

Shedding light on the $t\bar{t}$ asymmetry: the photon handle

J.A. Aguilar-Saavedra,^a E. Álvarez,^b A. Juste^{c,d} and F. Rubbo^d

^a*Departamento de Física Teórica y del Cosmos, Universidad de Granada,
E-18071 Granada, Spain*

^b*CONICET, IFIBA Universidad de Buenos Aires,
1428 Buenos Aires, Argentina*

^c*Institució Catalana de Recerca i Estudis Avançats (ICREA),
E-08010 Barcelona, Spain*

^d*Institut de Física d'Altes Energies (IFAE),
E-08193 Bellaterra, Barcelona, Spain*

E-mail: jaas@ugr.es, sequi@df.uba.ar, juste@ifae.es, frubbo@ifae.es

ABSTRACT: We investigate a charge asymmetry in $t\bar{t}\gamma$ production at the LHC that provides complementary information to the measured asymmetries in $t\bar{t}$ production. We estimate the experimental uncertainty in its measurement at the LHC with 8 TeV and 14 TeV. We argue that, for new physics models that simultaneously reproduce the asymmetry excess in $t\bar{t}$ production at the Tevatron and the SM-like asymmetry at the LHC, the measurement in $t\bar{t}\gamma$ production at the LHC is likely to deviate from the SM prediction. In two new physics models studied in detail we find that the deviations could be significant and observable at the 14 TeV run.

KEYWORDS: Phenomenological Models, Hadronic Colliders

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1 Introduction

After several Tevatron legacy measurements with the full data set [1–4] and the most recent data from the Large Hadron Collider (LHC) [5–7], the potential presence of new physics in $t\bar{t}$ production resulting in an anomalously large forward-backward (FB) asymmetry remains intriguing. Measurements at the Tevatron are above the Standard Model (SM) predictions [8–11], for example 2.2 standard deviations (2.2σ) in the case of the inclusive $t\bar{t}$ asymmetry A_{FB} [1], which raises to 2.5σ for high $t\bar{t}$ invariant masses $m_{t\bar{t}} > 450$ GeV. But, on the other hand, measurements of the $t\bar{t}$ charge asymmetry A_C at the LHC exhibit a good consistency with the SM expectations. At first glance, this is a surprising fact, because A_{FB} and A_C originate from the very same partonic asymmetries A_u and A_d in $u\bar{u} \rightarrow t\bar{t}$, $d\bar{d} \rightarrow t\bar{t}$, respectively [12]. Therefore, A_{FB} and A_C are tightly correlated [13] in the simple models [14] that were first proposed to explain the A_{FB} measurement [15–19]. In these models, with a single extra particle, either A_u or A_d is zero, or they have the same sign. Likewise, it is also expected that (isospin-symmetric) missing SM contributions that might increase the prediction of A_{FB} to make it closer to the experimental measurement, would also enhance A_C and worsen the agreement with experimental data [20]. Therefore, although Tevatron and LHC measurements are not incompatible, they are in tension within the SM and its simple extensions.

On the other hand, it is possible to have an excess at the Tevatron and no excess at the LHC if there is a cancellation of some type. There are two known ways to achieve this:

1. A cancellation between $u\bar{u}$ and $d\bar{d}$ contributions [12], as implemented for example in s -channel colour octet models [21]. If the asymmetries A_u , A_d have different sign, the higher importance of $d\bar{d}$ with respect to $u\bar{u}$ at the LHC — the ratio of cross sections $\sigma(d\bar{d})/\sigma(u\bar{u})$ is a factor of three higher at the LHC than at the Tevatron — makes it possible to have a positive asymmetry A_{FB} , dominated by A_u , at the Tevatron, and a very small asymmetry A_C at the LHC.

2. A cancellation between $q\bar{q} \rightarrow t\bar{t}$ (with $q = u, d$) and $qg \rightarrow t\bar{t}j$ contributions, as for example in Z' models [22–24]. The qg processes are irrelevant at the Tevatron but not at the LHC. There, a negative asymmetry in $ug \rightarrow t\bar{t}j$ could compensate a positive asymmetry in $u\bar{u} \rightarrow t\bar{t}$, if one considers not only $t\bar{t}$ production but also including additional jets. This model is disfavoured by the measurement of the high- $m_{t\bar{t}}$ tail at the LHC and may eventually be excluded with more precise measurements, but serves as a good benchmark for our discussion.

