

## Electroweak corrections in top physics (2)

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In this proceeding we review the calculations of electroweak corrections in top-quark physics. We discuss the impact of electroweak corrections to the top-quark charge asymmetry and to the cross sections of various subdominant top-quark production mechanisms at hadron colliders, namely, single-top production channels and the associate productions of a top-quark pair with a heavy boson.

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In this proceeding we review the calculations of electroweak corrections in top-quark physics at hadron colliders. The impact of electroweak corrections to the cross section of top-quark pair production is considered in another contribution of this conference proceedings [1] and has also been reviewed in [2].

## 1. Top-quark charge asymmetry

At the Tevatron, since the initial state is invariant under CP transformation, the top-quark charge asymmetry is equivalent to a forward-backward asymmetry. This observable has received particular attention in the recent years due to the observed deviations between Standard Model (SM) predictions and measured values, which reached up to  $3.5\sigma$  in the analysis presented in [3] by the CDF collaboration. At the LHC, a forward-backward asymmetry is not present, since proton–proton collisions are symmetric, but it is possible to measure a so-called central asymmetry, which has the same physics origin. In the following we will refer only to the forward-backward asymmetry, however, the same arguments apply also to the central asymmetry.

At LO, which is of  $\mathcal{O}(\alpha_s^2)$ , the top-quark pair hadroproduction originates from  $q\bar{q}$  and  $gg$  initial states via QCD interactions. However, LO contributions are symmetric. QCD induces asymmetric terms only starting from NLO corrections [4], which are of  $\mathcal{O}(\alpha_s^3)$ . The forward-backward asymmetry, independently from the specific definition employed, can be in general written as

$$A_{t\bar{t}} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}. \quad (1.1)$$

The numerator of the r.h.s of eq. (1.1) consists of the difference between the cross sections for the production of a top-quark respectively in the forward and backward direction, while the denominator is the total cross section. Thus, by expanding  $A_{t\bar{t}}$  in powers of  $\alpha_s$  we obtain that the LO prediction for  $A_{t\bar{t}}$  is of  $\mathcal{O}(\alpha_s)$ , *i.e.*, it is induced by the asymmetric NLO QCD corrections of  $\mathcal{O}(\alpha_s^3)$  to the cross section.

Electroweak interactions induce non-vanishing asymmetric terms to the numerator of  $A_{t\bar{t}}$  (see ref. [5]) starting from contributions of  $\mathcal{O}(\alpha_s^2\alpha)$  and  $\mathcal{O}(\alpha^2)$ . The former consists of NLO EW corrections to the cross section and leads to  $\mathcal{O}(\alpha)$  contributions to  $A_{t\bar{t}}$ , while the latter originates from tree-level only diagrams and lead to  $\mathcal{O}(\alpha^2/\alpha_s^2)$  contributions to  $A_{t\bar{t}}$ .

Independently from the perturbative order considered, since the  $gg$  initial state is symmetric, it cannot contribute to the asymmetry. Thus the asymmetric terms from the  $\mathcal{O}(\alpha_s^3)$ ,  $\mathcal{O}(\alpha_s^2\alpha)$  and  $\mathcal{O}(\alpha^2)$  contributions can originate from the  $q\bar{q}$  initial state but not from  $gg$ . In particular, the NLO QCD  $\mathcal{O}(\alpha_s^3)$  asymmetric terms originate only from the interference of tree-level diagrams and boxes and, equivalently, only from the interference of the real gluon emissions from the initial and final state.<sup>1</sup> For this reason it is useful to divide the NLO EW  $\mathcal{O}(\alpha_s^2\alpha)$  asymmetric terms into NLO QED contributions, which involve only QCD and QED interactions, and NLO Weak contributions involving the remaining weak interactions. Indeed, the asymmetric NLO QED contributions can be obtained by substituting in all the possible way one gluon into one photon in the matrix elements entering the calculation of the asymmetric NLO QCD contributions. Thus, the NLO QED

<sup>1</sup>Also (anti)quark radiation via the  $qg(\bar{q}g)$  initial state induces an asymmetry. However, its size is negligible and thus not discussed here.

contributions can be simply obtained by multiplying the NLO QCD contribution by the  $R_{QED}(Q_q)$  factor defined as

$$R_{QED}(Q_q) = \frac{36}{5} Q_q Q_t \frac{\alpha}{\alpha_s} \implies R_{QED}(Q_u) \sim 0.2, \quad R_{QED}(Q_d) \sim -0.1, \quad (1.2)$$

where  $Q_q$  is the charge of the quark in the initial state and the numerical factor is due to color. This result is independent of the specific definition used for the asymmetry and the cuts applied on the  $t\bar{t}$  pair.

