PROCEEDINGS OF SCIENCE

Higher-order and off-shell effects in top-quark processes at high-energy colliders

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The off-shell modelling of top-quark processes at high energies is essential to have realistic and accurate predictions to compare with data. In order to illustrate the relevant aspects of the off-shell description including QCD and electroweak radiative corrections, we present the calculation of off-shell tZj production at the LHC in the three-lepton decay channel, and of t$\bar{\text{t}}$ at future lepton colliders in the semi-leptonic decay channel.

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Introduction Improving the perturbative description of full off-shell top-quark processes at colliders is a mandatory step for realistic predictions, though not the only one (parton-shower matching, hadronisation etc.). Computing next-to-leading order (NLO) corrections of strong (QCD) and electroweak (EW) type in the Standard Model (SM) for such processes is not straightforward, owing to high-multiplicity final states, complicated resonant structures, non-resonant effects and spin correlations to be properly included, and the mixing of EW and QCD corrections at a given perturbative order. In order to show the importance of the off-shell modelling we present here two different calculations of off-shell top-quark processes. Firstly, we consider here the production and decay of a single top quark in association with a Z boson (tZj) at the LHC. Secondly, we consider the off-shell production of a top-antitop pair from electron-positron collisions in the semi-leptonic decay channel.

At the LHC: tZj in the three-lepton decay channel ATLAS and CMS have observed tZj with Run-2 data [2, 3], finding agreement with SM predictions. Recently, also differential measurements have started for this process [4]. Several phenomenological studies of tZj have targeted searches for vector-like top partners [5], anomalous couplings [6], and SMEFT operators [7]. This process gives access to possibly anomalous values of the top-quark-to-Z-boson, the triple-gauge, and the Wtb couplings, therefore tZj allows to constrain new-physics effects [8]. Since tZj is an EW-induced process, the top quarks produced in tZj are strongly polarised [1], providing a nice framework to study the helicity structure of the top-quark production and decay.

In the SM, the NLO QCD corrections to tZj production and decay are known since many years [9] in the narrow-width approximation. The NLO QCD and EW corrections to $\mathrm{t}\ell^+\ell^-\mathrm{j}$ have been matched to QCD parton shower [10], including top-quark decays at leading order (LO). Soft-gluon resummation has also been performed for on-shell top quarks [11].

The full off-shell modelling of tZj at NLO accuracy has been achieved only recently [12], in the three-charged-lepton decay channel. In Ref. [12] the process $\mathrm{p\,p} \to \mathrm{e^+e^-}\,\mu^+\nu_\mu\,\mathrm{j_b}\,\mathrm{J} + X$ is considered, where $\mathrm{j_b}$ is a b-tagged jet and J any jet. The calculation is performed in the five-flavour scheme, including the leading order at $O(\alpha^6)$ and the NLO corrections of orders $O(\alpha^7)$ and $O(\alpha_s\alpha^6)$. All resonant and non-resonant diagrams are accounted for at LO and at NLO, complete spin correlations are included. The ATLAS fiducial setup of Ref. [3] is considered.

Sizeable NLO corrections are found, as can be seen in Fig. 1, with negative EW cross sections at the 7% level and positive QCD corrections at the 30% level. A reduction in the QCD-scale uncertainties (evaluated with 7-point scale variations) is found between LO and NLO QCD, only for the downward variation. This effect comes from the pure EW nature of the LO process.

In fig. 1, it can also be seen how in a final state dominated by the top-quark resonance, a sizeable contamination from antitop quarks is found, coming from real contributions with a hadronically decaying antitop quark. Such an effect strongly distorts the shape of the distribution in the rapidity separation between the two tagged jets. While the dominant tZ topologies peak at $|\Delta y_{\mathrm{j_t j_s}}| \approx 2.5$, the irreducible antitop background fill the region $|\Delta y_{\mathrm{j_t j_s}}| < 1$. This contamination could not be observed with calculations that assume the factorisation of production and decays of top quarks.