Thus, the small SM-like asymmetry observed at the LHC may in principle result from two asymmetries of opposite sign (the naturalness of this mechanism is a different issue). But the addition of a final state photon completely changes this. An asymmetry can be defined in $t\bar{t}\gamma$ production

$$A_C^{t\bar{t}\gamma} = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}, \tag{1.1}$$

with $\Delta|y| = |y_t| - |y_{\bar{t}}|$ the difference between the moduli of the rapidities of the top and antitop. That is, the same definition for the charge asymmetry as in $t\bar{t}$ production. In the SM, this asymmetry arises already at the tree level in $q\bar{q} \rightarrow t\bar{t}\gamma$ due to the interference between diagrams where the photon is emitted from initial quarks and diagrams where it is emitted from final state quarks. At a centre-of-mass (CM) energy of $\sqrt{s} = 8$ TeV the tree-level value is $A_C^{t\bar{t}\gamma} = -0.058$, and at $\sqrt{s} = 14$ TeV it is $A_C^{t\bar{t}\gamma} = -0.038$. Comparing to $t\bar{t}$ alone, the effect of the extra photon is twofold. First, it increases the total $q\bar{q}$ fraction of events $F_u + F_d$, $F_u \equiv \sigma(u\bar{u})/\sigma$, $F_d \equiv \sigma(d\bar{d})/\sigma$, thus reducing the washout due to symmetric gg fusion. (For simplicity we ignore here $s\bar{s}$ and $c\bar{c}$ initial states, which are irrelevant for the discussion.) Second, and even more importantly, if there is a cancellation between new physics contributions to turn A_C small, the addition of a photon is likely to break it in $A_C^{t\bar{t}\gamma}$. This is expected to be a general fact, and indeed is confirmed in this paper for the two aforementioned mechanisms.

In the first case, namely a cancellation between $u\bar{u}$ and $d\bar{d}$ contributions at the LHC, such cancellation is broken mainly because the photon couples differently to up and down quarks, and $u\bar{u} \rightarrow t\bar{t}\gamma$ is enhanced with respect to $d\bar{d} \rightarrow t\bar{t}\gamma$. The effect can be clearly seen in figure 1 (left), where we plot the $q\bar{q}$ fraction $F_u + F_d$ against the ratio F_d/F_u for the SM processes. (See section 2 for details of the simulations used to obtain these numbers.) Kinematical cuts on the $t\bar{t}$ velocity β [25] and the $t\bar{t}$ invariant mass $m_{t\bar{t}}$ lead to small shifts in F_d/F_u and $F_u + F_d$ towards the Tevatron point. But, clearly, requiring a final state photon is much more effective: it renders F_d/F_u very close to the Tevatron value (thus breaking a possible cancellation) and also increases the $q\bar{q}$ fraction by a factor of two, leading to larger asymmetries. For new physics contributions — such as an s -channel colour octet — that do not significantly alter the kinematics of $t\bar{t}$ and $t\bar{t}\gamma$ production, the behaviour is the same. Note also that F_d/F_u is nearly the same at the LHC with $\sqrt{s} = 8$ TeV and $\sqrt{s} = 14$ TeV (as well as with 7 TeV), hence the possible cancellation will also operate at 14 TeV and the measurement of A_C at this energy is expected to show good consistency with the SM.

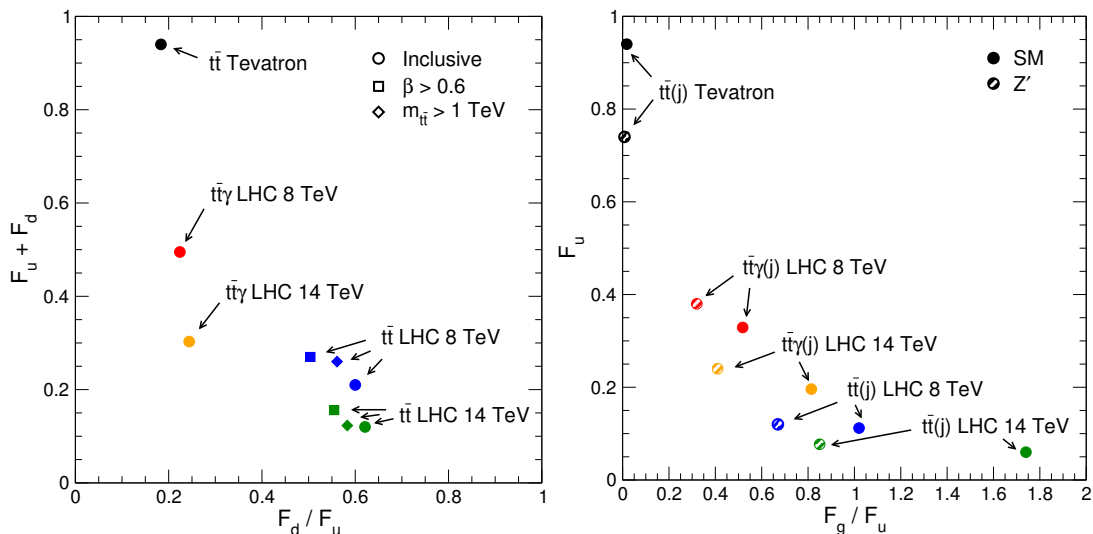


Figure 1. Left: Ratio $F_d/F_u = \sigma(d\bar{d})/\sigma(u\bar{u})$ and total $q\bar{q}$ fraction $F_u + F_d$ for $t\bar{t}$ and $t\bar{t}\gamma$ production in the SM. Right: $F_g/F_u = \sigma(ug)/\sigma(u\bar{u})$ and $u\bar{u}$ fraction F_u in $t\bar{t}(j)$ and $t\bar{t}\gamma(j)$, in the SM and for the production and decay of a Z' .

