The top quark charge asymmetry in $t\bar{t}\gamma$ production at the LHC

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Abstract We consider the top quark charge asymmetry in the process $pp \rightarrow t\bar{t} + \gamma$ at the 13 TeV LHC. The genuine tree level asymmetry in the $q\bar{q}$ channel is large with about -12% . However, the symmetric gg channel, photon radiation off top quark decay products, and higher order corrections wash out the asymmetry and obscure its observability. In this work, we investigate these effects at next-to-leading order QCD and check the robustness of theoretical predictions. We find a sizable perturbative correction and discuss its origins and implications. We also study dedicated cuts for enhancing the asymmetry and show that a measurement is possible with an integrated luminosity of 150 fb^{-1} .

1 Introduction

The charge asymmetry in the fermion annihilation process $f\bar{f} \rightarrow f'\bar{f}'$ is a well-studied phenomenon of Quantum Electrodynamics (QED) [1, 2] and Quantum Chromodynamics (QCD) [3, 4]. Even though C (charge) and P (parity) are good symmetries of QED and QCD, there can be interference between charge-odd amplitudes that lead to asymmetric terms under $p_{f'} \leftrightarrow p_{\bar{f}'}$. For $2 \rightarrow 2$ kinematics the C-odd interference appears at next-to-leading order (NLO) for the first time, causing a suppression by one power of the coupling constant and therefore yields a numerically small asymmetry.

At particle colliders where the initial state is not charge symmetric (e.g. at e^+e^- or $p\bar{p}$ colliders), a non-vanishing charge asymmetry A_C translates into a P-violating forward backward asymmetry A_{FB} . This feature received a lot of attention in the case of top quark pair production at the Tevatron. The NLO QCD theory prediction of $A_{FB}^{t\bar{t}} \approx 5\%$ [5] was in long lasting tension with the experimentally measured values by CDF and DZero, which were about two standard deviations higher [6]. The dust settled after more data was

collected and NNLO QCD and NLO electroweak corrections [7–9] were accounted for in the theory calculations. Now, the best prediction yields $A_{FB}^{t\bar{t}} = 9.5 \pm 0.7\%$ [9], which has to be compared to $A_{FB}^{t\bar{t}} = 10.6 \pm 3\%$ from DZero [10] and $A_{FB}^{t\bar{t}} = 16.4 \pm 5\%$ from CDF [11].

Recently, the top quark charge asymmetry enjoyed a revival at the Large Hadron Collider (LHC) because the delicate interference effects can be used as a sensitive probe for new physics searches, see e.g. Refs. [12–16] and references in [17]. The charge symmetric initial state at the LHC does, however, not produce a forward-backward asymmetry and makes the effect harder to capture. An observable effect can still be obtained thanks to the different parton distributions of valence and sea quarks in the proton, which, in conjunction with a non-zero A_C cause anti-top quarks to be scattered more centrally than top quarks. The canonical definition of the charge asymmetry at the LHC is

$$A_C = \frac{\sigma^{\text{asymm.}}}{\sigma^{\text{symm.}}} \quad \text{with} \\
\sigma^{\text{asymm.}} = \sigma(\Delta y > 0) - \sigma(\Delta y < 0), \\
\sigma^{\text{symm.}} = \sigma(\Delta y > 0) + \sigma(\Delta y < 0), \quad (1)$$

where $\Delta y = |y_t| - |y_{\bar{t}}|$ is the difference of the absolute top and anti-top quark rapidities. For $pp \rightarrow t\bar{t}$ at $\sqrt{s} = 8 \text{ TeV}$, the best prediction $A_C^{t\bar{t}} = 0.9\%$ [18] is in agreement with current experimental measurements [19, 20] that are, however, also compatible with zero given the smallness of the effect.

