Search for resonant top quark plus jet production in tt+ jets events with the ATLAS detector in pp collisions at $\sqrt{s} = 7$ TeV


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This paper presents a search for a new heavy particle produced in association with a top or antitop quark. Two models in which the new heavy particle is a color singlet or a color triplet are considered, decaying, respectively, to $tq$ or $tq$, leading to a resonance within the $t\bar{t} + \text{jets}$ signature. The full 2011 ATLAS $pp$ collision data set from the LHC (4.7 fb$^{-1}$) is used to search for $t\bar{t}$ events produced in association with jets, in which one of the $W$ bosons from the top quarks decays leptonically and the other decays hadronically. The data are consistent with the Standard Model expectation, and a new particle with mass below 430 GeV for both $W$ boson and color triplet models is excluded at 95% confidence level, assuming unit right-handed coupling.

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In the past few decades, remarkable agreement has been shown between measurements in particle physics and the predictions of the Standard Model (SM). The top quark sector is one important place to look for deviations from the SM, as the large top quark mass suggests that it may play a special role in electroweak symmetry breaking. The recent top quark forward-backward asymmetry measurements from the Tevatron experiments [1,2] are in marginal agreement with SM expectations. A non-SM explanation could come from a possible top-flavor-violating process [3–5]. In these models, a new heavy particle $R$ would be produced at the LHC in association with a top or antitop quark. Figure 1 shows representative production diagrams for these new particles, for the cases of $R = W^0$ or $R = \phi$ (see below). As shown in Ref. [6], the production mechanism in $pp$ collisions mainly involves quarks rather than antiquarks at $\sqrt{s} = 7$ TeV, even for relatively low mass particles.

The larger number of quarks relative to antiquarks produced in the initial state at the LHC leads to a resonance $R$ that decays predominantly to either the $t + \text{jet}$ or $\bar{t} + \text{jet}$ final state, where baryon number conservation restricts the models that are available. Two models that can give rise to these final states are a color singlet resonance ($W^0$) mostly in the $\bar{t}q$ system, and a di-quark color triplet model with a resonance ($\phi$) in the $tq$ system. In both cases a $t\bar{t} + \text{jet}$ final state is produced, but a peak will be present in only one of the $t + \text{jet}$ or $\bar{t} + \text{jet}$ invariant mass distributions. The new resonances are assumed not to be self-conjugate, which makes searches for same-sign top quarks insensitive to them [7–9], and to have only right-handed couplings.

The $t$ or $\bar{t}$ then decays to $W^+b$ or $W^-\bar{b}$, respectively. This paper considers the decay signature of events in which one $W$ boson decays leptonically (to an electron or muon, plus neutrino final state) and the other $W$ boson decays hadronically. The first direct search for such particles was performed at CDF [10], which excluded color triplet resonances with masses below 200 GeV and $W'$ resonances with masses below 300 GeV, for particles with unit right-handed coupling ($g_R$) to $tq$. As is done in this paper, CDF used the formalism in Ref. [3] to define $g_R$. CMS recently performed a search that excluded a new $W'$ with a mass less than 840 GeV [11] for particles with $g_R = 2$ [12].

The analysis presented here uses the full ATLAS 7 TeV $pp$ collision data set collected in 2011, corresponding to $4.7 \pm 0.2$ fb$^{-1}$ of integrated luminosity [13,14] delivered by the LHC. ATLAS [15] is a multipurpose particle physics detector with cylindrical geometry [16]. The inner detector (ID) system consists of a high-granularity silicon pixel detector and a silicon microstrip detector, as well as a transition radiation straw-tube tracker. The ID is immersed in a 2 T axial magnetic field and provides charged particle tracking in the range $|\eta| < 2.5$. Surrounding the ID, electromagnetic calorimetry is provided by barrel and endcap liquid-argon (LAr)/lead accordion calorimeters and LAr/copper sampling calorimeters in the forward region. Hadronic calorimetry is provided in the barrel by a steel/scintillator tile sampling calorimeter, and in the endcaps and forward region by LAr/copper and LAr/tungsten sampling calorimeters, respectively. The muon spectrometer comprises separate trigger and high-precision tracking chambers measuring the deflection of muons in a magnetic field with a bending power of 2–8 Tm, generated by three superconducting air-core toroid systems. A three-level trigger system is used to select interesting events. The level-1 trigger is implemented in hardware and uses a subset of detector information to reduce the event rate to a design value of at most 75 kHz. This is followed by two
software-based trigger levels, level-2 and the event filter, which together reduce the event rate to $\sim 300$ Hz.