In the second case, the cancellation is broken due to two effects. First, there is a decrease in $F_g/F_u = \sigma(ug)/\sigma(u\bar{u})$ in $t\bar{t}\gamma(j)$ with respect to $t\bar{t}(j)$ merely due to kinematics, which already happens in the SM. Secondly, there is a further decrease in the new physics Z' contribution because in $u\bar{u} \rightarrow t\bar{t}$ it is more likely to emit a photon than in $ug \rightarrow tZ'$, since in the former there are more charged particles. We can observe this clearly in figure 1 (right), where the solid points correspond to the SM, and the hashed points are the ones for the Z' model,¹ as described in section 3. Notice also that F_g/F_u is larger at 14 TeV, increasing the negative component of A_C , but the washout due to gg fusion increases too, and generically one does not expect to have visible asymmetries in $t\bar{t}$ production at 14 TeV if a cancellation of this type takes place.

As the main consequence of this simplified analysis, one can say that the requirement of an extra photon in $t\bar{t}$ production at the LHC “reweights” the new physics asymmetries in the different subprocesses, if present, recovering to a large extent the situation at the Tevatron. This is expected to be a rather general feature, and the exact numerical calculations carried out in this paper for two benchmark models confirm this semi-quantitative argument.

The remainder of this paper is organised as follows. In section 2 we present the simulation details and event selection to suppress radiative top decays, and we estimate the expected uncertainty in $A_C^{t\bar{t}\gamma}$. In section 3 we study $A_C^{t\bar{t}\gamma}$ for two different new physics models that explain the excess in A_{FB} and the absence of an excess in A_C . Our conclusions and final remarks are given in section 4.

¹For this model we focus on inclusive asymmetries and do not investigate the effect of kinematical cuts. It is well known for example that Z' exchange enhances the high-mass $m_{t\bar{t}}$ tail at the LHC [14, 26], and kinematical differences are important already in the $t\bar{t}$ differential distributions.

2 Simulation details

In order to estimate the experimental uncertainty in the measurement of $A_C^{t\bar{t}\gamma}$, we focus on the semileptonic $t\bar{t}$ decay channel, which constitutes the golden mode for this measurement owing to the relatively large branching ratio ($\sim 30\%$), manageable background after b tagging requirements, and the ability to fully reconstruct the $t\bar{t}$ event kinematics. A complication arises from the fact that any realistic estimate should in principle take into consideration the full $2 \rightarrow 7$ calculation for the process $pp \rightarrow \ell\nu b q \bar{q}' \bar{b} \gamma + X$, since only a fraction of the cross section for this final state originates from photon radiation off the initial state quarks or the top/antitop quarks (referred to as “radiative top production”), that is, $pp \rightarrow t\bar{t}\gamma + X$ with subsequent decay of the $t\bar{t}$ pair. As we will see in the following, the cross section is actually dominated by photon radiation off the top decay products (b quark, W boson and its charged decay products), referred to here as “radiative top decay”. Therefore, it is necessary to design an event selection capable of effectively suppressing the contribution from radiative top decays, which would dilute the sensitivity of $A_C^{t\bar{t}\gamma}$ to new physics in the production process.

We use MADGRAPH 5 [27, 28] to generate SM samples for the $2 \rightarrow 3$ process $pp \rightarrow t\bar{t}\gamma + X$, as well as the following two $2 \rightarrow 7$ processes: $pp \rightarrow t\bar{t}\gamma + X$ with $t\bar{t} \rightarrow \ell\nu b q \bar{q}' \bar{b}$ and $\ell = e, \mu$ (i.e. restricted to radiative top production), and $pp \rightarrow \ell\nu b q \bar{q}' \bar{b} \gamma + X$ (i.e. including both radiative top production and decay). In the latter case we consider only resonant Feynman diagrams with two on-shell top quarks and two on-shell W bosons. The samples are generated for $\sqrt{s} = 8$ TeV and 14 TeV using the CTEQ6L1 parton distribution set [29] and the event-by-event renormalisation and factorisation scale as implemented by default in MADGRAPH 5. A top quark mass of $m_t = 173$ GeV is assumed throughout this study. All samples are generated requiring for the photon transverse momentum $p_T(\gamma) > 20$ GeV and pseudo-rapidity $|\eta(\gamma)| < 2.5$. In the case of the $2 \rightarrow 7$ samples, additional requirements are made on final-state partons:

- $p_T(\ell) > 10$ GeV, $|\eta(\ell)| < 2.5$,
- $p_T(j) > 20$ GeV, $|\eta(j)| < 5.0$ (in the following we will use j to denote q or b),
- lego-plot distance $\Delta R(\ell, \gamma) > 0.4$, $\min\{\Delta R(\ell, j)\} > 0.4$, $\min\{\Delta R(\gamma, j)\} > 0.4$, $\min\{\Delta R(j, j)\} > 0.4$.

