Z$^0$-boson production in association with a top anti-top pair at NLO accuracy with parton shower effects

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Abstract

We present predictions for the production cross section of a Standard Model Z$^0$-boson in association with a t$\bar{t}$ pair at the next-to-leading order accuracy in QCD, matched with shower Monte Carlo programs to evolve the system down to the hadronization energy scale. We adopt a framework based on three well established numerical codes, namely the POWHEG-BOX, used for computing the cross section, HELAC-NLO, which generates all necessary input matrix elements, and finally a parton shower program, such as PYTHIA or HERWIG, which allows for including t-quark and Z$^0$-boson decays at the leading order accuracy and generates shower emissions, hadronization and hadron decays.

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With increasing collider energies, the t-quark plays an increasingly important role in
particle physics. Its production cross section grows faster with energy than that of any
other discovered Standard Model (SM) particle. Already after the first year of successful
run of the LHC, the $t\bar{t}$ production cross section is measured with unprecedented accuracy
at $\sqrt{s} = 7$ TeV, so that the corresponding SM theoretical prediction will be challenged
soon [1, 2]. However, many other t-quark properties have not yet been directly accessed. In
particular, its couplings to neutral gauge (especially the $Z^0$) and scalar bosons are still prone
to large uncertainties. In Refs. [3, 4] the possibility of measuring the $t\bar{t}Z$ and $t\bar{t}\gamma$ couplings
was studied based upon leading-order (LO) parton level predictions. Although such precision
is sufficient for feasibility studies, finding the optimal values of the experimental cuts requires
indeed predictions at higher accuracy.

An essential step towards higher accuracy is the inclusion of next-to-leading order (NLO)
radiative corrections. Recent theoretical advances made possible our computation of the
$pp \rightarrow t\bar{t}Z$ cross section at the parton level, including QCD corrections at NLO [5]. In
order though to get the optimum benefit and to produce predictions that can be directly
compared to experimental data at the hadron level, a matching with parton shower (PS) and
hadronization implemented in shower Monte Carlo (SMC) programs is ultimately inevitable.
Thus, in this letter we present first predictions for $pp \rightarrow t\bar{t}Z$ production at LHC at the
matched NLO + PS accuracy.

In constructing a general interface of PS to matrix element (ME) computations with
NLO accuracy in QCD, we have chosen to combine the POWHEG [6, 7] method and FKS
subtraction scheme [8], as implemented in the POWHEG-BOX [9] computer framework, with the
HELAC-NLO [10] approach, respectively. In particular, POWHEG-BOX requires the relevant
MEs as external input. We obtain the latter in a semi-automatic way by codes in the
HELAC-NLO package [11]. With this input POWHEG-BOX is used to generate events at the Born
plus first radiation emission level, stored in Les Houches Event Files (LHEF) [12], that can
be interfaced to standard SMC programs. Previous applications of the whole framework,
proving its robustness, were presented in Refs. [13, 14]. This same setup also allows for
exact NLO pure hard-scattering predictions. Further details on the implementation of the
computation of the $pp \rightarrow t\bar{t}Z$ hard-scattering cross-section in it, at NLO accuracy in QCD,
together with checks, were recorded in Ref. [5].
Figure 1. Transverse momentum (left) and rapidity (right) distributions of the $Z^0$-boson at NLO and after first radiation (PowHel). The lower panels show the ratio of the two predictions with combined uncertainties.

All these computations are steps of an ongoing project for generating event samples for $pp \rightarrow t\bar{t}X$ processes, where $X$ stays for a hard partonic object. The events we generate are stored in LHEF, made available on the web, and are ready to be interfaced to standard SMC programs to produce predictions for distributions at the hadron level. Such predictions can be useful for optimizing the selection cuts applied to disentangle the signal from the background, in order to improve the experimental accuracy of the $t$-quark coupling measurements.

Interfacing NLO calculations to SMC programs allows to estimate the effects of decays, shower emissions and hadronization, therefore we have analyzed the process at hand at three different stages of evolution:

**PowHel:** we analyzed the events including no more parton emissions than the first and hardest one, collected in LHEF produced as output of **POWHEG-BOX** + **HELAC-NLO** (PowHel).

**Decay:** we just included on-shell decays of $t$-quarks and the $Z^0$-boson, as implemented in **PYTHIA** [15], and further decays of their decay products, like charged leptons (the $\tau$ is considered as unstable) and gauge bosons ($W$), turning off any initial and final PS and hadronization effect.
**Full SMC:** decays, shower evolution, hadronization and hadron decays have been included in our simulations, using both **PYTHIA** and **HERWIG** [16].

