Comment on measuring the tt[over ¯] forward-backward asymmetry at ATLAS and CMS

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Phys. Rev. D **84**, 071504 — Published 28 October 2011

DOI: 10.1103/PhysRevD.84.071504

Comment on measuring the $t\bar{t}$ forward-backward asymmetry at ATLAS and CMS

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We suggest a new possibility for ATLAS and CMS to explore the $t\bar{t}$ forward-backward asymmetry measured at the Tevatron, by attempting to reconstruct $t\bar{t}$ events, with one of the tops decaying semileptonically in the central region ($|\eta| < 2.5$) and the other decaying hadronically in the forward region ($|\eta| > 2.5$). For several models which give comparable Tevatron signals, we study the charge asymmetry at the LHC as a function of cuts on $|\eta|$ and on the $t\bar{t}$ invariant mass, $m_{t\bar{t}}$. We show that there is an interesting complementarity between cuts on $|\eta|$ and $m_{t\bar{t}}$ to suppress the dominant and symmetric $gg \to t\bar{t}$ rate, and different combinations of cuts enhance the distinguishing power between models. This complementarity is likely to hold in other new physics scenarios as well, which affect the $t\bar{t}$ cross section, so it motivates extending $t\bar{t}$ reconstruction to higher $|\eta|$.

I. INTRODUCTION

The hints of an enhancement of the forward-backward asymmetry in the production of $t\bar{t}$ pairs seen by CDF [1] and DØ [2] a few years ago generated a lot of interest. The top quark, via its large coupling to the Higgs, can be especially sensitive to new physics at the TeV scale. The hint of a possible deviation from the standard model has become more significant recently, when CDF found that the asymmetry arises from $t\bar{t}$ events with high invariant masses [3],

$$\begin{aligned} A_{t\bar{t}}(m_{t\bar{t}} > 450\,\mathrm{GeV}) &= 0.475 \pm 0.114\,, \\ A_{t\bar{t}}(m_{t\bar{t}} < 450\,\mathrm{GeV}) &= -0.116 \pm 0.153\,, \end{aligned} \qquad (1)$$

while the standard model predictions are 0.088 ± 0.013 and 0.040 ± 0.006, respectively. The DØ result, only available integrated over $m_{t\bar{t}}$, and uncorrected for effects from reconstruction or selection, $A_{t\bar{t}} = 0.08 \pm 0.04$ [4], is consistent with the integrated CDF result, $A_{t\bar{t}} = 0.158 \pm 0.075$ [3]. So is the CDF measurement in the dilepton channel, $A_{t\bar{t}} = 0.417 \pm 0.157$ [5]. The large asymmetry at high masses points toward tree-level exchange of a new particle, with large couplings to first and third generation quarks [6–16].

The identically defined forward-backward asymmetry vanishes at the LHC, since it is a symmetric collider. It has long been known that the same physics would manifest itself in a different pseudorapidity distribution for the t and the $\bar{t}$ quarks [17], yielding a nonzero charge asymmetry,

$$A_c = \frac{N\big(|\eta_t| > |\eta_{\bar{t}}|\big) - N\big(|\eta_{\bar{t}}| > |\eta_t|\big)}{N\big(|\eta_t| > |\eta_{\bar{t}}|\big) + N\big(|\eta_{\bar{t}}| > |\eta_t|\big)}\,. \qquad (2)$$

This asymmetry is interesting to study for cuts that are symmetric between the t and $\bar{t}$ decays. However, there is a severe dilution at the LHC due to the dominance of the $gg \to t\bar{t}$ process, which generates no asymmetry, over $q\bar{q} \to t\bar{t}$, which dominates at the Tevatron. A measurement of this asymmetry has been performed by the CMS collaboration using $\int \mathcal{L}\,\mathrm{d}t = 1.09\ \mathrm{fb}^{-1}$ data, integrated over $m_{t\bar{t}}$, yielding $A_c = -0.019 \pm 0.030(\mathrm{stat.}) \pm 0.019(\mathrm{syst.})$ [18]. A similar measurement, with the asymmetry defined for top rapidities instead of pseudorapidities, using $0.70\ \mathrm{fb}^{-1}$ of data by the ATLAS collaboration yields $A'_c = -0.024 \pm 0.016(\mathrm{stat.}) \pm 0.023(\mathrm{syst.})$ [19]. The statistical uncertainty of such measurements are expected to approach the percent level with a few inverse femtobarns, but the systematic uncertainties are not expected to improve at the same pace. Assuming that systematic uncertainties better than a couple of percent will be difficult to achieve in the near future, we attempt to maximize the size of A_c to a level which would allow to observe a significant excess by selecting a favorable phase space of $t\bar{t}$ events, even at the price of reducing the $t\bar{t}$ sample, given the large LHC integrated luminosity expected in the near future.