The NLO Weak contributions originate from the same diagrams of the NLO QED ones, where the photon has to be replaced by a Z boson.<sup>2</sup> In this case the value cannot be expressed via a simple factor that is independent on the cuts and the specific definition of  $A_{t\bar{t}}$ .

The  $\mathcal{O}(\alpha^2)$  contributions simply originate from tree-level diagrams with only EW interactions, *i.e.*, from the  $s$ -channel production via a photon or a Z boson.

The total size of the EW  $\mathcal{O}(\alpha) + \mathcal{O}(\alpha^2/\alpha_s^2)$  contributions to  $A_{t\bar{t}}$  amounts to  $\sim 20\%$  of the  $\mathcal{O}(\alpha_s)$  contribution from pure QCD effects, the precise value of this quantity depends on the specific definition of  $A_{t\bar{t}}$ , the cuts and the input parameters. On the contrary, the dominant component of the electroweak contributions, the QED part of the  $\mathcal{O}(\alpha)$ , is independent of the cuts applied, the  $A_{t\bar{t}}$  definition and, obviously, the QCD renormalisation scale.

The electroweak contributions to the asymmetry, being  $\sim 20\%$  of the QCD-induced one and with the same overall sign, decrease the deviation between the SM theoretical predictions and the values measured by the CDF and D0 collaborations. Very recently also the NNLO QCD corrections of  $\mathcal{O}(\alpha_s^4)$  to the numerator of  $A_{t\bar{t}}$  have been calculated [6] and, together with the new results from analyses based on larger data sets, they have further contributed to diminish the previously observed deviations. Moreover, this calculation has *a posteriori* proved that the approach consisting in a pure expansion in powers of  $\alpha_s$  and  $\alpha$  for  $A_{t\bar{t}}$ , as presented here, is preferable to the inclusion of  $\mathcal{O}(\alpha_s^3)$  terms in the denominator of  $A_{t\bar{t}}$  without the  $\mathcal{O}(\alpha_s^4)$  terms in the numerator. Indeed both contributions enter the  $\mathcal{O}(\alpha_s^2)$  term of  $A_{t\bar{t}}$ , but they have opposite signs and largely cancel each other. As said, the same physics can be studied at the LHC via a central asymmetry. In this case the relative size of the EW contributions is a bit smaller, *i.e.*,  $\sim 15 - 20\%$  of the QCD-induced term, depending on the proton–proton c.o.m. energy (see for further details Refs. [7, 8]). In the case of the central asymmetry at the LHC, no significant deviation between SM predictions and measured values is present at the moment.

Besides EW fixed-order contributions, effects from resummed EW Sudakov logarithms have also been studied in [9] and found to be  $\sim 5\%$  of the QCD-induced  $\mathcal{O}(\alpha_s)$  contribution of  $A_{t\bar{t}}$ . However, this result cannot be straightforwardly added to the previously discussed fixed-order contributions, because it would lead to a non-negligible double counting of  $\mathcal{O}(\alpha)$  Sudakov logarithms.

## 2. Top-quark pair production in association with a heavy boson

The production of a top-quark pair in association with a heavy boson consists of the following different final states:  $t\bar{t}H$ ,  $t\bar{t}Z$ ,  $t\bar{t}W^+$  and  $t\bar{t}W^-$ . All these processes are relevant in the context of SM

<sup>2</sup>Although it can be formally included, the Z boson real radiation ( $t\bar{t}Z$ ) is typically discarded, since it leads to negligible contributions.

