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# LHC Charge Asymmetry as Constraint on Models for the Tevatron Top Anomaly

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## Abstract

The forward-backward asymmetry  $A_{FB}^{t\bar{t}}$  in top quark production at the Tevatron has been observed to be anomalously large by both CDF and D0. It has been suggested that a model with a  $W'$  coupling to  $td$  and  $ub$  might explain this anomaly, and other anomalies in  $B$  mesons. Single-top-quark production in this model is large, and arguably in conflict with Tevatron measurements. However the model might still be viable if  $A_{FB}^{t\bar{t}}$  is somewhat smaller than its current measured central value. We show that even with smaller couplings, the model can be discovered (or strongly excluded) at the LHC using the 2010 data sets. We find that a suitable charge-asymmetry measurement is a powerful tool that can be used to constrain this and other sources of anomalous single-top production, and perhaps other new high-energy charge-asymmetric processes.

The forward-backward asymmetry in top quark pair-production has been measured by CDF and D0 to be anomalously large [1, 2, 3]. It seems difficult to explain the size and nature of the asymmetry using Standard Model physics, Monte Carlo subtleties, or experimental difficulties. Various models of new physics have been proposed, in which a new particle contributes to  $t\bar{t}$  production. Most of these have problems with fitting other data. For instance, the insertion of a  $Z'$  that couples to  $u$  and  $t$  quarks, allowing for  $u\bar{u} \rightarrow t\bar{t}$ , creates a large rate for  $uu \rightarrow tt$ . This is especially true at the LHC, where both the  $u$  quarks are valence quarks. The corresponding signal of two same-sign leptons has hardly any Standard Model background and is easily excluded for a  $Z'$  of the required mass [4, 5].<sup>1</sup>

One model recently proposed by Shelton and Zurek [7] involves a similar structure, but with a  $W'$  exchange. The  $W'$  considered is called “maximally flavor violating” — one might rather say “maximally generationally violating” — in that it couples right-handed quarks  $u$  to  $b$ , and also  $t$  to  $d$ , with all other couplings strongly suppressed to avoid new sources of flavor-changing neutral currents.<sup>2</sup> The  $W'$  is imagined to be of order 600 GeV, with the  $Z'$  considerably heavier to be consistent with precision electroweak measurements. Note the  $Z'$  has little or no flavor-changing couplings and does not contribute to low-background observables at the Tevatron or LHC. The  $W'td$  coupling is necessary to explain the  $t\bar{t}$  asymmetry. But the authors of [7] suggest further that a  $W'ub$  coupling could explain (at least) several anomalies in the  $B$  meson system: the D0 measurement of the like-sign dimuon charge asymmetry in semileptonic  $b$  decays [11]; the deviation of  $B_s - \bar{B}_s$  mixing from Standard Model predictions in measurements of  $\Delta\Gamma_s$  and  $S_{\psi\phi}$  by both D0 [12] and CDF [13]; and indications of new CP violation in the  $B_d$  system in  $B_d \rightarrow \psi K_s$  [14, 15] and  $B_d \rightarrow (\phi, \eta', \pi, \rho, \omega) K_s$  [16].

However, in the presence of a  $W'ub$  coupling with the same strength as a  $W'td$  coupling, the same logic that limits a  $Z'ut$  coupling potentially applies to a  $W'$ . A new source of single-top quark production, through the processes  $ub \rightarrow td$  and  $ud \rightarrow tb$  (and their conjugates), becomes possible via  $W'$  exchange. The  $t$ -channel  $W'$  exchange process,  $ud \rightarrow tb$ , can proceed from a color-octet initial state and can be large at the Tevatron, even for a heavy  $W'$ . At the LHC, meanwhile, this process is enormous, due to the fact that both quarks in the initial state are from valence distributions. Meanwhile the huge gluon flux at small  $x$  and the accessibility of the  $W'$  resonance means that the color-singlet  $s$ -channel process  $ub \rightarrow td$  is also quite large at the LHC.

Despite this large cross-section, the final state contains only one lepton, and is not as distinctive as the same-sign dileptons arising in the  $uu \rightarrow tt$  case. There are therefore large backgrounds from  $W$ -plus-jets and from  $t\bar{t}$ .

What makes this signal extraordinary — also true of the  $uu \rightarrow tt$  signal in the  $Z'ut$  model — is its charge asymmetry at the LHC. In comparison to single-top production in the Standard Model, which already has substantial asymmetries (a forward-backward asymmetry at the Tevatron and a roughly 2:1 charge asymmetry at the 7 TeV LHC), single top

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<sup>1</sup>Note that these limits may be mitigated in  $Z'$  models arising from gauged flavor symmetries, as in [6].

<sup>2</sup>Various  $W'$  proposals for explaining the forward-backward asymmetry involving a  $W'td$  coupling but no  $W'ub$  coupling were considered previously in [8, 9, 10, 5].

production in the  $W'$  model has an LHC charge asymmetry of order 16:1. This can be put to use, applying a variant of the simple but powerful method that was suggested by Bowen [17] (following [18]) for measuring single top in the Standard Model (SM) at the LHC.

The use of charge asymmetries at  $pp$  colliders has been discussed actively in the past. Examples have appeared in the literature on supersymmetry, which can give observable asymmetric signals; see for example [19]. The use of charge asymmetries in SM single top searches was suggested in [20] at the UNK collider, prior to the independent work of [17] for the LHC. The need to apply charge asymmetries systematically for new physics searches has been argued for by one of us [21], and independently by Stirling and Kom [22], who have performed a serious investigation of SM backgrounds. The current discussion of new models to explain the forward-backward top asymmetry at the Tevatron now provides us a first opportunity to put these variables in play at the LHC.

The rate for single-top production in the  $W'$  model depends on the  $W'$  mass  $M_{W'}$  and its coupling  $g_R$  to  $td$  and  $ub$ . In [7] the preferred  $W'$  mass was about 600 GeV and the coupling  $g_R$  was preferred in the range 1.5 to 2, following [9]. We will take the coupling  $g_R = 1.5$  and  $M_{W'} = 600$  GeV as the “fiducial values” for the parameters, and call this the “fiducial point” in parameter space.