The role of the $q\bar{q} \to t\bar{t}$ process can be enhanced by demanding a high invariant mass [12, 20, 21], and the models proposed to fit the CDF measurement generically predict at least a factor of $2-3$ enhancement of $\mathrm{d}\sigma/\mathrm{d}m_{t\bar{t}}$ at the LHC at $m_{t\bar{t}}$ above $1-1.5$ TeV [15, 22, 23]. However, in the SM only about 1% [0.1%] of the $t\bar{t}$ events pass the $m_{t\bar{t}} > 1$ TeV [1.5 TeV] cut. These models also predict an $\mathcal{O}(10\%)$ enhancement of the inclusive $t\bar{t}$ cross section at the LHC. Both of these effects would be hard to detect with large significance in the near future, due to either low statistics or theoretical and experimental uncertainties.

Another possibility to enhance the $q\bar{q} \to t\bar{t}$ process and increase the sensitivity to the charge asymmetry is to select events boosted in the beam direction (see, e.g., Ref. [24, 25]). A proposal to carry out such an analysis at LHCb was made in Ref. [26] where only the muon and b-jet of a leptonically decaying top are identified in the detector range of $2 < |\eta| < 5$. The $t\bar{t}$ physics programs at CMS and ATLAS have so far concentrated on selecting leptons and jets within $|\eta| \lesssim 2.5$ motivated by the availability of the full detector features in that range, such as lepton identification, requiring the lepton to pass through the tracking system and either the fine-grained electromagnetic calorimeter (for electrons) or muon spectrometer (for muons), and b-tagging, again requiring tracking. However, the calorimeters of both experiments have the capability to identify and measure jets up to $|\eta| \lesssim 4.5$. Several physics measurements have already been performed using such forward jets, prominent examples being the observation of single top quark production by CMS [27] and ATLAS [28]. Therefore, in this paper, we assume that the reconstruction of $t\bar{t}$ events can be extended to using forward jets in an attempt to increase the observed $t\bar{t}$ asymmetry. We note that some of the experimental difficulties involved by increasing the jet $|\eta|$ range cannot be covered in this study, such as the increased jet energy scale uncertainty. These questions will require a dedicated study using the full ATLAS and CMS detector simulations to be answered properly.

II. MODELS

To explore the dependence of the charge asymmetry signal on η and $m_{t\bar{t}}$, we consider several models recently studied in the literature. Their parameter values are chosen such that they give rise to roughly comparable $A_{t\bar{t}}(m_{t\bar{t}} > 450\,\text{GeV})$ signals at the Tevatron.

Our benchmark models are (i) a Z' coupling off-diagonally to ut [6]; (ii) an axigluon coupling with opposite sign to first and third generation quarks such that $g_A^u = -g_A^t$ [7]; (iii) and a scalar triplet diquark (the "high-mass" reference point in Ref. [15]). The masses and couplings of these models are

$$\begin{aligned} Z': &\quad m_{Z'} = 260\text{ GeV}, &\quad \alpha_{Z'} = 0.048\,, \\ \text{Axigluon}: &\quad m_A = 2\text{ TeV}, &\quad g_A = 2.4\,, \\ \text{Scalar }\mathbf{3}: &\quad m_S = 750\text{ GeV}, &\quad \lambda = 3.0\,. \end{aligned} \tag{3}$$

The contributions to the Tevatron forward-backward asymmetries in these models are shown in Table I, which also shows the relative change in the $t\bar{t}$ cross sections at the Tevatron and at the LHC due to these new physics contributions. We chose these models because (as emphasized in Ref. [16]) due to the different angular distributions in vector and scalar exchanges in different channels (s, t, or u) for the new particles, we expect to get a good sampling of the dependence of new physics scenarios on the selection criteria we study. (Other models may in fact provide better fits to the latest data; see, e.g., Refs. [29, 30].)