An interesting twist enters the discussion when studying top quark pair production in association with massless gauge bosons. Hadronic production of $t\bar{t} + \text{jet}$ is one example that has been studied extensively [21–24]. C asymmetric interference terms enter already at leading order causing a sizable negative value of the asymmetry. Somewhat surprisingly, the inclusion of higher order corrections shifts the LO value by more than 100% [21] into the positive direction. This feature appears in contrast to $t\bar{t}$ production where the asymmetry

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at NLO does not receive large corrections at NNLO [9]. In Ref. [22] a reasoning for this pattern was given based on a separation of *soft* and *hard* degrees of freedom that enter the asymmetry at different orders of perturbation theory.

In this work, we investigate the charge asymmetry for top quark pair production in association with a photon at the LHC. An experimental measurement of this quantity was not undertaken at the Tevatron and is not yet achieved at the LHC. This is surprising since $t\bar{t} + \gamma$ production is particularly interesting for probing physics beyond the Standard Model. For example, in a pioneering study the authors of Ref. [25] investigated the use of $A_C^{t\bar{t}\gamma}$ to resolve cancellation mechanisms between up-type and down-type initial states arising from possible new physics contamination of the SM signal. Here, we elevate previous studies at LO to NLO QCD precision. This is motivated by a foreseeable measurement in the near future and by the importance higher order corrections played in the similar process $pp \rightarrow t\bar{t} + \text{jet}$. A first NLO QCD calculation for A_C in $t\bar{t} + \gamma$ production was presented in Ref. [26] for stable top quarks. In this work put special attention to a realistic description of the process, accounting for the full decay chain in the lepton+jets final state, $b\bar{b}\ell\nu jj + \gamma$, including all spin correlations, photon emission off all charged particles, and NLO QCD corrections in production and decay. We demonstrate that every of these features is crucial for a reliable description of the charge asymmetry in this process. Moreover, we devise dedicated selection cuts to enhance the asymmetry while simultaneously maintaining the statistical significance of a measurement.

2 Setup

We consider the process $pp \rightarrow t\bar{t} + \gamma \rightarrow b\bar{b}\ell\nu jj + \gamma$ at $\sqrt{s} = 13$ TeV, summing over $\ell = e^+, e^-, \mu^-$ and μ^+ . In this final state, the top quark momenta can be reconstructed unambiguously from the decay products since the neutrino momentum is constrained by momentum conservation. Hence, the top quark rapidities in Eq. (1) can be calculated unambiguously. Top quarks are treated in the narrow-width approximation (NWA). We require intermediate on-shell states which result from a q_t^2 -integration over their (undistorted) Breit-Wigner propagator,

$$\int dq_t^2 \left| \frac{1}{(q_t^2 - m_t^2 + i\Gamma_t m_t)} \right|^2 \rightarrow \frac{\pi}{m_t \Gamma_t} \int dq_t^2 \delta(q_t^2 - m_t^2) \quad (2)$$

in the limit $\Gamma_t/m_t \rightarrow 0$. It is well known that this treatment leads to a parametric approximation of the cross section up to terms $\mathcal{O}(\Gamma_t/m_t)$. In this case, the amplitude for $t\bar{t}$ production factorizes according to

$$\mathcal{M}_{ij \rightarrow t\bar{t} \rightarrow b\bar{b}f\bar{f}'\ell\nu}^{\text{NWA}} = \mathcal{P}_{ij \rightarrow t\bar{t}} \otimes \mathcal{D}_{t \rightarrow b f \bar{f}} \otimes \mathcal{D}_{\bar{t} \rightarrow \bar{b} f' \bar{f}'}, \quad (3)$$

where $\mathcal{P}_{ij \rightarrow t\bar{t}}$ describes the $t\bar{t}$ production process and $\mathcal{D}_{t \rightarrow b f \bar{f}}$ the top quark decay dynamics. The symbol $\otimes$ indicates the inclusion of spin correlations.