In our computation, we adopted the following parameters: $\sqrt{s} = 7$ TeV, CTEQ6.6M PDF set from **LHAPDF**, with a 2-loop running $\alpha_s$, 5 light flavours and $\Lambda_{\overline{MS}}^5 = 226$ MeV, $m_t = 172.9$ GeV, $m_Z = 91.1876$ GeV, $G_F = 1.16639 \cdot 10^{-5}$ GeV$^{-2}$. The renormalization and factorization scales were chosen equal to the default scale $\mu_0 = m_t + m_Z/2$. We used the last version of the SMC fortran codes: **PYTHIA** 6.425 and **HERWIG** 6.520. Following our implementation of $t\bar{t}H$ hadroproduction in Ref. [14], in both SMC setup muons (default in **PYTHIA**) and neutral pions were assumed as stable particles. All other particles and hadrons were allowed to be stable or to decay according to the default implementation of each SMC. Masses and total decay widths of the elementary particles were tuned to the same values in **PYTHIA** and **HERWIG**, but each of the two codes was allowed to compute autonomously partial branching fractions in different decay channels for all unstable particles and hadrons. Multiparticle interaction effects were neglected (default in **HERWIG**). Additionally, the intrinsic $p_\perp$-spreading of valence partons in incoming hadrons in **HERWIG** was assumed to be 2.5 GeV.

First, to check event generation, we compared several distributions from events including no more than first radiation emission (**PowHel** level) with the NLO predictions of Ref. [5]. We found agreement for all considered distributions. As examples, we show in Fig. 1 the transverse momentum and rapidity distributions of the $Z^0$-boson.

Next, we studied the effect of the full SMC by comparing distributions at the decay and SMC level. Since particle yields are very different at the end of these two stages, we made such a comparison without any selection cut, in order to avoid the introduction of any bias. As an illustrative example, we present the distributions of the transverse momentum and rapidity of the hardest jet, $p_\perp^j$ and $y_j$, in Fig. 2. Jets are reconstructed through the anti-$k_\perp$ algorithm with $R = 0.4$, as implemented in **FastJet** [17]. The softening of the transverse momentum spectrum is apparent as going from the decay level to the full SMC one, while the effect of the shower on the rapidity of the hardest jet is almost negligible and rather homogeneous. The cross-section at both level amounts to $\sigma = 138.7 \pm 0.01$ fb. Using our setup for the full SMC’s, we found agreement between **PYTHIA** and **HERWIG** predictions within very few percent, despite the conceptual differences between the two SMC generators as for the shower ordering variables and hadronization models, confirming the level of agreement.
Figure 2. Transverse momentum (left) and rapidity (right) distributions of the hardest jet after decay and after full SMC. The lower panels show the ratio of all predictions to PowHel+SMC using PYTHIA.

already reported in Ref. [14] in the study of a different process.

Next, we made predictions for t\bar{t}Z hadroproduction at the LHC including experimental selection cuts. For this analysis, in the absence of a dedicated tune for NLO matched computations, PYTHIA was tuned to the Perugia 2011 set of values, one of the most recent LO tunes [18], updated on the basis of recent LHC data, providing a p_⊥-ordered PS. Its application turned out to increase our particle yields by about 10%. As a consequence, the agreement between the tuned PYTHIA and untuned HERWIG predictions decreases (as for HERWIG, the default configuration was used, providing instead an angular-ordered PS), and we present only the PYTHIA ones.

In case of t\bar{t}Z hadroproduction overwhelming backgrounds come from t\bar{t}+jets final states. In Ref. [4] the differential cross section as a function of missing transverse momentum for the production of p_⊥b\bar{b}+4 jets was found a useful tool for differentiating the signal and the possible backgrounds. The proposed set of selection cuts is rather exclusive and the rates decrease so much that the measurement for the present LHC run at \sqrt{s} = 7 TeV looks quite demanding from the statistical point of view, therefore, we restrict ourself to present predictions for the future runs at \sqrt{s} = 14 TeV (\sigma_{all\,cut,14}/\sigma_{all\,cut,7} \sim 7 and 8 at the decay and at the full SMC level, respectively).

In Fig. 3 we show the distributions of transverse momentum and rapidity of the hardest
Figure 3. Transverse momentum (left) and rapidity (right) distributions of the hardest jet after decay and after full SMC (PYTHIA), under selection cuts (1–8) implemented at both levels. The lower panels show the ratio of the predictions at different levels.