In Table I, we include for the Tevatron calculations an $|\eta| < 2.0$ cut, while for the LHC we impose $|\eta| < 2.5$. The asymmetry predictions for the new physics models are quoted from the leading order calculation (both in Table I and thereafter), so the SM contribution, which starts at next-to-leading order, should be added to obtain the experimental predictions. To calculate the effect of the cuts on the charge asymmetry generated in the SM (starting at next-to-leading order) we used MCFM [31], while for the NP contributions (at leading order) we used MadGraph [32]. There is an additional electroweak contribution to the asymmetry [33, 34] in the SM, which has neither been included in our results nor in any of the numerical predictions in the literature to our knowledge. The related uncertainty is small, so it should not affect our conclusions about the observability of a deviation from the SM as a function of the different cuts.

Predictions	new physics models		
	Z'	Axigluon	Scalar $\mathbf{3}$
$A_{t\bar{t}}^{\text{TEV}}(m_{t\bar{t}} > 450\,\text{GeV})$	0.30	0.26	0.29
$A_{t\bar{t}}^{\text{TEV}}$	0.15	0.14	0.17
$\sigma_{t\bar{t}}^{\text{TEV}}/\sigma_{t\bar{t}}^{\text{TEV,SM}}$	0.85	1.08	1.19
$\sigma_{t\bar{t}}^{\text{LHC}}/\sigma_{t\bar{t}}^{\text{LHC,SM}}$	1.01	1.16	1.11

TABLE I: Comparison of the three models studied. The prediction for the experimentally relevant measurable asymmetries is given by adding to the numbers in the first [second] row the SM contributions, $A_{t\bar{t}}^{\text{SM}} = 0.09$ [0.04] [3].

III. CUTS AND RESULTS

We study the effect of imposing combinations of cuts on the reconstructed top quarks' pseudorapidities (R_i) and invariant masses (M_i) in $t\bar{t}$ events, to enhance the charge asymmetry signal, as well as the effect on the signal efficiency ε, defined as $\sigma_{\text{cuts}}/\sigma_{t\bar{t}}$. We study the cuts

$$\begin{aligned} R_1: &\quad |\eta_{1,2}| < 2.5\,, \\ R_2: &\quad |\eta_1| < 2.5 \text{ and } |\eta_2| < 4.5\,, \\ R_3: &\quad |\eta_1| < 2.5 \text{ and } 2.5 < |\eta_2| < 4.5\,, \\ M_1: &\quad m_{t\bar{t}} > 450\text{ GeV}\,, \\ M_2: &\quad m_{t\bar{t}} > 550\text{ GeV}\,, \end{aligned} \tag{4}$$

motivated by the ATLAS and CMS detector geometries and the CDF analysis. Table II shows the efficiencies, ε, and the generated charge asymmetries, A_c, for the SM and our three benchmark models in the hypothetical scenario in which the cuts in Eq. (4) could be imposed on the t and the $\bar{t}$ directly. Table III shows the more realistic and experimentally more relevant results, when the cuts are imposed on the observable decay products of the t and the $\bar{t}$ instead. For the semileptonically decaying top in the central region we only impose $|\eta| < 2.5$ on the lepton and the b-jet (and not on the neutrino). By the cuts R_1 and R_2 we now mean that each of the three jets from the hadronically decaying top quark must satisfy $|\eta| < 2.5$ and $|\eta| < 4.5$, respectively, but we impose no constraint on the pseudorapidity of the reconstructed top itself. For R_3 we keep the $|\eta| < 4.5$ selection criteria on the jets of the decay products of the hadronically decaying top quark, but we demand that the reconstructed top quark has $|\eta| > 2.5$. Note that we do not impose an upper bound on the reconstructed pseudorapidity of the hadronically decaying top, thus including some tops at $|\eta| > 4.5$, with decay products distributed across the beam axis from the direction of the top.

