PROCEEDINGS OF SCIENCE

$t\bar{t}X$ Calculations and Modeling

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In this talk, we review the status of calculations for the associated production of a top pair and a Higgs, W or Z boson at the Large Hadron Collider. In particular, we focus on the resummation of soft gluon emission effects and on their combination with the complete set of next-to-leading-order corrections of both QCD and electroweak origin, in calculations in which the final state top pair and massive boson are kept on shell. The impact of these corrections on the total cross section and several differential distributions is studied.

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1. Introduction

The associated production of a top pair and a Higgs, W or Z boson at the Large Hadron Collider was intensively studied in the last few years. These processes are of interest for several reasons: $t\bar{t}H$ production provides direct information about the top-quark Yukawa coupling and $t\bar{t}Z$ production can be employed to detect anomalies in the top-quark Z-boson coupling. In addition, both $t\bar{t}W^{\pm}$ and $t\bar{t}Z$ production are backgrounds in the measurement of the leptonic signatures in $t\bar{t}H$ production.

Theory predictions for these processes can be subdivided in two categories: calculations for exclusive observables in which the decay of the heavy particles in the final state is considered, and calculations for inclusive observables in which the final state top pair and weak boson are considered on-shell. The many interesting developments in off-shell, non-resonant calculations for the three processes, now including next-to-leading order (NLO) QCD and electroweak (EW) corrections, were reviewed elsewhere in this conference [1]. In the present proceedings, we focus on calculations for an on-shell top pair and weak bosons, that allow one to obtain precise predictions for the total cross section and for distributions that are differential w.r.t. the final state heavy particle momenta.

In this context, NLO QCD corrections for $t\bar{t}H$ [2, 3] and $t\bar{t}W^{\pm}$ [4–6], $t\bar{t}Z$ [7, 8] were completed several years ago. More recently, the complete set of NLO corrections of both QCD and EW origin (Complete-NLO) have also been calculated [9–12]. In addition, soft gluon emission corrections in the threshold limit were resummed to next-to-next-to-leading logarithmic (NNLL) accuracy. Renormalization group improved perturbation theory was first employed to obtain approximate next-to-next-to-leading order (NNLO) corrections in $t\bar{t}H$ production [13], and then to resum soft gluon emission corrections in $t\bar{t}W^{\pm}$ [14], $t\bar{t}H$ [15], $t\bar{t}Z$ [16] production. For all of the three processes, threshold resummation and Complete-NLO were combined in [17]. Soft gluon resummation was also employed in study a possible pseudoscalar of the top quark Yukawa coupling [18]. In a parallel effort, threshold resummation at NNLL accuracy for the three processes was studied by means of "direct QCD" methods in [19, 20] and combined to Complete-NLO in [21]. The results in [17] and [21] are compatible. In this work, the techniques and results employed in [10, 12–17] are briefly reviewed; the results in [19–21] were discussed elsewhere at this conference [22].

2. Complete-NLO predictions

A generic observable Σ for the process $pp \longrightarrow t\bar{t}V(+X)$ ($V \in \{H, W, Z\}$) can be expanded in powers of α_s and α as follows

$$\Sigma^{t\bar{t}V}(\alpha_s, \alpha) = \sum_{m+n\geq 2} \alpha_s^m \alpha^{n+1} \Sigma^{t\bar{t}V}_{m+n+1,n}\,, \tag{1}$$

with m and n positive integers. The LO contributions are characterized by $m + n = 2$, while NLO contributions are characterized $m + n = 3$. NLO corrections include also contributions from tree level quark-gluon initiated events, while LO corrections receive contribution only from gluon fusion diagrams and/or quark annihilation diagrams. LO QCD contributions are the ones proportional to $\alpha_s^2\alpha$ while NLO QCD corrections are proportional to $\alpha_s^3\alpha$. The Complete-NLO calculations in [17] were carried out with the version of MadGraph5_aMC@NLO described in [12] and include the complete set of all LO and NLO contributions entering Eq. (1).