We perform our studies at the parton level but attempt to obtain reasonable estimates for the event selection efficiency and dilution in the measurement of $A_C^{t\bar{t}\gamma}$. We do not include backgrounds, although experimental studies of $t\bar{t}\gamma$ production at the LHC [30, 31] find that the overall background can be comparable to the signal, and dominated by $t\bar{t}$ production with an electron or jet being misidentified as a photon. Although such background contribution is large, its associated asymmetry can be precisely measured in dedicated data control samples. Estimating the effect of the background on the statistical and systematic uncertainty on $A_C^{t\bar{t}\gamma}$ is beyond the scope of this exploratory work and should be done in the context of the actual experimental analyses.

Events are required to fulfill basic preselection requirements aimed at selecting the semileptonic signature:

- exactly one lepton (electron or muon) with transverse momentum $p_T > 20$ GeV and pseudorapidity $|\eta| < 2.5$;
- missing transverse momentum $\cancel{p}_T > 20$ GeV;
- four quarks with $p_T > 25$ GeV and $|\eta| < 4.5$;
- exactly one photon with $p_T > 20$ GeV and $|\eta| < 2.5$;
- $\Delta R(\ell, \gamma) > 0.4$, $\min\{\Delta R(\ell, j)\} > 0.4$, $\min\{\Delta R(j, j)\} > 0.4$.

With these requirements, the leading-order (LO) effective cross section at $\sqrt{s} = 14$ TeV is 0.13 pb in the case of the $2 \rightarrow 7$ calculation without radiative top decays, while it is 0.23 pb for the full $2 \rightarrow 7$ calculation, clearly showing the need to have additional cuts to suppress the large contribution from radiative top decays. This can be accomplished by a combination of cuts [32]:

- tighter ΔR requirements between the photon and charged top quark decay products: $\Delta R(\gamma, \ell) > 1.0$, $\min\{\Delta R(\gamma, q)\} > 0.7$, $\min\{\Delta R(\gamma, b)\} > 0.5$;
- veto radiative W decays: $m(jj\gamma) > 90$ GeV, $m_T(\ell\gamma; \cancel{p}_T) > 90$ GeV, where $m(jj\gamma)$ is the invariant mass of the $jj\gamma$ system and $m_T(\ell\gamma; \cancel{p}_T)$ is the cluster transverse mass defined as

$$m_T^2(\ell\gamma; \cancel{p}_T) = \left(\sqrt{p_T^2(\ell\gamma) + m^2(\ell\gamma)} + \cancel{p}_T \right)^2 - \left(\vec{p}_T(\ell\gamma) + \vec{\cancel{p}}_T \right)^2,$$

with analogous definitions for particles other than the photon and the charged lepton;

- veto radiative top decays: reject events satisfying either of the following conditions:
 1. $m_T(b_{1,2}\ell\gamma; \cancel{p}_T) < m_t + 20$ GeV and $m_t - 20$ GeV $< m(b_{2,1}jj) < m_t + 20$ GeV;
 2. $m_T(b_{1,2}\ell; \cancel{p}_T) < m_t + 20$ GeV and $m_t - 20$ GeV $< m(b_{2,1}jj\gamma) < m_t + 20$ GeV,

where $b_1, b_2 = b, \bar{b}$, and $b_1 \neq b_2$;

- consistency with radiative top production: $m_T(b_{1,2}\ell; \cancel{p}_T) < m_t + 20$ GeV and $m_t - 20$ GeV $< m(b_{2,1}jj) < m_t + 20$ GeV.

After all requirements, the effective cross section at $\sqrt{s} = 14$ TeV becomes 0.083 pb in the case of the $2 \rightarrow 7$ calculation without radiative top decays, while it is also 0.083 pb for the full $2 \rightarrow 7$ calculation, demonstrating that the contribution from radiative top decays has been effectively eliminated. The effect of the sequential application of these cuts in some of the relevant kinematic distribution can be visualised in figure 2, where it is shown that after all requirements there is good agreement in both normalisation and shape between the full $2 \rightarrow 7$ calculation and the $2 \rightarrow 7$ calculation without radiative top decays. As a final