Cuts	SM MCFM	new physics models		
		Z'	Axigluon	Scalar **3**
R_1	$A_c = 0.011$	$A_c = 0.019$ $\varepsilon = 0.77$	$A_c = 0.025$ $\varepsilon = 0.78$	$A_c = 0.038$ $\varepsilon = 0.79$
R_2	$A_c = 0.018$	$A_c = 0.034$ $\varepsilon = 0.95$	$A_c = 0.031$ $\varepsilon = 0.94$	$A_c = 0.044$ $\varepsilon = 0.95$
R_3	$A_c = 0.028$	$A_c = 0.10$ $\varepsilon = 0.18$	$A_c = 0.058$ $\varepsilon = 0.17$	$A_c = 0.072$ $\varepsilon = 0.16$
R_1 & M_1	$A_c = 0.018$	$A_c = 0.038$ $\varepsilon = 0.44$	$A_c = 0.040$ $\varepsilon = 0.42$	$A_c = 0.059$ $\varepsilon = 0.48$
R_2 & M_1	$A_c = 0.021$	$A_c = 0.064$ $\varepsilon = 0.54$	$A_c = 0.046$ $\varepsilon = 0.50$	$A_c = 0.068$ $\varepsilon = 0.57$
R_3 & M_1	$A_c = 0.037$	$A_c = 0.18$ $\varepsilon = 0.10$	$A_c = 0.080$ $\varepsilon = 0.082$	$A_c = 0.12$ $\varepsilon = 0.087$
R_1 & M_2	$A_c = 0.022$	$A_c = 0.075$ $\varepsilon = 0.21$	$A_c = 0.061$ $\varepsilon = 0.19$	$A_c = 0.089$ $\varepsilon = 0.25$
R_2 & M_2	$A_c = 0.029$	$A_c = 0.12$ $\varepsilon = 0.27$	$A_c = 0.10$ $\varepsilon = 0.22$	$A_c = 0.10$ $\varepsilon = 0.29$
R_3 & M_2	$A_c = 0.041$	$A_c = 0.29$ $\varepsilon = 0.057$	$A_c = 0.10$ $\varepsilon = 0.036$	$A_c = 0.16$ $\varepsilon = 0.041$

TABLE II: Asymmetries and efficiencies resulting from the cuts defined in Eq. (4), applied at the $t\bar{t}$ level. The asymmetries for the NP models are calculated including both the SM and NP at leading order, to which the next-to-leading order SM results (in the second column) should be added to obtain the predictions for the observable asymmetries.

Cuts	SM MCFM	new physics models		
		Z'	Axigluon	Scalar **3**
R_1	$A_c = 0.014$	$A_c = 0.022$ $\varepsilon = 0.55$	$A_c = 0.032$ $\varepsilon = 0.56$	$A_c = 0.041$ $\varepsilon = 0.56$
R_2	$A_c = 0.019$	$A_c = 0.032$ $\varepsilon = 0.65$	$A_c = 0.033$ $\varepsilon = 0.65$	$A_c = 0.042$ $\varepsilon = 0.65$
R_3	$A_c = 0.020$	$A_c = 0.083$ $\varepsilon = 0.14$	$A_c = 0.048$ $\varepsilon = 0.14$	$A_c = 0.054$ $\varepsilon = 0.13$
R_1 & M_1	$A_c = 0.022$	$A_c = 0.049$ $\varepsilon = 0.30$	$A_c = 0.050$ $\varepsilon = 0.28$	$A_c = 0.062$ $\varepsilon = 0.33$
R_2 & M_1	$A_c = 0.023$	$A_c = 0.067$ $\varepsilon = 0.36$	$A_c = 0.051$ $\varepsilon = 0.33$	$A_c = 0.068$ $\varepsilon = 0.38$
R_3 & M_1	$A_c = 0.042$	$A_c = 0.18$ $\varepsilon = 0.072$	$A_c = 0.077$ $\varepsilon = 0.057$	$A_c = 0.099$ $\varepsilon = 0.060$
R_1 & M_2	$A_c = 0.025$	$A_c = 0.079$ $\varepsilon = 0.15$	$A_c = 0.070$ $\varepsilon = 0.13$	$A_c = 0.092$ $\varepsilon = 0.17$
R_2 & M_2	$A_c = 0.023$	$A_c = 0.12$ $\varepsilon = 0.18$	$A_c = 0.072$ $\varepsilon = 0.15$	$A_c = 0.10$ $\varepsilon = 0.20$
R_3 & M_2	$A_c = 0.044$	$A_c = 0.28$ $\varepsilon = 0.041$	$A_c = 0.092$ $\varepsilon = 0.026$	$A_c = 0.14$ $\varepsilon = 0.029$