13 TeV : $\delta(\%)$	$t\bar{t}H$	$t\bar{t}Z$
NLO QCD	$29.7^{+6.8}_{-11.1} \pm 2.8$ ( $24.2^{+4.8}_{-10.6} \pm 4.5$ )	$45.9^{+13.2}_{-15.5} \pm 2.9$ ( $40.2^{+11.1}_{-15.0} \pm 4.7$ )
LO EW	$1.2 \pm 0.9$ ( $2.8 \pm 2.0$ )	$0.0 \pm 0.7$ ( $2.1 \pm 1.6$ )
LO EW no $\gamma$	$-0.4 \pm 0.0$ ( $-0.2 \pm 0.0$ )	$-1.1 \pm 0.0$ ( $-0.3 \pm 0.0$ )
NLO EW	$-1.2 \pm 0.1$ ( $-8.2 \pm 0.3$ )	$-3.8 \pm 0.2$ ( $-11.1 \pm 0.5$ )
NLO EW no $\gamma$	$-1.4 \pm 0.0$ ( $-8.5 \pm 0.2$ )	$-4.1 \pm 0.1$ ( $-11.5 \pm 0.3$ )
HBR	0.89 (1.87)	0.96 (2.13)

**Table 1:** Relative corrections for  $t\bar{t}H$  and  $t\bar{t}Z$  production in the  $\alpha(m_Z)$ -scheme at 13 TeV. The errors correspond to PDF uncertainties, for the NLO QCD also the scale uncertainties are displayed.

13 TeV : $\delta(\%)$	$t\bar{t}W^+$	$t\bar{t}W^-$
NLO QCD	$50.1^{+14.2}_{-13.5} \pm 2.4$ ( $59.7^{+18.9}_{-17.7} \pm 3.1$ )	$51.5^{+14.8}_{-13.8} \pm 2.8$ ( $66.3^{+21.7}_{-19.6} \pm 3.9$ )
LO EW	0	0
LO EW no $\gamma$	0	0
NLO EW	$-7.7 \pm 0.2$ ( $-19.2 \pm 0.7$ )	$-6.7 \pm 0.2$ ( $-18.3 \pm 0.8$ )
NLO EW no $\gamma$	$-8.0 \pm 0.2$ ( $-20.0 \pm 0.5$ )	$-7.0 \pm 0.2$ ( $-19.1 \pm 0.6$ )
HBR	3.88 (7.41)	6.50 (15.01)

**Table 2:** Same as in Table 1, but for  $t\bar{t}W^+$  and  $t\bar{t}W^-$

and Beyond-the-Standard-Model (BSM) both as background and signal. For instance, the measurements of  $t\bar{t}H$  and  $t\bar{t}Z$  production can be respectively used to directly probe the coupling of the top quark with the Higgs and Z boson. On the other hand,  $t\bar{t}Z$  and  $t\bar{t}W^\pm$  can be irreducible backgrounds of  $t\bar{t}H$  production. Thus, precise predictions for these processes are extremely important.

NLO QCD calculations to the production of a top-quark pair in association with a heavy boson have been computed for the first time in [10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20]. These corrections have been recently (re-)calculated in [21] for all these processes and also for the associate production of a top-quark pair with two vector bosons and for four-top production. In [21] NLO QCD corrections to several distributions and at different hadronic c.o.m. energies are shown and their dependence on renormalisation and factorisation scale definitions is discussed in detail. In the following we focus on effects from electroweak corrections. NLO Weak corrections to  $t\bar{t}H$  production have been calculated in [22] with a semi-automatic approach and including also NLO QED effects in [23]. Afterwards, NLO EW (Weak+QED) corrections have been calculated in a completely automated approach in [24] for the  $t\bar{t}H$ ,  $t\bar{t}Z$ ,  $t\bar{t}W^+$  and  $t\bar{t}W^-$  processes, together with NLO QCD corrections. We will discuss these results from [24], which have been calculated within the same framework (MADGRAPH5\_AMC@NLO [25]) and using the same input parameters.