3. Resummation of Soft Gluon Emission Corrections

At lowest order in QCD, the associated production of a top pair and a V boson receives contributions from the partonic processes

$$i(p_1) + j(p_2) \longrightarrow t(p_3) + \bar{t}(p_4) + V(p_5),$$

where $i, j \in \{q\bar{q}, \bar{q}q, gg\}$ if $V \in \{H, Z\}$. If $V = W^\pm$ instead, $i, j \in \{q\bar{q}'\}$ where i labels a light up-type quark and j a down-type light quark. Two Mandelstam invariants are relevant:

$$\hat{s} = (p_1 + p_2)^2 = 2p_1 \cdot p_2\,, \quad \text{and} \quad M^2 = (p_3 + p_4 + p_5)^2.$$

These two quantities coincide at LO, but differ when additional radiation is emitted in the final state. One can introduce the quantity $z \equiv M^2/\hat{s}$ and define the soft or partonic threshold region as the region where $z \to 1$. In this limit, the final state radiation X can only be soft. In the partonic threshold limit, the cross section of the three processes of interest here factors as follows [13]

$$\sigma\left(s, m_t, m_V\right) = \frac{1}{2s}\int_{\tau_{\text{min}}}^{1} d\tau \int_{\tau}^{1} \frac{dz}{\sqrt{z}} \sum_{ij} \mathit{ff}_{ij}\left(\frac{\tau}{z}, \mu\right) \int d\text{PS}_{t\bar{t}V}\, \text{Tr}\left[\mathbf{H}_{ij}\left(\{p\}, \mu\right) \mathbf{S}_{ij}\left(\frac{M(1-z)}{\sqrt{z}}, \{p\}, \mu\right)\right], \tag{2}$$

where $d\text{PS}_{t\bar{t}V}$ is the reduced tree-level 3-body phase space. The quantities ff_{ij} are the channel -dependent partonic luminosity functions, while s is the square of the hadronic center-of-mass energy. Finally, $\tau_{\text{min}} \equiv (2m_t + m_V)^2/s$ and $\tau \equiv M^2/s$. The (process dependent) hard functions $\mathbf{H}_{ij}$ are matrices in color space and receive contributions from the color-decomposed one-loop corrections to the tree-level diagrams. The NLO hard functions are evaluated by customizing the loop provider `Openloops` [23] in combination with the library `Collier` [24], and are cross-checked numerically by means of a modified version of `Gosam` [25, 26]. The soft functions $\mathbf{S}_{ij}$ are the color-decomposed real emission corrections in the soft limit. The analytic expressions of $\mathbf{S}_{ij}$ involve plus distributions and Dirac delta functions depending on z [13, 15]. The hard and the soft functions satisfy renormalization group equations (RGE) which are controlled by anomalous dimension matrices. In order to achieve NNLL accuracy in the resummation, the hard functions, soft functions and anomalous dimensions need to be computed up to NLO in α_s. The NLO soft functions and anomalous dimensions are equal for all three processes and were evaluated in [13, 15, 27]. The resummed cross section is most conveniently evaluated in Mellin space:

$$\sigma(s, m_t, m_V) = \frac{1}{2s}\int_{\tau_{\text{min}}}^{1} \frac{d\tau}{\tau}\frac{1}{2\pi i}\int_{c-i\infty}^{c+i\infty} dN \tau^{-N} \sum_{ij} \widetilde{\mathit{ff}}_{ij}\left(N, \mu\right) \int d\text{PS}_{t\bar{t}V}\, \widetilde{c}_{ij}\left(N, \mu\right)\,, \tag{3}$$

where $\widetilde{\mathit{ff}}_{ij}$ and $\widetilde{c}_{ij}$ are the Mellin transforms of the luminosity functions and of the product of the hard and soft functions [14, 15]. In Mellin space, the partonic threshold region corresponds to the limit $N \to \infty$. The hard and soft functions can be evaluated in fixed order perturbation theory at scales (indicated by μ_h, μ_s) at which they are free from large logarithmic corrections. It is then possible to solve the RGEs in order to evolve the hard-scattering kernel $\widetilde{c}_{ij}$ to the factorization scale μ_f, which is the scale at which the parton densities are evaluated (see [15, 17] for details).