The factorization for the $t\bar{t} + \gamma$ process is obtained from Eq. (3) by inserting a photon in either of the three terms, unfolding it into a sum of three terms at $\mathcal{O}(\alpha)$. As a consequence, $t\bar{t} + \gamma$ production is governed by two very different dynamics: (i) photons can be emitted in the hard scattering process of $t\bar{t}$ production, followed by the top decays; and (ii) photons can be emitted off the top quark decay products, which is preceded by $t\bar{t}$ production. We refer to these two mechanisms as *photon radiation in production* and *radiative top quark decays*, respectively. An equivalent way of phrasing this circumstance is: The photon can be radiated either before or after the top quarks went on-shell.

To account for a finite detector volume and resolution we require

$$\begin{aligned} p_T^\gamma &\geq 20 \text{ GeV}, \quad |y_\gamma| \leq 2.5, \quad R_{\gamma\ell} \geq 0.2, \quad R_{\gamma\text{jet}} \geq 0.2, \\ p_T^\ell &\geq 15 \text{ GeV}, \quad |y_\ell| \leq 5.0, \quad p_T^{\text{miss}} \geq 20 \text{ GeV}, \\ p_T^{\text{jet}} &\geq 15 \text{ GeV}, \quad |y_{\text{jet}}| \leq 5.0. \end{aligned} \quad (4)$$

We define jets by the anti- k_T jet algorithm [27] with $R = 0.3$ and request at least two b -jets. Photons in a hadronic environment are defined through the smooth-cone isolation [28] with $R = 0.2$. We perform our calculations within the TOPAZ framework described in Ref. [29]. The input parameters to our calculation are

$$\begin{aligned} \alpha &= 1/137, \quad G_F = 1.16639 \times 10^{-5} \text{ GeV}^{-2}, \\ m_t &= 173 \text{ GeV}, \quad M_W = 80.419 \text{ GeV}, \end{aligned} \quad (5)$$

from which follows

$$\begin{aligned} \Gamma_t^{\text{LO}} &= 1.495 \text{ GeV}, \quad \Gamma_t^{\text{NLO}} = 1.367 \text{ GeV}, \\ \Gamma_W^{\text{LO}} &= 2.048 \text{ GeV}, \quad \Gamma_W^{\text{NLO}} = 2.118 \text{ GeV} \end{aligned} \quad (6)$$

at $\mu_R = m_t$. We use the parton distribution functions NNPDF31_nlo_as_0118_luxqed [30], with the corresponding running of the strong coupling constant α_s .

Finally, we note that thanks to the advent of complete NLO off-shell calculations [31, 32], it has become possible to check the range of validity of the NWA for differential distributions. For the $t\bar{t} + \gamma$ process no such benchmark comparison exists yet. However, the effect on the cross section (in the presence of realistic acceptance cuts) has been quoted as 2.5% in Ref. [31], which is consistent with the parametric estimate $\mathcal{O}(\Gamma_t/m_t)$. Further studies of differential distributions exist for $t\bar{t}$ [33, 34] and $t\bar{t} + \text{jet}$ [35] production. Their results follow a common pattern: Over large parts of the phase space the accuracy remains in the few percent range, only when kinematic threshold are passed the deviations can reach tens of percent. Since our analysis involves differences of forward and backward rapidity bins only, and the applied cuts do not

involve kinematic edges, we believe that the NWA is a reliable framework given the uncertainties involved. Of course, only a complete off-shell calculation will yield an accurate error estimate.

