}) = 1$ for $F(\{p,f\}_{m+1}) \neq 0$, i.e. when generation cuts are more inclusive than cuts on the final observable.

4. Application: $pp \to t\bar{t}j+X$

The implementation details of the scheme presented in the previous section in the HELAC-NLO framework [20] can be found in Ref. [13]. We now present results for $pp \to t\bar{t}j+X$ at the LHC. The NLO QCD corrections have been already presented in Ref. [21]. First parton shower matched calculations using the POWHEG method were presented in Ref. [22], while merging several matched calculations for different jet multiplicities is discussed in Ref. [23].

We consider the LHC at $\sqrt{s} = 8$ TeV. The top quark mass is $m_t = 173.5$ GeV. In the shower we set the parton masses of charm and bottom quarks to $m_c = 1.4$ GeV and $m_b = 4.75$ GeV. We use the MSTW2008NLO PDF [24] set in our calculation and provided it at $\mu_F = 1$ GeV to DEDUCTOR. Renormalization and factorization scales are set to $\mu_R = \mu_F = \mu_0 = m_t$. We use the anti-$k_T$ jet algorithm [25] with $\Delta R = 1$ and the analysis cuts are $p_T(j_1) > 50$ GeV and $|y(j_1)| < 5$, while the generation cut is $p_T(j_1) > 30$ GeV. The initial shower time is chosen to be

$$e^{-t_0} = \min_{i \neq j}\left\{\frac{2p_i \cdot p_j}{\mu_T^2 Q^2}\right\} , \tag{4.1}$$

where the parameter μ_T allows us to address parton shower uncertainties. For our central prediction we choose $\mu_T = 1$. The shower evolution is restricted to LC and spin-averaged contributions. In addition we do not include non-perturbative effects or top quark decays. The comparison with other Monte Carlo generators is, therefore, performed at the level of the perturbative evolution. For the comparison we use aMC@NLO [2] with the MC@NLO matching in conjunction with PYTHIA8 [6] (p_T ordered parton shower) and PYTHIA6Q [7] (virtuality ordered parton shower). For the POWHEG matching we use the POWHEG-BOX [26] results together with PYTHIA8.

In Fig. 1 we address scale and parton shower uncertainties: $m_t/2 < \mu_0 < 2m_t$ and $1/2 < \mu_T < 2$. The p_T of the hardest jet shows a flat and reduced scale variation with respect to both parameters μ_0 and μ_T. This is expected since it is already an NLO-accurate observable. On the contrary, the p_T of the $t\bar{t}j_1$ system presents a stronger dependence on the shower parameter μ_T in the low p_T regime, where the parton shower dominates. The scale dependence sets in once the real matrix element is present, i.e roughly at 30 GeV, and grows rapidly with transverse momentum.

Fig. 2 illustrates the comparison with other MC generators. For inclusive observables, like the p_T of the top quark in the left panel, we do not observe substantial differences between the

MC generators. This is expected because this observable is already accurate at NLO and serves as a good cross check of our implementation. For exclusive observables like the p_T of the $t\bar{t}j$ system, that is shown in the right panel of Fig. 2, we find a strong dependence on the initial shower conditions. We observe that aMC@NLO+PYTHIA and POWHEG+PYTHIA overshoot the high p_T tail, where one would like to recover the real matrix element description. On the other hand, HELAC-NLO+DEDUCTOR and aMC@NLO+PYTHIA6Q preserve the prediction in the high energy tail. The comparison for other observables can be found in Ref. [13].

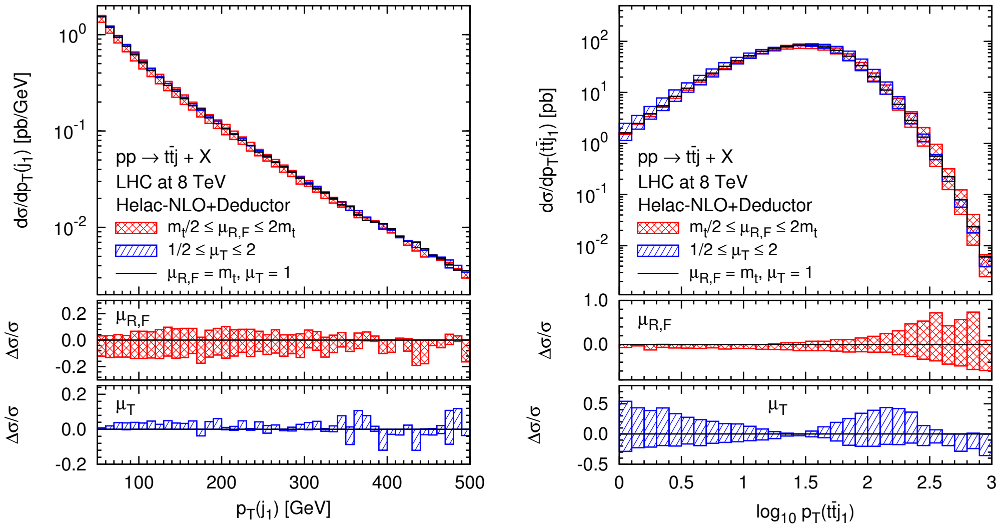

Figure 1: *Differential cross section as a function of the transverse momentum of the hardest jet (left panel) and of the $t\bar{t}j_1$ system (right panel).*

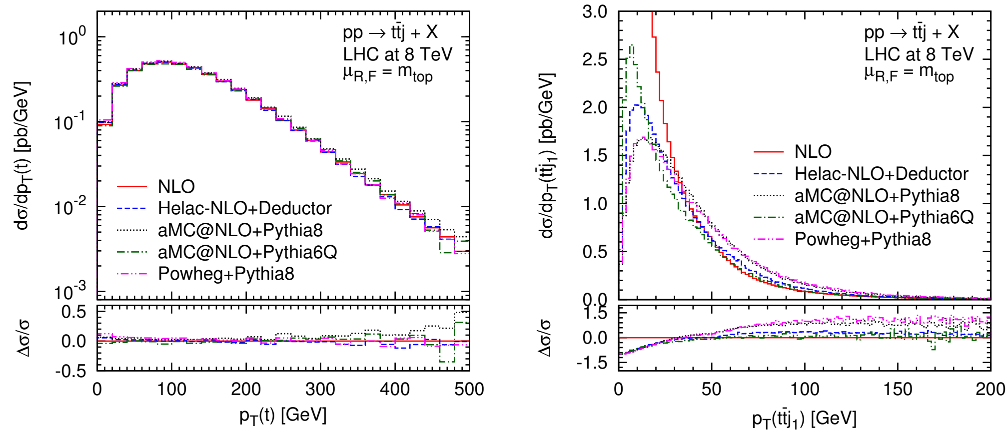

Figure 2: *Differential cross section as a function of the transverse momentum of the top quark (left panel) and of transverse momentum of the $t\bar{t}j_1$ system (right panel).*

5. Summary and Outlook

We presented the NLO matching scheme for the Nagy-Soper parton shower in the spirit of the MC@NLO method. We studied the production of $t\bar{t}j$ at the LHC using the HELAC-NLO+DEDUCTOR framework and compared it to the other MC generators. We want to stress that the current accuracy of HELAC-NLO+DEDUCTOR is only LC and spin-averaged, i.e the same as for other MC programs. However, this comparison is an important validation of our implementation. Differences, present in exclusive observables, can be traced back, for example, to the choice of the initial shower conditions.

In the future we want to extend the matching scheme implemented in HELAC-NLO to include full colour and spin correlations. Nevertheless, those effects have to be first added to DEDUCTOR.

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