Before exploring the signal at the LHC, let us first consider it at the Tevatron. At the fiducial point, we find that single-top production at the Tevatron is increased, relative to the Standard Model, by a factor of 2, most of it in the  $t$  channel. (Note there is no interference with standard model single-top production, which has a final state antiquark.) Here we are taking the leading-order new-physics result and comparing it to the next-to-leading-order (NLO) Standard Model single-top cross-section; the  $K$  factor for the new physics is likely above 1, so we are probably conservative by taking it to be  $\sim 1$ . If  $g_R$  were 2, the rate for single-top production would grow to 5 times the SM prediction. Uncertainties on the measured cross-section at CDF and D0 are relatively small, of order 25% of the Standard Model cross-section,  $\sigma^{\text{theory}} \sim 2.9$  pb [23, 24]. We therefore believe that  $g_R \sim 2$  is already strongly excluded, and 1.5 is considerably disfavored.

Yet the situation is difficult to interpret just with cross-sections, because the single top signal at the Tevatron is extracted using a complex multivariate analysis from a very large background, assuming the shape of the signal is that of the SM. The addition of the new single-top signal from  $ud \rightarrow tb$  and its conjugate to the SM processes will change that shape, so the analysis must be repeated by those who performed it originally.

That said, it seems likely that the model at its fiducial point would already have revealed itself through a single-top excess at the Tevatron. But the fiducial values of the parameters were chosen in [7, 9] to fit the central value of the CDF measurement of  $A_{FB}^{t\bar{t}}$ , which is very large, but has a large statistical error bar. For the usual reasons, it may be expected that the true value of  $A_{FB}^{t\bar{t}}$  is lower than the current central value. The  $W'$  model might then survive, and still explain the  $A_{FB}^{t\bar{t}}$  data, with a slightly larger mass and/or smaller coupling constant. Moreover, since the effect on  $A_{FB}^{t\bar{t}}$  is through interference, while the single-top measurement is the square of a non-interfering amplitude, a reduction in the asymmetry by a factor  $z$  is

accompanied by a reduction in  $t$ -channel single-top production by roughly a factor of  $z^2$ .

Furthermore, as a sociological statement, one might note that single-top production was predicted with precision in the SM well in advance of its observation at the Tevatron, and thus there is no truly unbiased measurement of this process. The measurement is complicated, and hard to check by eye in a single plot. We might wish to remain a bit cautious until the results are confirmed by an entirely different technique.

Therefore, while we would view the  $W'$  model as disfavored somewhat, it does not seem to us to be obviously excluded. A much more detailed Tevatron study would be needed, and arguments might still ensue as to the limits obtained.

However, at the LHC it seems possible to discover or exclude the model more cleanly, using only the existing 2010 data sets of  $\sim 35$  inverse pb per experiment. We will argue below that the charge asymmetry in a sample consisting of a single lepton, a small amount of missing transverse momentum ( $\cancel{E}_T$ , or MET), and at least two jets is already sensitive to signals of this type. Application of simple kinematic cuts and/or heavy-flavor tagging permits an excess charge asymmetry to be observed even for a signal much smaller than arises in the fiducial case. This in turn means that the coupling and mass of the  $W'$  can be strongly constrained by this measurement.

For the fiducial point, we find that the LO production cross-section  $\sigma_t^{(0)}$  for single top quarks from  $W'$  exchange is 220 pb. About two-thirds of the cross-section comes from  $t$ -channel  $W'$  exchange, through  $ud \rightarrow tb$  and its conjugate, and has a 20:1 charge asymmetry. The remainder goes through  $ub \rightarrow td$ , through the  $W'$  in the  $s$ -channel.<sup>3</sup> This channel has a charge asymmetry of order 10:1. There will be considerable corrections to these LO results, but we do not believe there will be significant reductions. There is also an interesting  $tW'$  process, but it is too small to affect our discussion.

We are going to show that even a fraction of these LO cross-sections can easily be observed relative to NLO-rescaled backgrounds. Since we do not know the NLO correction to the LO estimate, and the parameters need not be at the fiducial point, we define for convenience  $F_S \equiv \sigma_t^{true}/\sigma_t^{(0)}$  to be the appropriate normalization constant. For the most part we do not expect enormous differences in shapes as parameters vary or due to NLO corrections; in any case these could be computed in the future. Initial state radiation (ISR) can have an effect on some distributions, and we will account for that as appropriate. The largest shape variation will occur if  $M_{W'}$  is much above 600 GeV; the  $s$ -channel process, which is subdominant anyway, will be reduced the most, though this will be somewhat compensated by its higher-energy kinematic distribution.

Even without using the charge asymmetry, there is good reason to think that public results from the LHC already exclude the  $W'$  model at the fiducial point. Distributions of the total numbers of events with a lepton, MET and three or more jets, versus an effective

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<sup>3</sup>The  $W'$  resonance has a width of order 100 GeV, and may even be wider if the  $W'$  has other decay modes not included in the minimal model. The resonance might be reconstructable if the width is small enough, but since the width is model-dependent, we will not rely upon it below. Clearly, if a signal is observed, an attempt should be made to search for the resonance in  $t$ -plus-jet.

mass variable  $m_{\text{eff}}$  (the scalar sum of the  $p_T$  of the three leading jets) , have been shown in a recent supersymmetry search by ATLAS [25].<sup>4</sup> The signal region of this supersymmetry search requires large MET and large transverse mass. Our signal has a tail out to large MET, but this comes from a  $W$  decay, so it has low transverse mass, and relatively little will appear in the ATLAS signal region. However, control samples for this search, with low MET and low transverse mass, and with either zero or  $\geq 1$   $b$  tags, have been shown [26]. These have an event selection that would be somewhat sensitive to this signal.

The signal is so large, and extends to such large values of  $H_T^{\ell\nu jj}$ , that it seems at first obvious that  $F_S = 1$  is already excluded by the paucity of events at high  $H_T$  in the control regions of the ATLAS search. More study reveals that the exclusion is probable but not overwhelming. The restriction to a low range of MET ( $30 < \cancel{E}_T < 80$  GeV) eliminates of order half our signal, and also pulls down the  $H_T^{\ell\nu jj}$  distribution, reducing the tail at high values. The requirement of a third jet removes quite a bit of signal as well. A rough estimate suggests that at  $F_S = 1$  the new single-top signal would produce about 10 events above  $m_{\text{eff}} = 800$  GeV in the zero-tag control sample (called the “ $W$  region”). But the sample shows no events. Still, we remain cautious, because extracting a quantitative limit would require more details of how the control samples were obtained and normalized, and more information about relevant efficiencies. In any case, it does seem likely that  $F_S = 1$  is excluded, as at the Tevatron, but  $F_S \sim 0.25$  may well not yet be excluded. As we have noted, this and even lower values are still potentially interesting for the  $A_{FB}^{t\bar{t}}$  anomaly.