3 Higher order corrections to A_C

In the following we discuss the impact of higher order QCD corrections to the charge asymmetry and the cross section of $pp \rightarrow t\bar{t} + \gamma$. Applying the cuts in Eq. (4) and setting renormalization and factorization scales to $\mu_0 = m_t$, we find

$$A_C^{\text{LO}} = -1.3\%, \quad A_C^{\text{NLO}} = -0.5\%. \quad (7)$$

The leading order value of -1.3% arises from the asymmetric contribution in $q\bar{q} \rightarrow t\bar{t} + \gamma$, which has a genuine asymmetry of -12% that is diluted by the symmetric gg channel and radiative decays. Comparing LO and NLO asymmetries, the relative shift by more than -60% is striking and might raise questions about the perturbative convergence of this quantity. We therefore investigate the different perturbative corrections in greater detail and note that A_C by itself is not an observable. Only $\sigma^{\text{asymm.}}$ and $\sigma^{\text{symm.}}$, i.e. the numerator and denominator of A_C are experimentally accessible quantities. The term $\sigma^{\text{symm.}}$ is just the total cross section, which is known to receive large corrections (see e.g. Refs. [29,36]). We confirm this feature within our setup and find the leading and next-to-leading order cross sections

$$\begin{aligned} \sigma_{\text{LO}} &= 837 \text{ fb} \pm 25\%, \\ \sigma_{\text{NLO}} &= 1708 \text{ fb} \pm 19\%. \end{aligned} \quad (8)$$

Renormalization and factorization scales are varied by a factor of two around the central scale μ_0 and the respective cross sections are symmetrized. The large perturbative correction of 104% and the marginal reduction of scale uncertainty is a combination of various effects: Firstly, the dominant gg channel receives a sizable ($\approx +80\%$) perturbative correction. The main contribution arises from tree level type $t\bar{t}\gamma + g$ configurations, where the gluon constitutes a hard resolved jet (similar features were observed in Ref. [29]). Secondly, the kinematics of the light jets from $W \rightarrow jj$ are significantly restricted at leading order because of jet cuts and the jet algorithm. This restriction is lifted when an additional jet is allowed at next-to-leading order. It affects all partonic channels and leads to yet another increase of the NLO cross section by about $+20\%$. While the size of this kinematic effect cannot be estimated with scale variation, we believe it is sufficiently saturated at NLO, yielding a realistic and reliable prediction. Lastly, the qg initial state enters at NLO for the first time and is responsible for the sizable residual scale dependence of the NLO cross section in Eq. (8).

Let us now discuss the perturbative correction of the numerator of the asymmetry. We find a very different behavior

$$\begin{aligned} \sigma_{\text{LO}}^{\text{asymm.}} &= -10.7 \text{ fb} \pm 20\%, \\ \sigma_{\text{NLO}}^{\text{asymm.}} &= -8.0 \text{ fb} \pm 7\%. \end{aligned} \quad (9)$$

In contrast to $\sigma^{\text{symm.}}$ in Eq. (8), the asymmetric piece receives a moderate -25% correction and enjoys a significantly reduced scale dependence. Hence, the perturbative convergence seems under good control. This conclusion is further supported by another observation. Adopting the reasoning of Ref. [22] for $t\bar{t}$ + jet production, the asymmetry is governed by *soft* and *hard* degrees of freedom, which enter at different stages of perturbation theory. In the limit where the cross section is dominated by logarithms of $p_{T,\text{cut}}^\gamma/m_t$ one finds [22]

$$A_{q\bar{q} \rightarrow t\bar{t}\gamma}^{\text{NLO}} \approx A_{q\bar{q} \rightarrow t\bar{t}\gamma}^{\text{LO}} + A_{q\bar{q} \rightarrow t\bar{t}}^{\text{NLO}}. \quad (10)$$