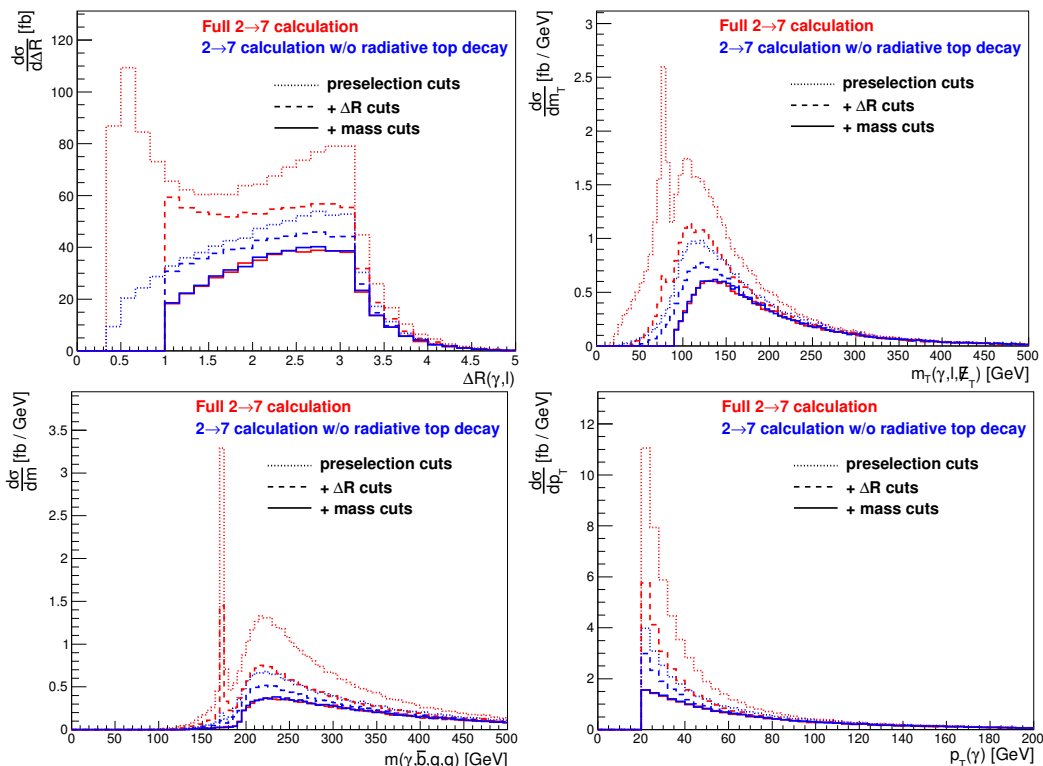


Figure 2. Comparison of the differential cross sections between the full $2 \rightarrow 7$ calculation (red) and the $2 \rightarrow 7$ calculation without radiative top decays (blue) as a function of several kinematic variables. The different line styles correspond to different stages of the event selection (see text for details): preselection cuts (dotted), preselection+ ΔR cuts (dashed), all selection cuts (solid).

check, we have compared $A_C^{t\bar{t}\gamma}$ between the $2 \rightarrow 3$ calculation with just the photon cuts, and the full $2 \rightarrow 7$ calculation including all selection cuts. The inclusive asymmetries are $A_C^{t\bar{t}\gamma} = -0.039(2)$ and $A_C^{t\bar{t}\gamma} = -0.035(2)$, respectively, where the numbers in parentheses represent the uncertainty from limited Monte Carlo statistics. Reasonable agreement is also found for $A_C^{t\bar{t}\gamma}$ differentially as a function of $m_{t\bar{t}}$ and $|\eta(\gamma)|$, as shown in figure 3.

Therefore, in the remainder of this paper we will only consider the simpler $2 \rightarrow 3$ calculation for the $t\bar{t}\gamma$ process together with the selection efficiency estimated from the above study and summarised below. For a more realistic estimate, the LO cross section for the $2 \rightarrow 3$ calculation is multiplied by a k-factor of 1.75, in order to reproduce the NLO cross section of ref. [33]. Therefore, the total $t\bar{t}\gamma$ cross section for $\sqrt{s} = 8$ TeV is 0.68 pb, and for $\sqrt{s} = 14$ TeV it is 2.73 pb, corresponding to the requirements of $p_T(\gamma) > 20$ GeV and $|\eta(\gamma)| < 2.5$.

The semileptonic branching ratio is taken to be 30%. The total selection efficiency for semileptonic decays, including the effect of the preselection cuts as well the additional cuts to veto radiative top decay, is estimated to be $\sim 20\%$ using a sample for the $2 \rightarrow 7$ process without radiative top decays, including only generator-level cuts on the photon of $p_T(\gamma) > 20$ GeV and $|\eta(\gamma)| < 2.5$. We also assume a total efficiency for lepton triggering and identification of 70%, a photon identification efficiency of 85% and a per-jet b tagging