We should note that our signal might show up more strikingly in the ATLAS control sample with high MET and low transverse mass. Unfortunately the plot for this control region was not shown in public.

It is our view that the use of a charge asymmetry, considered as a function of a variable such as  $m_{\text{eff}}$ , with no upper restriction on the MET, and with no requirement of a third jet, would be efficient for signal and allow for a much more powerful and convincing exclusion of the model even if  $F_S = 0.25$ . In particular, any excess at high  $m_{\text{eff}}$ , if this or any similar model is correct, should be almost exclusively in positively charged leptons. To this end, it would be very useful for excluding new types of physics if the full set of control samples of [25], separated into subsamples with positively and negatively charged leptons, would be made public.

Let us now turn to the relevant studies of charge asymmetries. To measure a charge asymmetry in a sample of events with one lepton is straightforward. Let  $N_{\pm}$  to be the number of events in the sample with an  $\ell^{\pm}$ , and let  $N_{\text{tot}} = N_+ + N_-$  and  $\Delta = N_+ - N_-$ . Then the charge asymmetry is  $A_C = \Delta/N_{\text{tot}}$ .

In 2005, Bowen [17], inspired by the forward-backward asymmetry techniques used in single-top measurements at the Tevatron [18, 27, 28], showed that charge asymmetries are useful in extracting information about single-top production at the LHC. He noted that in a 14 TeV LHC event sample consisting of a lepton of moderate  $p_T$ , moderate MET, and two

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<sup>4</sup>We thank J. Ruderman, D. Shih and N. Toro for suggesting this study might be relevant for us.

or more jets, one of which is  $b$  tagged, the dominant contribution to the sample is from  $t\bar{t}$ , which is nearly charge-symmetric. At NLO  $t\bar{t}$  production picks up a small negative charge asymmetry (found in [29] to be no larger in magnitude than  $\sim 2\%$ ) in a subtle way: it arises from the intrinsic forward-backward asymmetry in  $q\bar{q} \rightarrow t\bar{t}$ , which puts the distribution of  $\ell^+$  at higher  $|\eta|$  than that of  $\ell^-$ . A small fraction of the  $\ell^+$  events are then lost due to the geometric acceptance of the detector.<sup>5</sup> Meanwhile, the largest contribution to a charge asymmetry in this sample is from  $t$ -channel single top, with  $W$ -plus-jets contributions coming a bit behind. The reason  $W$ -plus-jets is so small is that  $b$ -tagging is effective at rejecting it, combined with the fact that events with charm jets actually have a negative asymmetry that cancels off part of the positive asymmetry from the other processes.

We first repeat this analysis at 7 TeV, accounting also for the new contribution from the  $W'$ . In the first numerical column of Table 2 we show our estimates of cross-sections with the event preselection cuts shown in Table 1; note we also veto on a second isolated lepton. (We will describe the methods used for event simulation later.)  $W$ -plus-jets (the majority of which is  $Wqg$ ) dominates the sample.

Item	$p_T$	$ \eta $
isolated $l^\pm$	$\geq 20$ GeV	$\leq 2.1$
MET (from $\nu$ )	$\geq 20$ GeV	-
at least two jets	$\geq 30$ GeV	$\leq 3.0$

Table 1: The preselection cuts for our samples. For current LHC data sets there is no problem with triggering or reconstruction at these values, but as we will see these cuts could be raised if necessary.

In [17] the next and final stage was to apply a heavy-flavor tag to at least one jet. In this approach the key is to reduce  $W$ -plus-jets as much as possible, and so one should apply a very tight tag, with a very low mistag rate. Let us get a feel for things by first considering the effect of a heavy-flavor tag with a very optimistic tagging rate. (This would be appropriate for any attempt to measure the SM single top contribution to the sample, since the required statistics would be very large, by which point tagging would be well-optimized. It will not be appropriate for discussion of the 2010 data sample.) The numbers in the second numerical column of Table 2 reflect a rough estimate of the cross-sections at the 7 TeV LHC that would result from a 70%  $b$ -tag efficiency, a 15%  $c$ -tag efficiency (conservatively low, since  $c$  quarks appear in the  $W$ -plus-jets background with a *negative* charge asymmetry), a 1% efficiency for mistagging light-quark jets, and a 3% efficiency for  $g$  jets (accounting both for mistagging and for heavy-flavor tagging following  $g \rightarrow c\bar{c}$  or  $g \rightarrow b\bar{b}$  splitting.) The reader may rescale

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<sup>5</sup>Since CDF and D0 find that  $A_{FB}^{t\bar{t}}$  is large, this small asymmetry may be enhanced; certainly this would be the case in the  $W'$  model under consideration. But because it arises from the subdominant  $q\bar{q}$  initial states, it remains small. In addition it has a negative sign, opposite to our signal, so we are conservative in neglecting it here. It can presumably be estimated, or bounded in absolute value, in data, using fully reconstructed  $t\bar{t}$  events.

the numbers in Table 2 as desired. At this stage the  $W$ -plus-jet sample is as important as the SM single-top sample, and the total asymmetry is small, just a few percent. At the fiducial point, the  $W'$  model would dramatically increase the asymmetry, and dominate it even for  $F_S = 0.25$ . Without the new signal, the SM asymmetry would be about 4.5%. In its presence, this would become 14.5%. Given that the sample has more than 2000 events, this is a signal of more than  $4\sigma$ .

However, this is highly optimistic, especially in 2010. First, we have not even accounted correctly here for geometric acceptance; tagging rates drop off to zero at  $|\eta| = 2.5$ , and the rapidity distribution of the signal's jets is quite wide. More realistic heavy-flavor tagging and mistagging rates, and proper treatment of their  $p_T$  and  $\eta$  dependence, would reduce the significance. Mistagging is likely to be worse than we assumed here, especially in the presence of additional radiated jets, and tagging efficiency is likely to be worse, especially for the  $t$ -channel signal whose primary  $b$  jet is often at quite high  $p_T$ . And the most serious problem could be the systematic error that comes from a lack of knowledge of the tagging and mistagging rates at high  $p_T$ .