At lepton colliders: $\mathrm{t\bar{t}}$ production in the semi-leptonic decay channel The production of a $\mathrm{t\bar{t}}$ pair in electron-positron scattering is EW induced and comes from an annihilation process. Although

order	σ [fb]	ratio [/LO]
LO [$O(\alpha^6)$]	$0.6416(0)\,^{+8.9\%}_{-13.5\%}$	100.0%
$\delta_{\rm QCD}$ [$O(\alpha_s\alpha^6)$]	0.1987(5)	31.0%
$\delta_{\rm EW}$ [$O(\alpha^7)$]	-0.0416(6)	-6.5%
NLO QCD	$0.8402(5)\,^{+8.6\%}_{-3.9\%}$	131.0%
NLO EW	$0.5999(6)\,^{+9.4\%}_{-13.9\%}$	93.5%
NLO QCD+EW	$0.7986(8)\,^{+9.4\%}_{-4.2\%}$	124.5%

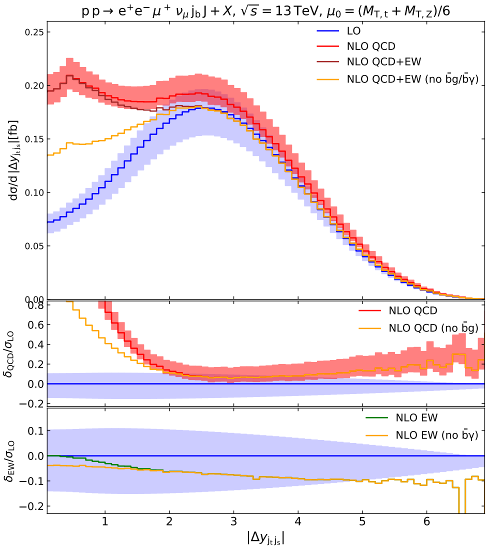

Figure 1: Fiducial and differential cross sections for tZj at the LHC.

the lepton collider represents a cleaner environment than the LHC, similar issues arise with the off-shell modelling of top-quark pairs, especially in the semi-leptonic channel. We consider the process $\mathrm{e^+e^-} \longrightarrow \mathrm{j_b j_b j\,j}\,\mu^+\nu_\mu$, namely with two b-tagged jets and two light jets, computed recently at NLO QCD accuracy [21]. The first relevant aspect is that the full process does not receive contribution uniquely from annihilation diagrams, but also from t-channel diagrams and in general from both resonant and non-resonant diagrams.

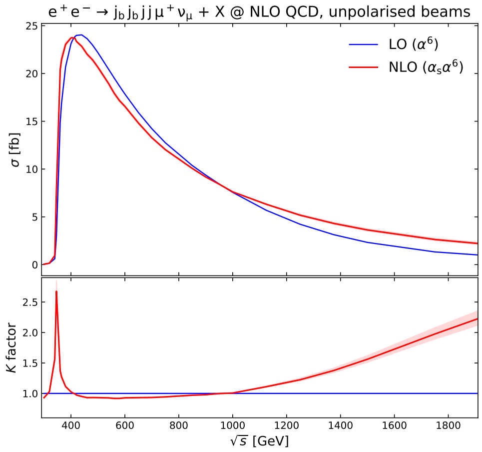

Figure 2: Dependence of the total cross section on the collision energy.

Higher-order and non-resonant effects strongly depend on the specific decay channel, as well as on the collider energy. In the left side of Fig. 2 we show the dependence of the total cross section in a rather inclusive setup (basic transverse-momentum and angular cuts) on the centre-of-mass energy of the collision. It can be seen that below and about threshold ($2\,m_{\rm top}$) similar QCD corrections are found as in the fully leptonic channel [22]. For an increasing collision energy, the irreducible background from non-resonant contributions becomes sizeable. Positive and increasing QCD effects are found for $\sqrt{s} \gtrsim 1$TeV. The huge QCD corrections at high energy also come from the event selections (2 light jets with $R = 0.4$) which typicaly cut away topolgies with a boosted W boson at LO.