TABLE III: Asymmetries and efficiencies resulting from applying the cuts in Eq. (4) to the partonic decay products of the $t\bar{t}$ pair, and also including the experimental cuts in Eq. (5). To get the total asymmetry, asymmetries should be added in the manner of Table II

In addition to these cuts, to obtain the results in Table III, we also imposed

$$\begin{aligned} p_T^{\rm jet} &> 25 \text{ GeV}, \\ p_T^{\ell} &> 20 \text{ GeV}, \\ E_T^{\nu} &> 25 \text{ GeV}, \end{aligned} \tag{5}$$

following similar selections in the ATLAS and CMS analyses. We expect the leading order MadGraph calculation to give a useful guide to the expected asymmetries and efficiencies in Tables II and III as a function of the kinematical cuts. As mentioned above, the predicted asymmetry is the sum of the SM and NP contributions in Tables II and III, to a very good approximation.

In Figures 1, 2, and 3, we plot the charge asymmetries and efficiencies in the three benchmark models, as functions of the lower cut on $m_{t\bar{t}}$. For no cut (that is, $m_{t\bar{t}}$ lower cut below $2m_t$), the cut at 450 GeV, and at 550 GeV, the plotted values reproduce those in Table III.

To assess the prospects for observing a given model for a given set of cuts, we need to make some assumptions on the achievable experimental uncertainties. From the CMS result [18] we assume that systematic uncertainties on A_c below ≈ 0.02 will be difficult to achieve in the near future. Therefore, we assume that, for a clear observation of the $t\bar{t}$ asymmetry, one is likely to need to choose cuts that increase A_c above 0.10 for a given model. We assume that the systematic uncertainties are the same for every cut, although in reality is should be somewhat larger at high jet η and large $m_{t\bar{t}}$. A more realistic assessment of systematic uncertainties will require a dedicated study with full detector simulations. Furthermore, based on the CMS analysis we assume that a statistical uncertainty of ≈ 0.13 is achievable with a dataset of 36 pb^{-1} for the cuts R_1, and that it will scale with the integrated luminosity. Taking into account the different relative acceptances between the cuts, this allows us to provide a rough estimate of how much data will be needed to observe a given model. Again, a full detector simulation will be needed to make a precise estimate of the expected statistical uncertainty for given cuts.

Referring to Table III, We note that simply using the basic set of cuts, R_1, will not be sufficient to obtain a clear signal of the asymmetry. Allowing or requesting tops with high pseudorapidity (cuts R_2 and R_3) increases the asymmetry for each model, but not to a level likely to be soon observable experimentally. By selecting events with $m_{t\bar{t}} > 550$ GeV for the basic set of cuts R_1 (R_1 & M_2), one can increase A_c to about 0.08, which should be enough to start seeing an evidence of a $t\bar{t}$ asymmetry in the near future, but which will probably require experimental systematic uncertainties to improve significantly to obtain a clear observation. By allowing jets of the hadronic top in the forward region and selecting