Process	Preselection	Tag only	$H_T^{\ell\nu jj} > 350$ GeV only	$H_T^{\ell\nu jj} > 550$ GeV only
$W^+ jj$	130	4.9	15	2.5
$W^- jj$	71	2.6	6.5	1.1
$W^+ cj, W^+ c\bar{c}$	18	2.7	1.5	0.11
$W^- cj, W^- c\bar{c}$	24	3.6	2.2	0.41
$W^+ bb$	0.44	0.40	0.045	0.009
$W^- bb$	0.26	0.24	0.017	0.003
SM NLO $tb, tq, tbq$	3.5	2.5	0.36	0.050
SM NLO $\bar{t}b, \bar{t}q, \bar{t}bq$	2.0	1.4	0.13	0.014
SM NLO $t\bar{t} \rightarrow \ell^+$	22	20	5.1	0.67
SM NLO $t\bar{t} \rightarrow \ell^-$	22	20	5.1	0.67
New LO $td$	12	8.4	8.2	2.1
New LO $\bar{t}\bar{d}$	0.90	0.63	0.61	0.15
New LO $tb$	24	21	16.3	9.4
New LO $\bar{t}\bar{b}$	1.2	1.1	0.82	0.26

Table 2: Cross-sections for SM backgrounds and  $W'$ -model signals in picobarns. Results after preselection (see Table 1), after applying a heavy-flavor tag requirement along the lines of [17] (a rough and optimistic estimate, with no  $p_T$  or  $\eta$  dependence), and after applying cuts on  $H_T^{\ell\nu jj}$  (with no heavy-flavor tag) are shown. Details of the Monte Carlo simulation can be found in the main text.

Still, the basic observation seems robust. It seems likely that  $F_S = 0.25$ , and perhaps beyond, could be excluded through the simple technique of [17].



Because of the uncertainties surrounding the effectiveness of tagging, we now consider an alternative and complementary approach, in which we omit tagging and do a kinematic cut instead. We will consider the variable

$$H_T^{\ell\nu jj} = p_T^\ell + p_T^{j,1} + p_T^{j,2} + \cancel{E}_T \quad (1)$$

where  $p_T^{j,n}$  is the transverse momentum of the  $n^{\text{th}}$ -hardest jet,  $\cancel{E}_T$  is the missing transverse momentum in the event, and the sum is a scalar sum of transverse momenta. We will start by requiring  $H_T^{\ell\nu jj} > 350$  GeV (but *without* applying a heavy-flavor tag). This gives the numbers in the third numerical column of Table 2.

For this variable to be properly modeled, it is important that the first and second jet be simulated correctly. In both signal and  $t\bar{t}$ , there are jets from  $t$  decays that have relatively low  $p_T$ , and ISR may easily give a jet that is at higher  $p_T$ . In order to account for the additional jets, we have generated a matched  $t\bar{t}$  sample with up to one additional jet using MadEvent [30] with the implemented MLM matching and the `xqcut` variable set to 20 GeV. We then passed the events through PYTHIA [31] for resonance decays (including tops), showering and hadronization. Jets and geometric acceptance were accounted for using PGS [32] with the CMS parameter set and  $\Delta R = 0.4$  cone jets. There are large error bars associated with the use of this simulation tool, but we believe they are no worse than other uncertainties that we are dealing with. The total  $t\bar{t}$  cross section was normalized to the NLO result [33] from MCFM [34]. The signal was simulated using the `usrmod` functionality in MadGraph and run through PYTHIA and PGS in the same way.

For the  $W$ -plus-jets background we have been less careful, and have performed only a parton level analysis, as the two leading jets are simulated reasonably well in a  $W$ -plus-two-partons simulation. We included the effects of off-diagonal CKM matrix elements, as this has a significant effect on  $c$  quark production. We have used these LO distributions to obtain the relative efficiencies of our kinematic cuts on the  $W$ -plus-jets sample. This has known pitfalls, because tails in distributions in variables such as  $H_T^{\ell\nu jj}$  may be larger after NLO corrections. In a moment we will account for the unknown normalization in the  $W$ -plus-jets contribution by rescaling it by a constant that can be extracted from the data. However, the NLO effect on the charge asymmetry is not expected to be large, so we take the LO result for the charge asymmetry after the kinematic cut as our best estimate.

The efficiency of SM single top under the  $H_T^{\ell\nu jj}$  cut has also been treated at LO parton-level, with the overall rates rescaled to match the NLO cross section at 7 TeV [35, 36]. Relative to the large new signals, this process is too small to influence our results.

Despite the large uncertainties in the  $W$ -plus-jets normalization, the numbers in the last column of Table 2 already show that the asymmetry in the SM and in the presence of the fiducial signal are very different. Even if we have underestimated the  $W$ -plus-jets background by a factor of 4, the SM asymmetry is at about 32% with a statistical uncertainty of about 1.7%, whereas in the presence of the fiducial signal it is at 43%, or  $7\sigma$  away from the SM expectation. We will see in a moment that we have statistical sensitivity down to and potentially below  $F_S = 0.25$ .

Systematic errors other than the overall normalization of the  $W$ -plus-jets contribution may be very important. These may arise from many sources, including the top quark cross-section (which depends on the top quark mass and also has NNLO corrections), the uncertainty in the  $W$ -plus-jets asymmetry at NLO (which is believed to be small — see for example [22]), and the small top-quark charge asymmetry discussed earlier. There are also uncertainties in the signal, as we have not used an NLO cross-section. However, to the extent our preselection efficiencies and that of the  $H_T^{\ell\nu jj}$  cut do not change too much at NLO, one can compensate for this effect by rescaling the overall  $W'$  coupling, which is directly absorbed into  $F_S$ .

Certainly the largest uncertainty comes from normalizing the  $W$ -plus-jets background subject to our simulation method and cuts. We do not trust the normalization of our  $W$ -plus-jets sample, and suspect it is significantly underestimated. Therefore we will multiply the  $W$ -plus-jets background by a fudge factor  $F_W$ , which we will imagine extracting from the data. We may then consider the observed asymmetry, and the observed cross-section of our sample  $\sigma_{tot}$  after our cuts, as a function of the two most important unknowns  $F_W$  and  $F_S$ . The observed cross-section of the sample is quite sensitive to  $F_W$ . By measuring both  $\sigma_{tot}$  and  $A_C$ , we can disambiguate, to a large extent, the effect of  $F_W$  and that of  $F_S$ .