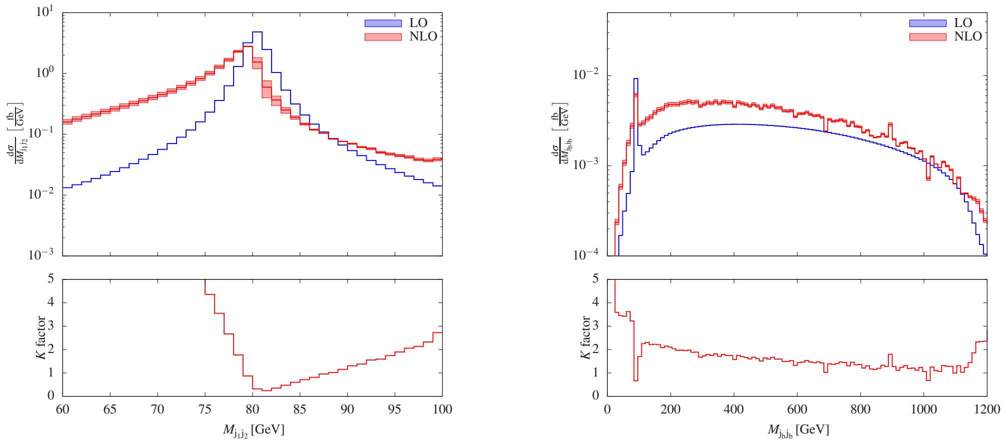

Figure 3: Differential distributions in the invariant mass of the light-jet pair at 365GeV collisions (left) and of the b-jet pair at 1.5TeV (right).

The differential distributions at 365GeV centre-of-mass collision energy in Fig. 3 (left) show a strong distortion in the invariant-mass spectrum of the two-light-jet system, with a huge radiative tail and hard-gluon radiation affectinf also the high-energy tail (even larger effects are present at 1.5TeV). The impact of off-shell effects and irreducible backgrounds is especially sizeable at 1.5TeV, as shown in the invariant-mass distribution of the two-b-jet system (right side of Fig. 3), where a Z-boson peak (from the $\mathrm{Z} \to \mathrm{j_b j_b}$ decay) sits on top of $\mathrm{t\bar{t}}$ and single-top contributions. For this observable, small QCD corrections are found when approaching the maximum allowed (for on-shell top quarks), while QCD effects become larger towards the spectrum end-point.

Interestingly, the QCD corrections are found [21] to be independent of the polarisation of the incoming $\mathrm{e}^{\pm}$ beams at 365GeV, while at high collision energies very different QCD K-factors characterise the left-right and right-left initial-polarisation states, owing to real radiation that opens up LO-suppressed helicity configurations, and to increased irreducible backgrounds.

Summary It is essential to model off-shell effects in top-quark-associated processes for upcoming fiducial and differential measurements at the LHC and at future lepton colliders. We have presented the calculation of NLO QCD and EW corrections to off-shell tZj production and decay at the LHC [12] and the calculation of NLO QCD corrections to $\mathrm{t\bar{t}}$ production at $\mathrm{e^+e^-}$ colliders in the semi-leptonic decay channel [21]. In both processes, the NLO corrections sizeably change the distribution shapes (also angular ones) and the off-shell description in fiducial volumes lead to several diagram topologies alread at LO, which do not necessarily contain the expected top-quark resonant structures. New resonance structures may open up at NLO, giving noticeable contaminations to the signal. The off-shell effects are especially relevant in the tails of invariant-mass and p_{T} distributions. At lepton colliders, the beam polarisation can play a relevant role especially at high energies, when accounting for non-resonant effects and complete spin correlations.

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