The LO cross section for the associate production of a top-quark pair with a heavy boson is of  $\mathcal{O}(\alpha_s^2\alpha)$ . In [24] the NLO QCD corrections of  $\mathcal{O}(\alpha_s^3\alpha)$ , the NLO EW corrections of  $\mathcal{O}(\alpha_s^2\alpha^2)$  and the  $\mathcal{O}(\alpha_s\alpha^2)$  contribution from only tree-level diagrams, the so-called LO EW contribution, have been calculated. The EW corrections (LO EW and NLO EW) have been presented both with and without the contribution from initial-state photons, which has been evaluated via the NNPDF2.3\_QED PDF set [26] including the photon PDF. We have summarised inclusive results at 13 TeV in Table 1 for  $t\bar{t}H$  and  $t\bar{t}Z$  and in Table 2 for  $t\bar{t}W^+$  and  $t\bar{t}W^-$ . Results in brackets refers to

the boosted regime where a cut of 200 GeV on the transverse momenta of the top, the antitop and the heavy boson is applied. These kind of cuts are particularly interesting for the case of  $t\bar{t}H$ , since it was shown in [27] that the signal over background ratio could be enhanced with boosted Higgs boson and top quarks. As expected, due to the Sudakov logarithms, NLO EW corrections are in this regime larger in magnitude and negative.

For  $t\bar{t}H$  and  $t\bar{t}Z$  production, electroweak corrections to the total cross-section are within the NLO QCD scale uncertainties, whereas in the boosted regime or in general for large  $p_t$ 's they are comparable in size with scale uncertainties and thus very important. Relatively to the size of the corrections, the PDF error is large and mostly induced by the initial-state photons in the LO EW. The situation for  $t\bar{t}W^+$  and  $t\bar{t}W^-$  is analogous, but corrections are much larger and LO EW contributions are analytically zero. Also photon PDF errors are relatively small. In both Tables 1 and 2 the contribution from the radiation of an additional heavy boson (HBR), which is of  $\mathcal{O}(\alpha_s^2\alpha^2)$  as the NLO EW, is also listed. Depending on the specific experimental analyses, this final state may contribute to the inclusive associate production of a top quark pair with a heavy boson, leading to partial cancellations of the EW Sudakov logarithms or, in the case of  $t\bar{t}W^\pm$  even to overcompensations (see [24] for details).

### 3. Single top

Single top production can be classified in three classes of processes:  $s$ -channel,  $t$ -channel and associate  $tW$  production. Again, we focus only on EW corrections. An updated list of references of calculations of QCD corrections can be found in the recent review in [28], which covers several aspects of top-quark physics at colliders.

The calculation of NLO EW corrections of the associated  $tW$  production has been performed firstly without taking into account hard real-photon radiation in [29] and then by including it in [30]. Both the calculations have been performed for the extended MSSM NLO EW corrections, explicitly separating the SM subset from the contribution induced by loops with supersymmetric particles. Similarly, the calculation of NLO EW corrections to the  $t$ -channel production has been performed firstly without hard radiation in [31] and then by including it in [32], again within the MSSM and separating the SM-subset contribution. The partonic NLO EW corrections to  $s$ - and  $t$ -channel production have been calculated also in [33] and integrated in the Monte-Carlo tool MCSANC-V1.01 [34]. All these calculations have been performed in the five-flavour scheme. In the following we will comment results for the LHC with 14 TeV c.o.m. energy from [30, 32, 34].

In  $tW$  associate production, NLO EW corrections to the  $m(tW)$  distribution range from +5% of the LO prediction, at the threshold, to -3% at  $m(tW) = 1.3$  TeV. In  $t$ -channel production NLO EW corrections to the total cross section are  $\sim -3.6\%$  of the LO, *i.e.*, almost of the same absolute size of NLO QCD corrections ( $\sim +4\%$ ). However, they grow in magnitude for large  $p_T(t)$ , *e.g.*, they reach the value of -15% at  $p_T(t) = 500$  GeV. In  $s$ -channel production, NLO EW corrections are  $\sim -2\%$  of the LO prediction.

All these results do not include contributions from initial-state photons, which may be not negligible and potentially introduce large uncertainties due to the photon PDF. However, similarly to the case of NLO QCD, photon-initiated quark radiation would introduce, *e.g.*,  $t\bar{t}$  resonant configurations, which have to be removed or subtracted.

## 4. Conclusion

In this proceeding we have discussed the impact of EW corrections in top-quark physics. Specifically, we focused on the case of the top-quark charge asymmetry, the associate production with a heavy boson and the single-top production mechanisms. The size of the corrections is in general not negligible, especially for the case of the charge asymmetry and in the tail of the distributions in single-top and associate production.

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