In Figure 1 we show  $A_C$  versus the total cross section  $\sigma_{tot} = N_{tot}/(35 \text{ pb}^{-1})$  for the SM (solid line,  $F_S = 0$ ), plotted from  $F_W = 0.5$  (at left) to  $F_W = 4$  (at right). We have also done so for the SM plus the fiducial signal ( $F_S = 1$ ), the top (dashed) curve, and for a reasonable target limit of  $F_S = 0.25$ , the middle (dash-dotted) curve. For the SM and  $F_W = 0.5, 1, 2, 4$ , we also show *three-sigma* statistical error-ellipses corresponding to the statistical errors in  $A_C$  and in  $\sigma_{tot} \times 35 \text{ pb}^{-1}$ , ignoring correlations as well as non-linearities in the  $A_C$  uncertainties. Clearly there is excellent statistical separation everywhere except where  $F_S$  approaches 0.25 and  $F_W$  approaches 4. Reaching this level of sensitivity requires reducing the other systematic errors. The ongoing measurements of the  $t\bar{t}$  cross-section will help pin down the normalization of  $t\bar{t}$  needed here. Other measurements, such as the cross-section and asymmetry in our preselection sample, for which (at  $F_S = 0.25$ ) our signal makes no significant contribution, can help determine the  $W$ -plus-jets cross-section given our  $H_T$  cut. In particular, it may be important to provide a bound from above on  $F_W$ , using other measurements and theory.

So far we have taken an approach that tries to maximize the size of the sample and minimizes our errors in understanding tails of distributions. Does it make sense to be more aggressive with the  $H_T^{\ell\nu jj}$  cut? We will see that we get only slightly better statistical sensitivity, and there is a greater risk of systematic errors in the efficiency of the cut. But there may still be benefits.

In the final column of Table 2 we repeat the previous exercise while requiring  $H_T^{\ell\nu jj} > 550$  GeV. Note that the composition of the sample has significantly changed. The  $t\bar{t}$  fraction is reduced, due presumably to the fall in the  $gg$  parton luminosity. The corresponding plot of  $A_C$  versus  $\sigma_{tot}$  is given in Figure 2. Again we allow  $F_W$  to vary up to 4; note that the appropriate value of  $F_W$  for this figure will not be equal to that for the previous figure, as the

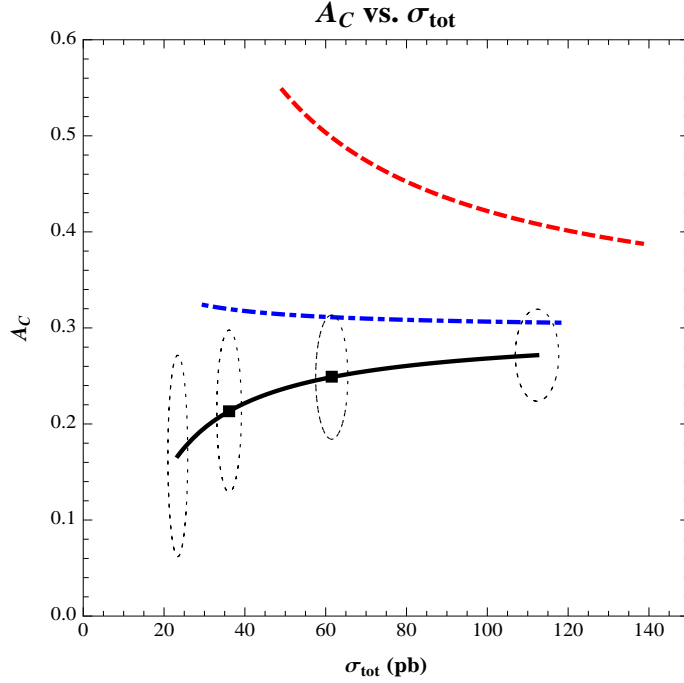


Figure 1: We plot  $A_C$  vs  $\sigma_{tot}$  in three cases: the SM ( $F_S = 0$ , lower solid curve), the SM plus 1/4 the fiducial signal ( $F_S = 0.25$ , middle dot-dashed curve) and SM plus the fiducial signal ( $F_S = 1$ , top dashed curve.) (By the fiducial signal we mean the signal at  $g_R = 1.5$  and  $M_{W'} = 600$  GeV.) Curves run from  $F_W = 0.5$  at left to  $F_W = 4$  at right, where  $F_W$  is the fudge factor for the  $W$ -plus-jets normalization. Ellipses showing an estimate of  $3\sigma$  statistical uncertainties at  $35 \text{ pb}^{-1}$  are shown for the SM and  $F_W = 0.5, 1, 2, 4$ . Strong statistical separation is seen even for  $F_S = 0.25$ , unless  $F_W$  is very large.

error in our estimate of  $W$ -plus-jets will vary with the kinematic cuts. We see for  $F_S = 0.25$ , statistical power improves for small  $F_W$ , though not for  $F_W \rightarrow 4$ .

Since even  $t\bar{t}$  is well out on its high-momentum tail, we should worry about how uncertain is the efficiency of our kinematic cut. Though we use a  $t\bar{t}(j)$  matched sample passed through PYTHIA to help us model that tail, still one must not take our numbers for the  $t\bar{t}$  background too seriously. But here heavy-flavor tagging becomes useful.

The first point is that the SM in this range produces a charge asymmetry that comes dominantly from a contribution that is  $b$ -poor. Meanwhile the SM plus the  $F_S = 0.25$  signal produces a slightly larger asymmetry due to a  $b$ -rich contribution. Therefore, when a heavy-flavor tag is applied, the asymmetry will generally *decrease* significantly if  $F_S = 0$  (pure SM), and *increase* if  $F_S = 0.25$ . Moreover, especially at large  $F_W$  where separation of signal and background is worst before tagging, the reduction in  $\sigma_{tot}$  after tagging is much greater in the SM than in the presence of an  $F_S = 0.25$  signal. Neither of these statements is true for the  $H_T^{\ell\nu jj} > 350$  GeV sample, because there is too much  $t\bar{t}$  left after tagging, which dilutes the asymmetry of the signal and contributes significantly to  $\sigma_{tot}$ .