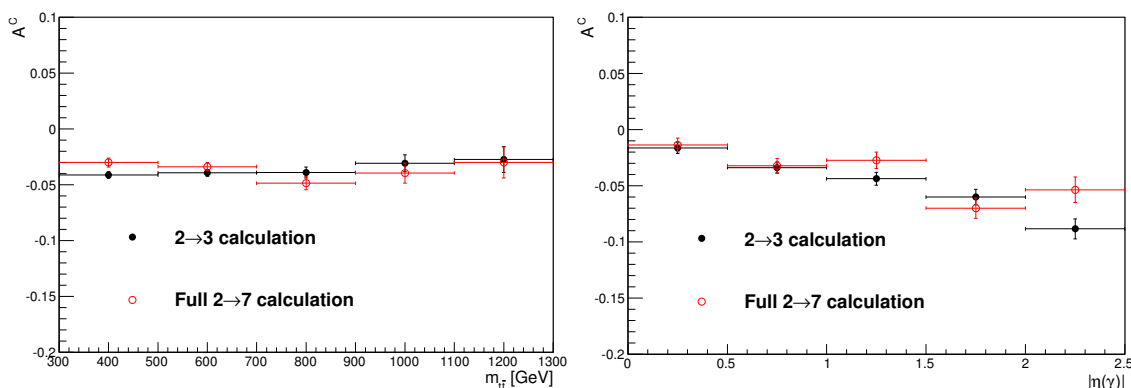


Figure 3. Left: $A_C^{t\bar{t}\gamma}$ as a function of $m_{t\bar{t}}$ at $\sqrt{s} = 14$ TeV. Right: $A_C^{t\bar{t}\gamma}$ as a function of $|\eta(\gamma)|$ at $\sqrt{s} = 14$ TeV. The predicted $A_C^{t\bar{t}\gamma}$ is compared between the $2 \rightarrow 3$ calculation with just the photon cuts (solid black points), and the full $2 \rightarrow 7$ calculation including all selection cuts (open red points). The error bars reflect the uncertainty from Monte Carlo statistics. See text for details on the exact selection requirements.

efficiency of 70%, resulting in an efficiency for a requirement of at least one b -tagged jet of 90%. The product of the above numbers results in a total efficiency times branching ratio of 3.2%. Therefore, the expected number of selected events for a total integrated luminosity of 20 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$ is ~ 440 , resulting in an expected statistical uncertainty on $A_C^{t\bar{t}\gamma}$ of ± 0.045 . At a CM energy of $\sqrt{s} = 14 \text{ TeV}$ with 100 fb^{-1} the expected number of events is ~ 8800 , giving a statistical uncertainty on $A_C^{t\bar{t}\gamma}$ of ± 0.01 .

In the next section we will compute $A_C^{t\bar{t}\gamma}$ (see eq. (1.1)) from y_t and $y_{\bar{t}}$ at the parton level using the $2 \rightarrow 3$ calculation for the $pp \rightarrow t\bar{t}\gamma + X$ process in the presence of new physics. Experimentally, the charge asymmetry would be computed after a kinematic reconstruction of the $t\bar{t}$ system in $t\bar{t}\gamma$ events similar to that used for the measurement of $A_C^{t\bar{t}}$ in $t\bar{t}$ production [6, 7]. In the case of experimental measurements of $A_C^{t\bar{t}}$, the fraction of events with the sign of $\Delta|y|$ correctly reconstructed is $\sim 75\%$. Using the simplified $t\bar{t}$ event reconstruction of ref. [25], we have verified that the fraction of events with the sign of $\Delta|y|$ correctly reconstructed is in fact $\sim 5\%$ higher in absolute term for $t\bar{t}\gamma$ compared to $t\bar{t}$ production, possibly related to the higher longitudinal boost of the $t\bar{t}$ system in the case of $t\bar{t}\gamma$ events from the higher fraction of $q\bar{q}$ -initiated production. Nevertheless, we will conservatively assume the same fraction of 75%, which corresponds to a “dilution” factor $D = 2 \times 0.75 - 1 = 0.5$. Such dilution results in a reduction by a factor of two of the measured $A_C^{t\bar{t}\gamma}$ which would effectively be corrected for by the unfolding procedure used in the experimental analyses, and can be taken into account here by an increase by a factor of two of the statistical uncertainty. Then, for $\sqrt{s} = 8 \text{ TeV}$ and an integrated luminosity of 20 fb^{-1} , the resulting expected statistical uncertainty is ± 0.09 , and at $\sqrt{s} = 14 \text{ TeV}$ with integrated luminosities of 100 fb^{-1} (400 fb^{-1}) it is ± 0.02 (± 0.01). Our estimates do not include systematic uncertainties since, based on the present experience with the A_C measurements, those are expected to be small (≤ 0.005). In any case, a careful assessment of systematic uncertainties would require a detailed analysis involving experimental simulations that are beyond the scope of this work.

3 Asymmetries in $t\bar{t}\gamma$ and $t\bar{t}$

The importance of $A_C^{t\bar{t}\gamma}$ to provide a complementary probe of asymmetric $t\bar{t}$ production at the Tevatron is shown here with two benchmark examples. They correspond to the two types of cancellations between new physics contributions that may yield a small A_C at the LHC. For our Monte Carlo calculations of $t\bar{t}$ with a colour octet we use PROTONS [34]. For $t\bar{t}\gamma(j)$ production in the colour octet and with an extra Z' we use MADGRAPH 5 [27, 28] coupled to PYTHIA [35] in its default tune with a MLM matching scheme [36] implemented to avoid double counting in the extra jet between the matrix element calculation and the parton shower. In both models the asymmetries $A_C^{t\bar{t}\gamma}$ are calculated at leading order. For the comparison with experimental data, especially at $\sqrt{s} = 14$ TeV, next-to-leading order (NLO) computations would be required, at least for the SM asymmetries. (The asymmetries including new physics contributions could be approximated, as usual, by summing the SM asymmetries at NLO and the new physics contributions at LO.) In any case, our leading-order calculations are sufficient to demonstrate the importance of this asymmetry and its potential to exhibit deviations from the SM predictions.