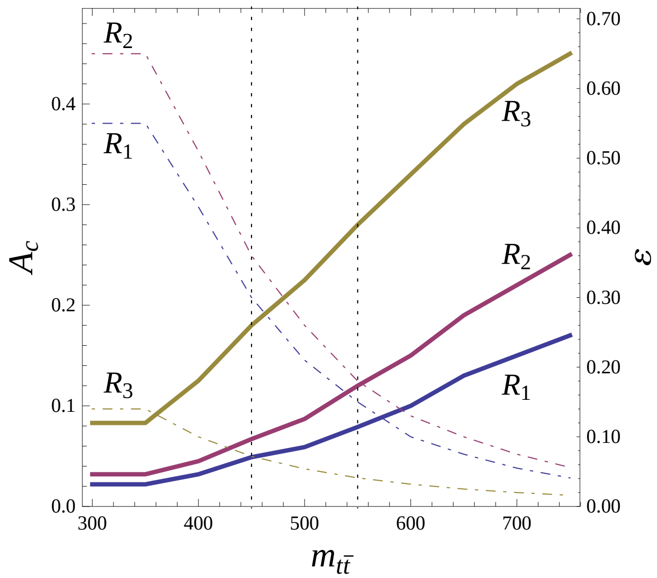

FIG. 1: Asymmetries (solid curves, legend on the left) and efficiencies (dashed curves, legend on the right) for the Z' model as a function of the lower cut on $m_{t\bar{t}}$. The curves are labelled as showing the effect of the mass cuts for R_1, R_2, and R_3 acceptances, respectively, and correspond to decayed tops, as in Table III. Vertical dotted lines indicate the mass cuts listed in Table III, with asymmetries/efficiencies for the cuts below $m_{t\bar{t}} = 2m_t$ remaining constant.

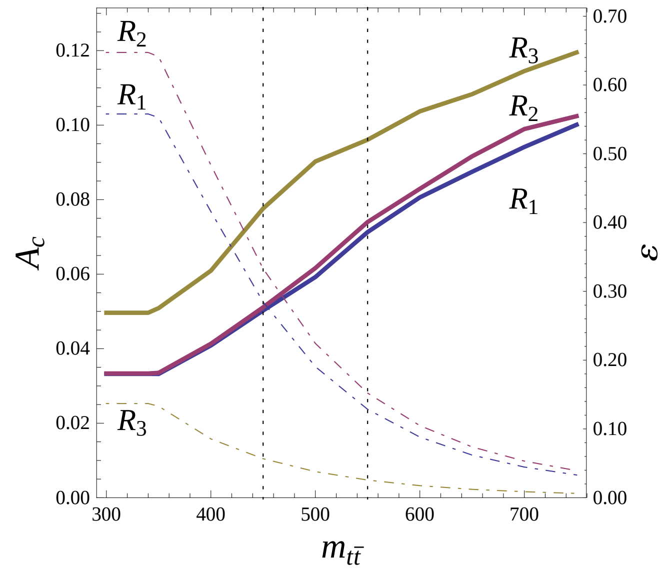

FIG. 2: Asymmetries and efficiencies for the axigluon model, as a function of $m_{t\bar{t}}$. The notations are as in Fig. 1.

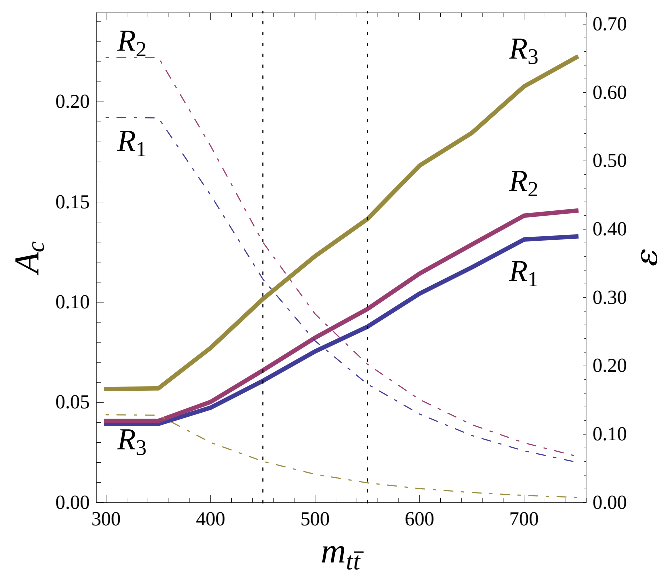

FIG. 3: Asymmetries and efficiencies for the scalar triplet model, as a function of $m_{t\bar{t}}$. The notations are as in Fig. 1.

events with $m_{t\bar{t}} > 550$ GeV (R_2 & M_2), one can increase A_c to above 0.10 in the Z' and scalar triplet models. The acceptance is reduced by a factor ≈ 3 compared to the basic cuts R_1, which results in statistical uncertainties of order 0.02 for a dataset of 5 fb^{-1} using the assumptions above. The asymmetry can be substantially increased by requesting that the hadronically decaying top has $|\eta| > 2.5$, but by paying the price of a significantly reduced acceptance. This R_3 cut increases the asymmetries by a factor of about 2 and 1.5 for the Z' and scalar triplet models, respectively. For example, the Z' model, for which A_c approaches 0.3 for the cut R_3 & M_2, should be clearly observable for datasets of 5 fb^{-1}, for which a statistical uncertainty of roughly 0.04 would be achievable with the assumptions described above. The increase is also present but not as significant for the axigluon model.