$t\bar{t}W^+$	$384.17(9)^{+51.52(+13.4\%)\ +8.16(+2.1\%)}_{-32.36(-8.4\%)\ -8.16(-2.1\%)}$
$t\bar{t}W^-$	$197.75(4)^{+26.41(+13.4\%)\ +5.41(+2.7\%)}_{-16.07(-8.1\%)\ -5.41(+2.7\%)}$
$t\bar{t}H$	$496.36(7)^{+38.64(+7.8\%)\ +11.92(+2.4\%)}_{-29.35(-5.9\%)\ -11.92(+2.4\%)}$
$t\bar{t}Z$	$810.9(2)^{+89.2(+11.0\%)\ +19.1(+2.4\%)}_{-77.8(-9.6\%)\ -19.1(-2.4\%)}$

Table 1: NLO+NNLL cross sections for the $t\bar{t}V$ processes [17].The first number in brackets corresponds to the statistical uncertainty in the Monte Carlo integration. The first number in the subscript/superscript is the uncertainty due to scale variations. The last number in the subscript/superscript is the PDF uncertainty.

4. Results

The results found in [17] include the Complete-NLO predictions and soft gluon resummation to NNLL accuracy. In order to obtain these results it is crucial to avoid the double counting of logarithmic corrections that are included in both the NLO QCD corrections and in resummed calculations. This is achieved by means of the matching procedure detailed in [17].

Two different choices for the scales μ_h, μ_s, μ_f were considered, one based on the invariant mass of the $t\bar{t}V$ system and one based on H_T, which is the sum of the transverse mass of the top quark, antitop quark and heavy vector boson. The uncertainty associated to the scale choices was estimated by varying the default values of the three scale by factors 2 and $1/2$. Predictions obtained with the two scale choices are in good a agreement. For this reason, the envelope of the calculations carried out with the two scale choices were presented as the final result of the analysis in [17].

The values for the total cross section for $t\bar{t}H, t\bar{t}Z, t\bar{t}W^+$ and $t\bar{t}W^-$ production found in [17] are summarized in Table 1. In $t\bar{t}W^\pm$ production, the Complete-NLO prediction increases the total cross section by about 6% w.r.t. the NLO QCD accuracy, an effect that can be traced back mostly to the opening of the t-channel-enhanced $tW \to tW$ scattering contribution [11, 28] at order $\alpha_s\alpha^3$. The inclusion of the NNLL resummation reduces the residual scale uncertainty w.r.t. the NLO cross section. The PDF uncertainty is much smaller than the residual scale uncertainty. In $t\bar{t}H$ production, the Complete-NLO prediction enhances the total cross section by 2.5% w.r.t. the NLO QCD result. The NNLL soft gluon emission corrections enhance the total cross section by $\sim 3.4\%$ and decrease the residual scale uncertainty w.r.t. the fixed order NLO calculation. For what concerns $t\bar{t}Z$ production, EW corrections are rather small and increase the NLO QCD cross section by $\sim 1\%$. The cross section increase due to NNLL resummation is $\sim 6.8\%$ and the inclusion of the soft emission corrections reduces the scale uncertainty w.r.t. the fixed order calculation.

In [17], several distributions differential w.r.t. the momenta of the final state particles were also evaluated to NLO+NNLL accuracy: in particular, for each of the $t\bar{t}V$ processes predictions were obtained for distributions differential w.r.t. the invariant mass of the $t\bar{t}V$ system, the invariant mass of the top-antitop pair, and the transverse momenta of the top quark, antitop quark, and V boson. Distributions differential w.r.t. the rapidity of the top quark and antitop quark were evaluated to nNLO, i.e. by including on top of the exact NLO corrections the NNLO corrections obtained by re-expanding the NNLL resummation formula to NNLO. The Z-boson transverse momentum and rapidity distributions obtained in [17], as well as other parton level distributions obtained with the same techniques, were recently compared with measurements by the ATLAS collaboration [29]. A good agreement between predictions and measurements was found.

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