3.1 $A_C^{t\bar{t}\gamma}$ for a colour octet

We scan the parameter space of couplings of a *light* colour octet [37–41], with a fixed mass $M = 250$ GeV and a large width $\Gamma/M = 0.2$, that is assumed in order to comply with dijet pair constraints [42, 43]. (This width may originate from additional decays to non-SM particles.) This scan is a particular subset of a more general parameter space scan to be presented and discussed elsewhere [44]. For simplicity, here we take the vector couplings of the up and down quarks to zero. The parameter space points considered here have a global agreement with $t\bar{t}$ experimental data at the level of 1σ or better, including several observables such as cross sections and asymmetries. The details of the fit are not essential here for our purposes, and it is sufficient to mention that the resulting points comprise high as well as low values of A_{FB} , that might — or not — explain the Tevatron anomaly. Analogously, the resulting values of A_C span a $\pm 2\sigma$ range above and below the SM predictions for 7 and 8 TeV. For these points, we present in figure 4 the asymmetry A_C at 8 TeV versus $A_C^{t\bar{t}\gamma}$ at 8 TeV (left) and 14 TeV (right). The shaded horizontal area corresponds to the CMS measurement $A_C = 0.005 \pm 0.009$ [7] and its 1σ uncertainty. The vertical lines represent the SM value of $A_C^{t\bar{t}\gamma}$ and its expected uncertainty, estimated in section 2. The points are coloured according to the value of the Tevatron asymmetry A_{FB} . From left to right: red points have A_{FB} below -2σ of the naive Tevatron average $A_{\text{FB}}^{\text{exp}} = 0.187 \pm 0.036$; orange points have A_{FB} between -2σ and -1σ ; green points have A_{FB} between -1σ and 1σ ; blue points have asymmetries above 1σ . In all cases the SM contribution to the asymmetries [11] is summed to the ones resulting from new physics.

The difference found between 8 TeV and 14 TeV is given by the much better statistics at the latter CM energy, which by far compensates the slightly smaller $A_C^{t\bar{t}\gamma}$ due to the increased gg cross section. (As pointed out before, the ratio F_d/F_u is nearly the same at these two energies.) Interestingly, for the parameter space points (in green) that predict an asymmetry A_{FB} within $\pm 1\sigma$ of the Tevatron average, the asymmetry in $t\bar{t}\gamma$ departs 1σ

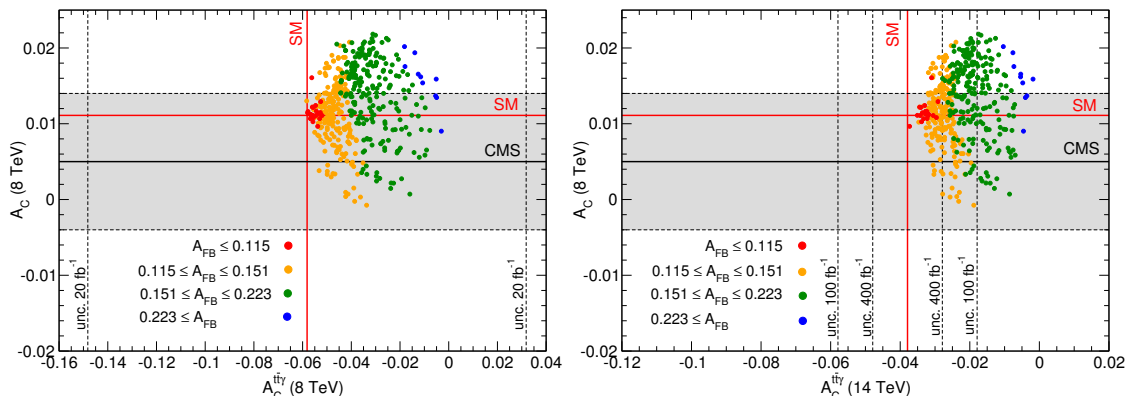


Figure 4. Charge asymmetry $A_C^{t\bar{t}\gamma}$ (at 8 TeV and 14 TeV) versus A_C for a colour octet.

or more above the SM value. This happens irrespectively of the value of the asymmetry in $t\bar{t}$ production A_C , that may even have the SM value. We also note that for all points the increase in $A_C^{t\bar{t}\gamma}$ with respect to the SM value is positive. This is expected from the behaviour shown in figure 1 (left), and is clearly because the increase in A_{FB} with respect to the SM value is also positive, as preferred by the fit to the Tevatron measurements.