jet using the following reduced set of cuts: 1) we reconstruct at least six jets with rapidity $|y| < 2.5$, 2) of these we require at least one b-jet and one $\bar{b}$-jet, 3) for b-jets $p_T > 20\text{ GeV}$, 4) for other jets $p_T^{\text{non-b}} > 30\text{ GeV}$, 5) at least 3 jets (b or non-b) with $p_T > 50\text{ GeV}$, 6) $\Delta R(j,j) > 0.4$, where $j$ denotes any (b or non-b) jet and $\Delta R$ is defined as $\sqrt{\Delta \phi^2 + \Delta y^2}$, 7–8) $\Delta \phi(p_T, p_T^b) > 100^\circ$, with $p_T$ meaning either $(p_T(\hat{b}_1) + p_T(\hat{b}_2))$ (cut 7), or $(p_T(\hat{t}_1) + p_T(\hat{t}_2) + p_T(\hat{t}_3) + p_T(\hat{t}_4))$ (cut 8), where $\hat{b}_1$, $\hat{b}_2$ and $\hat{t}_1$, $\hat{t}_2$, $\hat{t}_3$, $\hat{t}_4$ are the jets that allow for the best $t \rightarrow bW^+ \rightarrow bjj$ and $\bar{t} \rightarrow bW^- \rightarrow bjj$ invariant mass simultaneous reconstruction, since they minimize the

$$\chi^2(b_{1j1j2}; \hat{b}_{2j3j4}) = \frac{(m_{j1j2} - m_W)^2}{\sigma_W^2} + \frac{(m_{j3j4} - m_W)^2}{\sigma_W^2} + \frac{(m_{b1j1j2} - m_W)^2}{\sigma_W^2} + \frac{(m_{b2j3j4} - m_W)^2}{\sigma_W^2}$$

computed by considering all possible $j_kj_l$, $b_{ljkjl}$ and $\bar{b}_{jkljl}$ combinations. The $W \rightarrow jj$ and $t \rightarrow bjj$ invariant mass resolutions were set to $\sigma_W = 7.8\text{ GeV}$ and $\sigma_t = 13.4\text{ GeV}$, respectively [19]. The PowHel+PYTHIA cross sections after these cuts amount to $\sigma_{\text{dec}} = 65.56 \pm 0.15\text{ fb}$ and $\sigma_{\text{SMC}} = 53.74 \pm 0.13\text{ fb}$.

In Fig. 4 we plot the invariant mass distribution of the t-quark, as reconstructed from its decay products, by minimizing the $\chi^2$ above. At the decay level, the reconstruction leads to a clear peak centered around the $m_t$ value. On the other hand, after full SMC, due both to
Figure 4. Invariant mass distribution of the t-quark reconstructed from the decay products at both
decay and full SMC levels, for the tâZ signal and, at the decay level, for one background (tâ+jet)
after selection cuts (1–8) (wider distributions in abscissa values) and after selection cuts (1–10)
(narrower distributions).

further emissions which modify jet content and to hadron decays, there are more candidate
jets and the reconstruction is less successful. Although a peak is still visible (more evident
in non-log scale), it is smeared towards lower mass values. The effect of the shower and
hadronization turns out to be especially large in the peak region.

In Fig. 4 we also show the $m_{b jj}$ distribution after decay for an important background
process: tâ-pair production associated with a jet (obtained at the scale $\mu_0 = m_t$). Clearly,
the background overwhelms the signal, therefore, in order to select the peak region, we
include two more cuts: 9) $p_T(\text{due to all } \nu's) > 5\sqrt{\sum p_T^j}$ (of all jets, $b$ or non-$b$), and 10)
$\chi^2_{\text{min}} < 3$, where $\chi^2_{\text{min}}$ is the minimum of the $\chi^2$ above. Thus, we closely reproduce the cuts
in Ref. [4], aimed at favoring the $Z^0 \rightarrow \nu \nu$ decay channel. The effect of the whole set of
cuts on top reconstruction in $t\bar{t}Z$ and $t\bar{t}+\text{jet}$ events is also shown in Fig. 4. Although this set of cuts is effective in selecting the signal, the background is globally still larger: for the signal $\sigma_{\text{dec}} = 4.83 \pm 0.04 \text{ fb}$, while for the background $\sigma_{\text{dec}} = 9.86 \pm 1.05 \text{ fb}$. However, as can be understood from Fig. 5, where the distributions of the missing transverse momentum after decay are shown for both $t\bar{t}Z$ and $t\bar{t}+\text{jet}$, these cuts allow for disentangling the signal, at least at the decay level. At the shower level, the $p_{T}$ distributions of the $t\bar{t}Z$ signal still shows a harder spectrum than the one of the $t\bar{t}+\text{jet}$ background, but to a lesser extent. In this case, the effect of different top reconstruction strategies, still under investigation, can be crucial to help better disentangle the signal from the background in the $p_{T}b\bar{b}+4 \text{ jets}$ considered channel.

We studied the hadroproduction of a $Z^{0}$ boson in association with a $t\bar{t}$-pair, process of interest for measuring the $t\bar{t}Z$-coupling directly at the LHC. We studied the effect of heavy...
particle decays as well as the one of the full SMC. We produced predictions for the LHC. As the production cross section is rather small, measuring the $t\bar{t}Z$-coupling becomes more feasible after the planned 14 TeV energy upgrade. Once all background processes will be predicted with the same accuracy, our predictions will make possible a realistic optimization of the experimental cuts.

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