Events with an electron (muon) are required to have passed an electron (muon) trigger with a threshold of transverse energy $E_T > 20$ GeV (transverse momentum $p_T > 18$ GeV), ensuring that the trigger is fully efficient for the offline selection discussed below. Electrons reconstructed offline are required to have a shower shape in the electromagnetic calorimeter consistent with expectation, as well as a good quality track pointing to the cluster in the calorimeter. Candidate electrons with $E_T > 25$ GeV are required to pass the “tight” electron quality criteria [17], to fall inside a well-instrumented region of the detector ($|\eta| < 2.47$, excluding $1.37 < |\eta| < 1.52$), and to be isolated from other objects in the event. Muons with transverse momentum $p_T > 20$ GeV are required to pass muon quality criteria [18], to be well measured in both the ID and the muon spectrometer, to fall within $|\eta| < 2.5$, and to be isolated from other objects in the event.

Jets are reconstructed in the calorimeter using the anti-$k_T$ [19] algorithm with a radius parameter of 0.4. Jets are required to satisfy $p_T > 25$ GeV and $|\eta| < 2.5$. Events with jets arising from electronic noise bursts and beam backgrounds are rejected [20]. Jets are calibrated to the hadronic energy scale using $p_T$- and $\eta$-dependent corrections derived from simulation, as well as from test-beam and collision data [21]. Jets from the decay of heavy flavor hadrons are selected by a multivariate $b$-tagging algorithm [22] at an operating point with 70% efficiency for $b$ jets and a mistag rate for light quark jets of less than 1% in simulated $t\bar{t}$ events. Neutrinos are inferred from the magnitude of the missing transverse momentum ($E_T^{\text{miss}}$) in the event [23].

The signal region for this analysis is defined by requiring exactly one charged lepton and five or more jets, including at least one $b$-tagged jet. To select events with a leptonically decaying $W$ boson, events are required to have $E_T^{\text{miss}} > 30$ GeV ($E_T^{\text{miss}} > 20$ GeV) in the electron (muon) channel. Additionally, the event must have a transverse mass of the leptonically decaying $W$ boson $m_{W}^{T} > 30$ GeV in the electron channel, or scalar sum $E_T^{\text{miss}} + m_{W}^{T} > 60$ GeV in the muon channel [24]. Here, $(m_{W}^{T})^2 = 2E_T^{\text{miss}}E_T^{l}(1 - \cos\phi)$, where $E_T^{l}$ is the magnitude of the transverse momentum of the lepton, and $\phi$ is the angle between the lepton and the missing transverse momentum in the event.

A variety of Monte Carlo generators are used to study and estimate backgrounds. The generated events are processed through full detector simulation [25], based on GEANT4 [26], and include the effect of multiple $pp$ interactions per bunch crossing. To predict the event yield, the simulation is given an event-by-event weight such that
the distribution of the number of $pp$ collisions matches that in data.