3.2 $A_C^{t\bar{t}\gamma}$ for a Z'

We have chosen a reference point in the extra Z' model that represents the region of parameter space compatible with the relevant observables as stated in the study in ref. [45]. We have set $M_{Z'} = 275 \text{ GeV}$, $g_{utZ'} = 0.7$ and an invisible Z' branching ratio $\mathcal{B}(Z' \rightarrow \text{invisible}) = 3/4$. This model predicts a charge asymmetry at the LHC of $A_C = 0.015$ at 8 TeV, which is compatible with CMS measurement [7] and SM prediction. However, when an extra photon is required, its prediction yields $A_C^{t\bar{t}\gamma} = -0.048$ and $A_C^{t\bar{t}\gamma} = -0.018$ at 8 TeV and 14 TeV, respectively, which again is an excess over the SM expected asymmetry (compare to the SM prediction in figure 4). We see that also in this case, the 8 TeV measurement of $A_C^{t\bar{t}\gamma}$ would not differentiate this model from the SM, but we can expect that 400 fb^{-1} at 14 TeV could be able to do it.

3.3 A_C at 14 TeV

Finally, in order to stress the importance of $A_C^{t\bar{t}\gamma}$, we have checked that in both models the prediction of A_C in $t\bar{t}$ production at 14 TeV is always consistent with the SM, assuming an experimental uncertainty of ± 0.005 . This is expected from the arguments given in the introduction. If a cancellation between $u\bar{u}$ and $d\bar{d}$ contributions takes place to render the LHC asymmetry small at 7 and 8 TeV, it should also operate at 14 TeV, where F_d/F_u is similar. Or, if there exists a cancellation between $u\bar{u}$ and gu , at 14 TeV this cancellation is relaxed by the larger F_g/F_u but the resulting asymmetry is small anyway.

4 Conclusions

After several years of measurements with increasing precision, the excess asymmetry A_{FB} in $t\bar{t}$ production at the Tevatron and the SM-like charge asymmetry A_C in $t\bar{t}$ production at the LHC continue to be puzzling. If new data confirm the current central values and reduce their uncertainties, it is unlikely that both can be explained within the SM (also with additional isospin-conserving contributions yet unaccounted for) and simple extensions. Barring the possibility of unknown systematic uncertainties, the only way to explain these measurements is by means of some cancellation of new physics contributions at the LHC, to give approximately the SM value.

A previous attempt to solve this puzzle has been the introduction of the collider-independent asymmetries [12, 46] A_u, A_d that are the same at the Tevatron and the LHC, and whose measurement — quite demanding from the experimental point of view — could settle the issue. Also, the determination of ratios of differential asymmetries [47, 48] would be useful to uncover possible anomalies. In this paper we have pointed out that, if the pattern of large A_{FB} and SM-like A_C corresponds to some cancellation, such cancellation should not occur in $t\bar{t}\gamma$ production at the LHC, where the additional photon alters the balance between new physics contributions compared to the case of $t\bar{t}$ production. This fact turns extremely interesting the measurement of a charge asymmetry in $t\bar{t}\gamma$ production. Moreover, even if the Tevatron excess is not due to new physics, the measurement of $A_C^{t\bar{t}\gamma}$ could shed light into the nature of the Tevatron anomaly.

We have studied the feasibility of this measurement and we have shown that the unwanted contributions to the final state of interest, where the photon is radiated off the top quark decay products, can be effectively suppressed with a judicious set of kinematical cuts. We have then estimated the experimental uncertainty on the measurement of $A_C^{t\bar{t}\gamma}$, to investigate the potential to observe deviations from the SM. Our estimations are conservative, partly because the correct reconstruction of $|\Delta y|$ is better in $t\bar{t}\gamma$ than in $t\bar{t}$, and we have assumed the same performance. In addition, we expect that optimised experimental analyses could potentially achieve higher selection efficiencies than those assumed in this study. Finally, the measurements from ATLAS and CMS can be combined, which brings an advantage for a statistics-dominated measurement as in our case.

At 7 and 8 TeV, the statistics is likely not enough to reach a conclusive statement. At 14 TeV, we have shown that there are good chances of observing a deviation from the SM prediction in the case of a colour octet and in the extra Z' model. In both cases we do find an excess in $A_C^{t\bar{t}\gamma}$ with respect to the SM — and we argue that this should be in general expected for new physics models that yield an excess in A_{FB} . On the other hand, the predictions for the charge asymmetry A_C in $t\bar{t}$ production at 14 TeV are close to the SM expectation. Therefore — aside more demanding doubly-differential studies of the β and $m_{t\bar{t}}$ dependence of A_C [12] or ratios of differential asymmetries [47, 48] — the measurement of a charge asymmetry in $t\bar{t}\gamma$ seems the best avenue to explore FB-asymmetric $t\bar{t}$ production in the upcoming LHC run.

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