The *soft* degrees of freedom are contained in $A_{q\bar{q} \rightarrow t\bar{t}\gamma}^{\text{LO}}$ because it is generated dominantly by a soft photon exchange. Beyond LO, new asymmetric contributions appear from *hard* exchanges that are related to the asymmetry in $t\bar{t}$ production $A_{q\bar{q} \rightarrow t\bar{t}}^{\text{NLO}}$. To study these dynamics for our case, we perform an independent NLO QCD calculation for $pp \rightarrow t\bar{t} \rightarrow b\bar{b}\ell\nu jj$ at $\sqrt{s} = 13$ TeV, using the same cuts as in Eq. (4). We find $A_{q\bar{q} \rightarrow t\bar{t}}^{\text{NLO}} = +2.9\%$. Together with $A_{q\bar{q} \rightarrow t\bar{t}\gamma}^{\text{LO}} = -12.0\%$ and $A_{q\bar{q} \rightarrow t\bar{t}\gamma}^{\text{NLO}} = -8.9\%$, this nicely supports the prediction in Eq. (10).¹ Consequently, we follow the arguments presented in Ref. [22] and suggest that even higher order corrections (i.e. beyond NLO QCD) should stabilize the prediction of $\sigma^{\text{asymm.}}$ and will not drastically shift its value.

From these studies we conclude that the genuinely asymmetric cross section of $t\bar{t} + \gamma$ production is perturbatively under good control, whereas symmetric contributions from gg and qg initial states are converging slower with sizable scale dependence. The resulting relative uncertainty for the asymmetry

$$\frac{\delta A_C}{A_C} = \sqrt{\left(\frac{\delta\sigma^{\text{asymm.}}}{\sigma^{\text{asymm.}}}\right)^2 + \left(\frac{\delta\sigma^{\text{symm.}}}{\sigma^{\text{symm.}}}\right)^2} \quad (11)$$

is therefore dominated by $\delta\sigma^{\text{symm.}}/\sigma^{\text{symm.}} = \pm 19\%$. The significance of a measurement (assuming statistical uncertainties only) is

$$\begin{aligned} S &= |A_C|/\delta N \quad \text{with} \quad \delta N = 1/\sqrt{N} \\ &= |A_C|/\sqrt{\mathcal{L} \times \sigma_{\text{NLO}}}. \end{aligned} \quad (12)$$

¹ Note that the arguments presented in Ref. [22] only apply to photon radiation in production. Hence, we only considered this contribution in the numerical comparison.

Table 1 $t\bar{t} + \gamma$ cross sections, the charge asymmetry and the corresponding significance S for different sets of cuts. Scale variation uncertainties for the cross sections are given in relative terms ($\pm$) and in

absolute numbers (brackets) for the asymmetry and significance. A visualization of these results can be found in Fig. 2

	cuts Eq. (4)	cuts Eqs. (4)+(15)	cuts Eqs. (4)+(15)+ $ y_\gamma > 1.0$
$\sigma_{\text{LO}}^{\text{symm.}}$	$837 \text{ fb} \pm 25\%$	$301 \text{ fb} \pm 28\%$	$126 \text{ fb} \pm 25\%$
$\sigma_{\text{LO}}^{\text{asymm.}}$	$-10.6 \text{ fb} \pm 21\%$	$-9.2 \text{ fb} \pm 22\%$	$-5.6 \text{ fb} \pm 21\%$
$\sigma_{\text{NLO}}^{\text{symm.}}$	$1708 \text{ fb} \pm 19\%$	$647 \text{ fb} \pm 21\%$	$287 \text{ fb} \pm 22\%$
$\sigma_{\text{NLO}}^{\text{asymm.}}$	$-7.8 \text{ fb} \pm 6\%$	$-6.4 \text{ fb} \pm 6\%$	$-4.8 \text{ fb} \pm 2\%$
$A_{\text{C}}^{\text{NLO}}$	$-0.5(1)\%$	$-1.0(2)\%$	$-1.7(4)\%$
S_{NLO}	$2.3(3)\sigma$	$3.1(4)\sigma$	$3.5(4)\sigma$

Fig. 1 Left: Normalized photon rapidity distribution of the gg and $q\bar{q}$ initial states (upper pane) and relative contribution of the $q\bar{q}$ initial state with respect to the total contribution (lower pane). Right: Relative contribution of photon radiation in production and photon radiation in

decay with respect to the total contribution as a function of the photon rapidity. The upper pane includes the selection cuts in Eq. (4). The lower pane includes the suppression cuts in Eq. (15) in addition to Eq. (4)

The corresponding numerical values can be found in the first column of Table 1 for an integrated luminosity of 150 fb^{-1} .