The $t\bar{t}$ background is modeled with MC@NLO v4.01 [27] interfaced to HERWIG v6.520 [28] and JIMMY v4.31 [29]. An additional $t\bar{t}$ sample modeled with MC@NLO interfaced to PYTHIA v6.425 [30] is used to study potential systematic uncertainties. Other $t\bar{t}$ samples use POWHEG [31] interfaced either to PYTHIA or HERWIG, as well as AcerMC v3.8 [32]. The background from the production of single $W$ bosons in association with extra jets is modeled by the ALPGEN v2.13 [33] generator interfaced to HERWIG. The MLM matching scheme [34] is used to form inclusive $W$ boson + jets samples such that overlapping events produced in both the hard scatter and parton showering are removed. In addition, the heavy flavor contributions are reweighted using the data-driven procedures of Ref. [24] using the full 2011 LHC data set. Diboson events are generated using HERWIG. Single-top-quark events are modeled by MC@NLO, interfaced with HERWIG for the parton showering, in the $s$ channel and $Wt$ channel, and by AcerMC v3.8 in the $t$ channel. The small background in which multijet processes are misidentified as prompt leptons is modeled from a data-driven matrix method [35]. In determining the expected event yields, the $t\bar{t}$ cross section is normalized to approximate next-to-next-to-leading-order QCD calculations of $167^{+17}_{-16}$ pb for a top quark mass of 172.5 GeV [36,37], and the total $W$ + jets background is normalized to inclusive next-to-next-to-leading-order predictions [38]. Signal events are produced, for a range of $W'$ and $\phi$ masses, with MadGraph v5.1.3.16 [39] and interfaced to PYTHIA v6.425. Next-to-leading-order (NLO) cross sections are used for the predicted $W'$ boson signal normalization [6], and leading-order (LO) cross sections using MSTW2008 are used for the $\phi$-resonance normalization [3].

Events are reconstructed with a kinematic fitting algorithm that utilizes knowledge of the overconstrained $t\bar{t}$ system to assign jets to partons. In the fit, the two top quark masses are each constrained at the particle level to

![FIG. 3 (color online). Expected and observed distribution of $m_{tj}$ in the $W$ + jets control region. The example signal-only distributions are overlaid for comparison, where unit coupling for the new physics process is assumed. The total uncertainty shown on the ratio includes both statistical and systematic effects. The other background category includes single top production, diboson production, and multijet events.](image1)

![FIG. 4 (color online). Expected and observed distributions of (a) $m_{tj}$ and (b) $m_{j\ell}$ in the signal region. The example signal distributions assume unit coupling for the new physics process. The total uncertainty shown on the ratio includes both statistical and systematic effects. The other background category includes single top production, diboson production, and multijet events.](image2)
Signal/C27

Signal region yield

Total

W + jets

et al.

remaining jets not associated with the 
tm

the total expected background, including 

quark width of 1.5 GeV . The two 
variations from this nominal value and the natural top 
partons from the 

likelihood computation. All assignments of any four jets to 
full shapes of these transfer functions are used in the like-
momenta in the detector to true particle momenta. The 

hypothesis is tested and the assignment 
tj

selected. After the assignment is selected, the originally 
extra jet can (but 
does not necessarily have to) be used to form 
mj

These two masses are used as observables for the search. 

Several control regions are used to ensure good model-
and understanding of the backgrounds before the signal 
region is examined. The preselection control region 
requires at least four jets, but does not require a b tag. 
The dominant 
tt

background is tested in a control region 
with exactly four jets (including at least one b-tagged jet). 
The rejection of events with more than four jets reduces 
signal contamination. A second 
tt

control region is defined by events with exactly four jets with 

one of which must be b tagged, and exactly one additional 
jet with 
pT

between 20 GeV and 25 GeV. Signal contami-
nation is further reduced by requiring that the 

between the fifth jet and both the recon-

Figure 2 shows distributions in the two 
tt

control regions, where good agreement is observed between data and the 
prediction. The second major background, production of 

bosons in association with extra jets, is tested in a

TABLE I. Expected and observed yields in the four control regions (CR). Total refers to the 
total expected background, including 
tt, W + jets, and the other smaller backgrounds: single top 
production, diboson production, and multijet events. The last two lines show the expected 
number of events for two benchmark signal samples in each of these control regions. The errors 
include all systematic uncertainties.