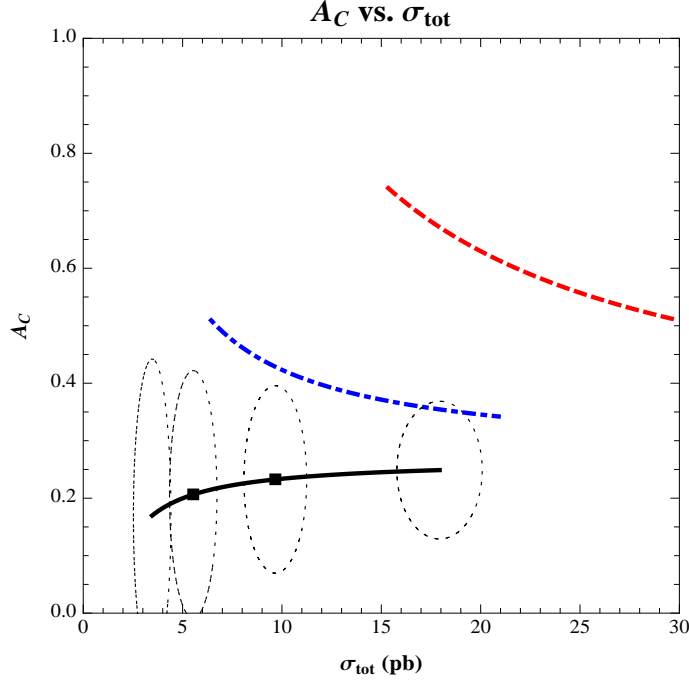


Figure 2: As in Figure 1, but with  $H_T^{\ell\nu jj} > 550$  GeV, and plotted from  $F_W = 0.5$  at left to  $F_W = 4$ . Ellipses showing an estimate of  $3\sigma$  statistical uncertainties are shown for the SM and  $F_W = 0.5, 1, 2, 4$ .

The asymmetry and cross-section after a single tag is required are somewhat sensitive to the amount of  $t\bar{t}$  remaining in the sample. But the  $t\bar{t}$  fraction can be estimated (or at least bounded from above) by also considering the sample with two tags. Double-tagging will completely remove  $W$ -plus-jets and leave a combination of  $t\bar{t}$  and some remaining  $t$ -channel signal. The asymmetry and cross-section can again be measured, constraining the  $t\bar{t}$  fraction independently.

Whether these methods allow any improvement in the statistical significance of the measurement is very sensitive to the details of the heavy-flavor-tagging technique. Many such techniques could be imagined. For instance, for the single-tag sample, one might tag only the two hardest jets, which would reduce  $t\bar{t}$  and avoid overly large mistag rates in  $W$ -plus-jets. Its efficiency for signal would need study. Alternatively, one might only apply tagging to the second-highest- $p_T$  jet, since this jet is often a  $b$  jet in signal, and has low enough  $p_T$  to be in the “sweet spot” for tagging with high efficiency. In contrast, the highest- $p_T$  jet, also often a  $b$ , is at such high  $p_T$  (typically  $> 250$  GeV) that its tagging efficiency is not that high. Meanwhile the second jet in the  $W$ -plus-jets background, unlike the hardest jet, is also often at low enough  $p_T$  that mistagging rates may be near their low point. There will be some loss of signal and increased theoretical errors compared to a technique that tags more widely, but the corresponding reduction in mistagging of the background, and in the uncertainties in tagging efficiencies, may be worth it.

Just to give a feel for the numbers, let us consider an example. Suppose mistagging of  $W$ -plus-jets could be brought down to 3% per event (10% for events with charm and 60% for  $Wb\bar{b}$ ), and if tagging of  $t\bar{t}$  events were of order 60%, with signal events tagged at 40% probability. Now suppose that a charge asymmetry of 30%, in a sample with a cross-section of 18 pb is measured. This is statistically consistent with  $F_S = 0, F_W = 4$  or  $F_S = 0.25, F_W = 3.3$ , whose asymmetries have central values of 25% and 35% respectively. Then for the SM alone, after tagging, we expect a cross-section of 1.7 pb and an asymmetry of 14%. In the presence of a  $F_S = 0.25$  signal, the asymmetry will instead move up to 41%, with a cross-section of 2.7 pb. With 35 inverse pb, the total number of events is of order 50 – 100, so statistical uncertainties are large. But progress has still been made. The progress is easily lost, however, if mistagging is a more serious problem, or if tagging of the signal is significantly worse.

Now let us put these results together. We have seen that by combining tagging and kinematic cuts we can get at least  $2.5 \sigma$  statistical sensitivity to  $F_S = 0.25$ , in several different ways. While these different ways are not independent, they do have very different combinations of backgrounds, and different sources of systematic errors. Properly combined, they should allow for even better sensitivity.

Surely the best way to do this, including all the information, is to simultaneously study the differential distribution versus  $H_T^{\ell\nu jj}$  of *both*  $A_C$  and the total number of events, both before and after the application of a wisely-chosen heavy-flavor-tagging method. It should be possible to discover or exclude the model even well below  $F_S = 0.25$ . This is an important range to aim at, as we have emphasized.

This said, we should add one caveat. We have shown that the  $W'$  model of [7] can easily be discovered or excluded down well below its fiducial cross-sections. But the absence of a signal might merely imply that the  $W'ub$  coupling is absent from the model. While the model then could not explain the anomalies in the  $B$  system, part of its original motivation, it might still explain the anomalous  $A_{FB}^{t\bar{t}}$  in top pair production through a  $W'td$  coupling. In this case, distortions in  $t\bar{t}j$  samples due to  $tW'$  production may be the dominant observable signal in such a model. Discovering such a model will be somewhat more challenging, but would still not take long, given the large coupling of the  $W'$  and the kinematic structures associated with its large mass.

Interestingly, charge asymmetries will have a crucial role to play in this case as well. Although there are equal numbers of positively and negatively charged leptons produced in  $tW'$  events, they will have very different  $p_T$  distributions. This is because the cross-section for  $tW'^-$  is very much larger than that for  $\bar{t}W'^+$ , and the  $t$  from the  $W'$  decay will have much higher  $p_T$  than the  $t$  produced directly. Therefore a plot of the lepton  $p_T$  will be very different for the two lepton charges. If a sufficiently clean sample can be obtained, for example by requiring two  $b$  tags, the backgrounds, mostly  $t\bar{t}$ , will show a much smaller difference.