4 Analysis and results

We proceed with a study of dedicated phase space cuts to enhance the charge asymmetry. The basic idea is to isolate asymmetric contributions while suppressing symmetric ones. The dominant asymmetric contribution originates from quark anti-quark annihilation with photon radiation in the production, $q\bar{q} \rightarrow t\bar{t} + \gamma$. Large symmetric contributions arise from gg scattering and photon emission in the top quark decay stage.

A suppression of the gg channel over the $q\bar{q}$ channel is notoriously difficult to achieve. However, we find that one can use shape differences in the photon rapidity distributions to separate the two channels. Fig. 1 (left, upper pane) illustrates this feature for the normalized distributions. The lower pane shows the relative percentage of $q\bar{q}$ versus gg as a function of

a photon rapidity at NLO QCD. It is evident that an increasing lower cut value

$$|y_\gamma| \geq y_\gamma^{\text{cut}} \quad (13)$$

is enhancing this relative percentage, while, at the same time, reducing the overall cross section.

The feature of radiative top quark decays is the second source of large symmetric contributions. Splitting the cross section into photon radiation in production (prod) and radiative decays (dec), we find for the cuts in Eq. (4)

$$\sigma_{\text{NLO}}^{t\bar{t}+\gamma} = 526 \text{ fb (prod)} + 1182 \text{ fb (dec)} = 1708 \text{ fb}. \quad (14)$$

Almost 70 % of the total rate is due to $t\bar{t}$ production followed by a radiative top quark decay. This is a somewhat counter-intuitive picture as one typically imagines the $t\bar{t} + \gamma$ final state as being produced altogether in the hard collision. We suppress radiative top quark decays using invariant masses of the decay products. To start, we associate the two b -jets with the *correct* side of the decay chain (b -jets belong to the t decay chain, $\bar{b}$ -jets belong to the $\bar{t}$ decay chain). This is achieved by pairing b -jet and leptonic decay chain which

Fig. 2 Left: Symmetric and asymmetric cross sections at LO and NLO QCD for different sets of cuts. The error bands correspond to a scale variation by a factor two around the central scale μ_0 . Right: Statistical significance as a function of the (negative) charge asymmetry at NLO

minimize $\{m_{\ell b_1}, m_{\ell b_2}\}$. The other b -jet is associated with the hadronic decay chain. Subsequently, we consider the minima

$$\min_{x \in D_i \cup D_{i\gamma}} \left\{ m_x^2 - m_t^2 \right\}, \quad i = \ell, h \quad (15)$$

for $D_\ell = \{b\ell v, b\ell v j\}$, $D_{\ell\gamma} = \{b\ell v\gamma, b\ell v j\gamma\}$, $D_h = \{bjj, bj j j\}$, and $D_{h\gamma} = \{bj j \gamma, bj j j \gamma\}$. If kinematics is such that $x \in D_{\ell\gamma}$ or $x \in D_{h\gamma}$, we consider it a radiative top quark decay event and reject it. All other events are kept. We find that these selection criteria are robust under QCD corrections, and we believe that the impact of off-shell effects is small because a smearing of the invariant masses around the top quark Breit-Wigner peak will not significantly change the minimization procedure. Fig. 1 (right) shows the relative contribution of photon emission in the production and radiative top quark decays. The upper pane shows the two contributions without the cuts of Eq. (15), the lower pane shows the contributions when the cuts are included. It is evident that this procedure works very efficiently in selecting photon emission in production. Moreover, the rapidity distribution is flat and remains flat after the cuts. Hence, the cuts for gg suppression (Eq. (13)) and radiative decays do not interfere with each other.