This by itself provides a strong motivation for studying the behavior of A_c as a function of the top pseudorapidity. Moreover, especially in concert with cuts on $m_{t\bar{t}}$, considering changes in A_c for varying top pseudorapidity acceptances allows for differentiation between the various proposed models from their qualitatively different behavior. For example, the increase in A_c for the axigluon comes almost entirely from the $m_{t\bar{t}}$ cuts, as can be seen from the nearly degenerate R_1 and R_2 lines in Fig. 2. On the other hand, for the Z' and the triplet, both the loosening of geometric cuts and the $m_{t\bar{t}}$ cut help in significantly increasing the asymmetry, with the geometric cuts being more significant for the Z' model. Larger datasets will be needed to unambiguously distinguish the various models, rather than merely detect the asymmetry. More complex information contained in the kinematic distributions, such as spin correlations [35], may also increase the discriminating power between models.

One concern about requiring the t or the $\bar{t}$ to be produced at higher pseudorapidities is that the resulting decay products may be too highly boosted to be effectively separated. Furthermore, a boosted top analysis might be complicated by the fact that the detector granularity worsens in the forward region of the ATLAS and CMS calorimeters. Imposing the condition that all three jets from the top with $|\eta| > 2.5$ be separated by $R > 0.4$ [0.6], we find that the fraction of events failing to meet this condition is below 11% [25%] for the R_3 & M_2 cuts, and is more typically $\mathcal{O}(5\%)$ [$\mathcal{O}(15\%)$]. If one only imposes the condition that at least two of the three jets are separated by $R > 0.4$ [0.6], and assumes the feasibility of an analysis that selects only two jets for the hadronically decaying top, with one of them at high mass due to the merged hadronically decaying W boson, then the fraction of events failing the cut is $\mathcal{O}(0.1\%)$ [$\mathcal{O}(1\%)$]. Therefore, we conclude that the experimental challenges created by the increased amount of boosted tops at high η and $m_{t\bar{t}}$ are likely to be surmountable.

We note that more complex analysis techniques, beyond our simple analysis, could increase the significance of a putative signal. A fully systematic survey consisting of a larger number of geometric cuts and their combinations, which has not been carried out herein, could be explored in order to optimize the sensitivity to a charge asymmetry.

IV. CONCLUSIONS

In conclusion, we explored the sensitivity to a class of new physics models, motivated by the Tevatron forward-backward asymmetry in $t\bar{t}$ production, that could be gained by ATLAS and CMS if the pseudorapidity ranges for $t\bar{t}$ reconstruction could be extended. We found that a combination of cuts based on pseudorapidities and invariant masses of the reconstructed tops in $t\bar{t}$ events greatly enhances the experimental sensitivity compared to just using one of these cuts. While it is clear that one of the tops that decays semileptonically and thus tags the flavor has to be in the central region, $|\eta| < 2.5$, our study shows that it would clearly be worthwhile to explore if the other one could be reconstructed at higher $|\eta|$, in its decay to jets. From our main results in Table III and in the figures, one clearly sees that if the R_3 selection cut (or something similar) becomes experimentally feasible at ATLAS and/or CMS, that would substantially enhance the sensitivity to new physics, and allow better discrimination between different models.

Acknowledgments

We thank Jernej Kamenik, Gilad Perez, and especially Martin Schmaltz for helpful conversations, and Johan Alwall and Tim Tait for help with MadGraph. Z.L. thanks the Aspen Center for Physics for hospitality while parts of this work were completed. This work was supported in part by the Director, Office of Science, Office of High Energy Physics of the U.S. Department of Energy under contract DE-AC02-05CH11231.

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