Similarly, as we mentioned in our introduction, there has been interest recently in models with a  $Z'$  that couples to  $ut$ , and allow for the highly asymmetric process  $uu \rightarrow t\bar{t}$ . In this case same-sign leptons that are mainly of positive charge rather than negative are a clear

sign of a process from a  $uu$  initial state; the plus-two charge of the  $pp$  collision is entirely transferred to leptons. There will also of course be an asymmetry in one-lepton samples, though the backgrounds to same-sign dilepton events are much smaller.<sup>6</sup>

In this paper, we have considered a  $W'$  coupling both to right-handed  $ub$  and  $td$ , which has been suggested [7] as a solution to both the  $A_{FB}^{t\bar{t}}$  excess and various puzzles in  $B$  mesons. We noted that the model has a large cross-section for single-top production. At fiducial coupling and mass of  $g_R = 1.5$  and  $M_{W'} = 600$  GeV, the model is probably ruled out by Tevatron single-top measurements [23], although a quantitative assessment requires use of the multivariate techniques employed by the detector collaborations. It also appears the fiducial parameter region is excluded by existing LHC measurements, as in the control regions of [25]. However, the model with somewhat smaller  $g_R$  and/or  $1/M_{W'}$  is harder to exclude with existing public results, and could still serve to explain the observed large  $A_{FB}^{t\bar{t}}$  if this anomaly turns out to be currently overestimated. We have argued (inspired by [17]) that even with a rate reduced by four or more relative to the fiducial model's LO rate, single-top-quark production in this model creates an significant excess charge asymmetry in a transparent sample with simple kinematic cuts and/or heavy-flavor tagging. Our conclusion is that the current 2010 data sets at ATLAS and CMS of  $\sim 35$  inverse picobarns apparently suffice to detect even this reduced signal, or to strongly disfavor the single-top process down to levels very significantly smaller than predicted by the fiducial model.

We would also like to emphasize the model-independent value of this measurement. We hope that any analysis along these lines is presented in a model-independent fashion, as well as in the form of limits on the specific  $W'$  model of [7].

It should be clear that the method we have outlined, and ones of a similar form, will work on any large charge-asymmetric signals that produce leptons, neutrinos and jets, and perhaps  $b$  jets. Our particular set of strategies will continue to be effective at higher luminosity and with higher kinematic cuts. We would argue that these techniques should be in the standard toolkit of the LHC experimental community: that at every significant step in increased integrated luminosity, it is important to produce a simultaneous analysis of differential charge asymmetries and cross-sections versus  $m_{\text{eff}}$ ,  $H_T$ , or other kinematic variables, for different numbers of heavy-flavor-tagged jets. These analyses will be significantly more powerful than analysis of differential cross-sections alone. Here we echo previous general arguments to this effect [21, 22]. The methods that we have proposed, and others along similar lines, will continue to be useful throughout the lifetime of the LHC.

**Note Added** — After this article was completed, results of powerful searches for Standard Model single-top production were announced by both CMS and ATLAS [38, 39]. We have reconsidered the situation in light of these new analyses.

As we suggested would be possible, limits from the LHC on the  $W'$  model of [7] appear

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<sup>6</sup>After this paper was completed, it was pointed out [37] that the one-lepton asymmetry would actually be quite sensitive, due to its larger statistics.

now to reach values of order  $F_S = 0.25$ . We conclude this not from the quoted limits in [38, 39] on the SM single-top cross-section, which were obtained by optimizing for that rather idiosyncratic process, but from plots characterizing the preselection samples. The most useful plots are Figures 3c and 3h of [39] and Figure 15 of [38]. By roughly reproducing these figures, and considering the size and shape of the signal from the  $W'$  model, we estimate that with  $F_S = 0.25$  the signal would be detected on the tails of these distributions, even with pessimistic efficiencies for lepton identification and heavy-flavor tagging.

But any accurate estimate of excluded values of  $F_S$  would require additional information about heavy-flavor tagging rates. As emphasized above, the precise limits depend sensitively on the tagging efficiency and mistagging rate for high  $p_T$  jets, and on how well these are known. This information was not provided in the ATLAS and CMS papers (only average information on the working point was given, and this is appropriate at lower values of  $p_T$  than is relevant for the high  $H_T$  or  $\hat{s}$  region.) We would encourage both ATLAS and CMS to provide more detailed information about tagging methods in future publications, so that the reported results can be more widely used.

One important fact we learn from the small numbers of events with two jets, at high  $H_T$  in the ATLAS figure<sup>7</sup> and at high  $\hat{s}$  in the CMS figure, is that the  $W$ -plus-jets background is small after tagging. However, this could have two possible causes. It could be that the  $Wjj$  cross-section (and therefore  $F_W$ , in our notation) is not much larger than given by our leading order estimate. If this is the case, then, as our figures suggest, these LHC studies will have strong sensitivity to the  $W'$  model. But if instead the small background is due to tight tagging, with a low mistag rate but a correspondingly relatively low  $b$ -tagging rate, then considerable sensitivity may have been lost.

Lacking the information, we will not try to explore these searches further at this time. Instead, we return to the analysis that we suggested above, and compare general aspects of the different strategies. We believe that if a method closer to the one we have proposed were adopted, it would allow for even stronger limits on the  $W'$  model, and perhaps on many other phenomena.

A key difference is that we are not seeking a region of zero background, because, in using the asymmetry as well as the cross-section, we do not need it. In particular, it appears disadvantageous to consider only the two-jet sample, as was deemed necessary for the SM single-top searches in [38, 39].

Moreover, we would suggest comparing the samples with the tighter and looser kinematic cuts, before and after tagging, to get even more sensitivity. Essentially, in our language, this pins down  $F_W$ , the  $W$  contribution to the sample, thus determining the expected SM cross-section and asymmetry to a greater degree.

To demonstrate this, we present two new figures, which are similar to our original ones but with the following differences.

First, tagging is imposed. We choose a mistag rate of 5% per  $Wjj$  event (*not* per jet),

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<sup>7</sup>Note there is one event at  $H_T > 400$  GeV not shown in Figure 3h of [39]; this can be inferred from the corresponding table in the text. We thank Kyle Cranmer of ATLAS for helpful discussions.

15% on average per  $Wcj$  and  $Wcc$  event, 75% for  $Wbb$ ,  $t\bar{t}$  and SM single top, and 50% for our signal (recalling that much of it has two  $b$  jets but often one jet has  $p_T > 200$  GeV, where tagging is degraded.) This may or may not be optimistic, but we note that  $Wjj$  is sufficiently small, after requiring  $H_T^{\ell\nu jj} > 550$  GeV, that moderate changes in mistagging do not drastically change the result. Consequently one can roughly adjust these figures for changes in tagging by rescaling the signal (background) almost linearly (quadratically) with the  $b$ -tagging efficiency.