In the following, we study the charge asymmetry as a function of the cuts in Eq. (13) and Eq. (15) including NLO QCD corrections. It is evident that applying the cuts on the one hand increases the asymmetry, and on the other hand reduces the cross section, therefore lowering the statistical significance of a measurement. Hence, we try to optimize the cuts such that the two competing effects are balanced. We vary the lower photon rapidity cut y_γ^{cut} from 0.0 to 1.4 in steps of 0.2. The results are given in the second and third column of Table 1 and displayed in Fig. 2. These are the main results of this work. We find that the perturbative pattern that we discussed in Sect. 3 persist if the cuts Eq. (13) and Eq. (15)

QCD. The lower line corresponds to cuts Eq. (4) and the upper line arises from the additional application of cuts Eq. (15). Each line consists of seven data points for increasing cut $|y_\gamma| \geq 0.0, 0.2, \dots, 1.2, 1.4$

are added. The asymmetric contribution receives a moderate NLO correction with small scale dependence. In contrast, the symmetric cross section gets large corrections and exhibits $\approx 20\%$ scale dependence. This uncertainty feeds into the uncertainty of the asymmetry A_C as the dominating one.

From Table 1 it is evident that the additional cuts significantly enhance the asymmetry. The initial value of -0.5% is doubled when the radiative decay suppression cuts in Eq. (13) are applied. Further, it is more than tripled when $|y_\gamma| > 1$ is required in addition. The relative uncertainties remain roughly constant at about 20%. The statistical significance is boosted to values above 3σ for an integrated luminosity of $\mathcal{L} = 150 \text{ fb}^{-1}$.

Figure 2 (right) illustrates the dependence on the cuts in more detail and allows to find the optimal cut values. We plot the significance $\mathcal{S}$ over the negative asymmetry A_C . The connected dots show the dependence on the monotonically increasing value y_γ^{cut} , with cuts in Eq. (4) (lower dotted line) and cuts in Eqs. (4)+(15) (upper dotted line). The colored bands indicate the corresponding uncertainties obtained from Eq. (11) for A_C and similar for $\mathcal{S}$. Comparing the pink and yellow bands it is obvious that the radiative decay suppression is very effective in enhancing the asymmetry and the statistical significance. Yet the uncertainties are somewhat inflated. Following the dotted lines of increasing y_γ^{cut} , we observe that the asymmetry can be strongly enhanced while the significance receives a mild increase and later deteriorates for too large values. The optimal point appears at $y_\gamma^{\text{cut}} \approx 1.0$.

Finally, we note that the corresponding LO results to Fig. 2 (right) suggest much larger asymmetries. For example, the yellow band at LO would range from -3% to -5% with a statistical significance of more than 4σ . We do not show these curves in Fig. 2 because we think that only NLO gives a first reliable estimate, given the arguments presented above.

However, one should keep in mind that perturbative corrections are sizable.

5 Summary

We study the top quark charge asymmetry in the lepton+jet final state of $t\bar{t} + \gamma$ production at the 13 TeV LHC. The asymmetry is an Abelian effect of interference between diagrams of even and odd charge-parity, a phenomenon that is well-studied for $t\bar{t}$ production at the Tevatron and the LHC. The $pp \rightarrow t\bar{t} + \gamma$ process is interesting because it exhibits an asymmetry already at leading order, which is significantly larger than in $t\bar{t}$ production. We present perturbative corrections to this observable, including top quark decays, and discuss uncertainties and enhancement strategies. We find that the asymmetric cross section is converging well and is under good theoretical control. In contrast, the symmetric cross section receives sizable corrections. As a result, leading order predictions turn out to be unreliable and next-to-leading order predictions carry sizable uncertainties. Yet, we find arguments to support the reliability of our NLO results within their uncertainties. In addition, we present a set of tailored cuts for enhancing the asymmetry by more than a factor of three such that a measurement with 150 fb^{-1} should be possible at the LHC.

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