Second,  $F_S = 1$  is thoroughly excluded, so we now show  $F_S = 0.25$  and  $F_S = 0.1$ .

Third, the statistics is so low, after tagging, for the background-only case that we can better illustrate the uncertainties by showing  $1\sigma$  and  $3\sigma$  statistical fluctuations on the signal-plus-background hypothesis. We center the contours on the point  $F_W = 1$ ,  $F_S = 0.1$ .

Finally, the two figures illustrate the difference between taking a two-or-more jet sample, shown in Fig. 3, and requiring two and only two jets, shown in Fig. 4. The reduction in  $t\bar{t}$  background arising from the two-jet restriction improves a pure counting experiment, but the remaining statistics is too low for  $A_C$  to be a useful variable. If instead one aims at dividing the events and comparing positively and negatively charged lepton samples, the two-jet restriction degrades sensitivity. (Similarly, very tight tagging requirements may well be counter-productive.) Our figures suggest that sensitivity would be improved — especially if one measures  $F_W$  using another method, such as determining it from the untagged sample — with the looser event requirements.

As an aside, we note that Figure 3 of [38] and Figure 15 of [39] combine positively and negatively charged leptons, rather than showing them separately. For the future, we encourage the CMS and ATLAS collaborations to present plots separated by charge, both in searches such as this one where charge asymmetries might obviously be of interest, and in other cases where the absence of a large charge asymmetry may be powerful in excluding various types of new physics.

We conclude this Note-Added with two messages. First, we strongly encourage the CMS and ATLAS collaborations to revisit their single-top analyses<sup>8</sup> to put proper limits on this model, with its two parameters  $g_R$  and  $M_{W'}$ . We expect that the model will be ruled out throughout the region in which it would have served its original purposes. Second, we urge the collaborations to consider the value of using more inclusive samples, as we have suggested in our article, compensating for the increase in background with the power of the charge asymmetry.

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<sup>8</sup>For example, it should be possible to reanalyze them using the RECAST method [40].



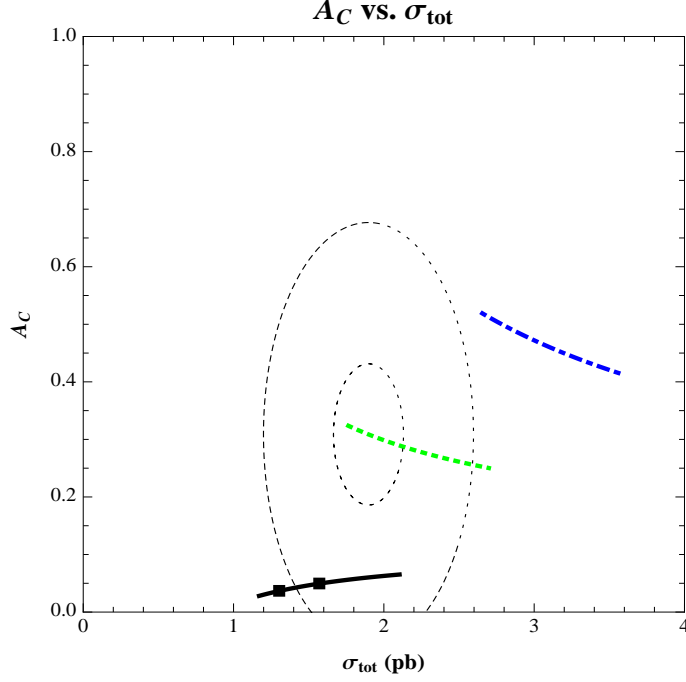


Figure 3: We plot  $A_C$  vs  $\sigma_{tot}$ , after requiring  $H_T^{\ell\nu jj} > 550$  GeV and imposing a heavy-flavor tag (see text for details), in three cases: the SM ( $F_S = 0$ , lower solid curve), the SM plus 1/10 the fiducial signal ( $F_S = 0.1$ , middle dotted curve) and the SM plus 1/4 the fiducial signal ( $F_S = 0.25$ , top dot-dashed curve.) Notice that we have not plotted the same quantities as in Figs. 1 and 2. Curves run from  $F_W = 0.5$  at left to  $F_W = 4$  at right, with dots on the SM curve at  $F_W = 1$  and 2, where  $F_W$  is the fudge factor for the  $W$ -plus-jets normalization. Ellipses showing an estimate of  $1\sigma$  and  $3\sigma$  statistical uncertainties are shown for the case of  $F_S = 0.1$  and  $F_W = 1$ .

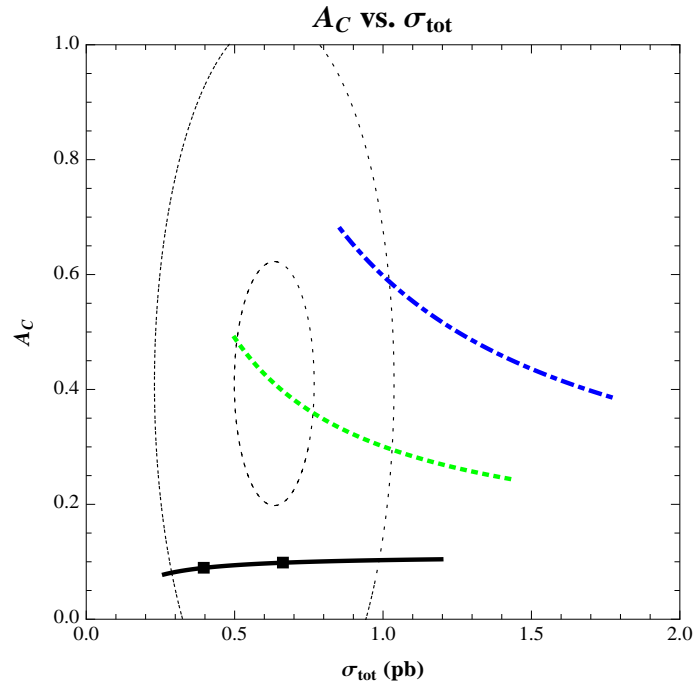


Figure 4: As in Fig. 3, but having also required two and only two jets (see text for details.) Notice the background is lower, but sensitivity is lost in our two-dimensional analysis.

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