|                  | Preselection CR | W + jets CR | Four-jet 
tt CR | Five-jet 
tt CR |
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tt               | 50000 ± 4700    | 2000 ± 400  | 19000 ± 600 | 2100 ± 200 |
| W + jets         | 46000 ± 14000   | 7000 ± 2900 | 3800 ± 800 | 360 ± 170 |
| Total            | 116000 ± 21000  | 12000 ± 3600 | 26000 ± 1300 | 2900 ± 440 |
| Observed         | 110933          | 11858       | 26197     | 2736     |
| 300 GeV W'       | 13900 ± 670     | 930 ± 110   | 3000 ± 400 | 400 ± 80  |
| 400 GeV φ        | 6100 ± 200      | 430 ± 60    | 1100 ± 100 | 200 ± 20  |

172.5 GeV by a penalty in the likelihood, computed from 

variations from this nominal value and the natural top 

quark width of 1.5 GeV. The two W boson masses are 
similarly constrained to 80.4 GeV within a width of 

2.1 GeV. This allows the z component of the momentum 
of the neutrino from the leptonically decaying W boson to 
be computed. Both solutions from the quadratic ambiguity 
of this computation are tested when computing the like-

likelihood. Charged lepton, neutrino, and jet four-momenta are 

constrained in the fit by resolution transfer functions 
derived from simulated 
tt

events that relate the measured 

momenta in the detector to true particle momenta. The 
full shapes of these transfer functions are used in the like-
kelihood computation. All assignments of any four jets to 
partons from the 
tt

decay are tested and the assignment 
with the largest likelihood output for the 
tt

hypothesis is selected. After the assignment is selected, the originally 

measured jet and lepton momenta and 

are used. The 

remaining jets not associated with the 
tt

partons are included to form 
mij

and 
mij

masses, where the charge of the lepton is used to infer which is the top candidate 

and which is the antitop candidate. All combinations of 

jets with the top and antitop quark candidates are 

considered, and the pairings that give the largest 
mij

and 
mij

masses are used. In this way, the same extra jet can (but 
does not necessarily have to) be used to form 
mij

and 
mij

. These two masses are used as observables for the search.

Several control regions are used to ensure good model-
and understanding of the backgrounds before the signal 
region is examined. The preselection control region 
requires at least four jets, but does not require a b tag. 
The dominant 
tt

background is tested in a control region 
with exactly four jets (including at least one b-tagged jet). 
The rejection of events with more than four jets reduces 
signal contamination. A second 
tt

control region is defined by events with exactly four jets with 

one of which must be b tagged, and exactly one additional 
jet with 
pT

between 20 GeV and 25 GeV. Signal contami-
nation is further reduced by requiring that the 

between the fifth jet and both the recon-

Figure 2 shows distributions in the two 
tt

control regions, where good agreement is observed between data and the 
prediction. The second major background, production of 

bosons in association with extra jets, is tested in a

TABLE II. Expected and observed yields in different signal regions. The errors include all systematic uncertainties. Total refers to the 
total expected background, including 
tt, W + jets, and the other smaller backgrounds: single top production, diboson production, 
and multijet events, which are not tabulated separately here. Signal window eff. refers to the efficiency for the signal to fall inside the 
optimized two-dimensional mass window. The signal region yield is calculated in the mass window at each benchmark signal point. 
Signal σ refers to the total expected signal cross section, not taking into account the t or t̄ plus jet branching fraction.

<table>
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<th>Entire signal region</th>
<th>300 GeV W'</th>
<th>600 GeV W'</th>
<th>400 GeV φ</th>
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mij window [GeV] |                      |            |            |           |           |
| 300 GeV W'       | 344 < 
mij < 494     | 566 < 
mij < 904 | 401 < 
mij < 455 | 766 < 
mij < 819 |
| 600 GeV W'       | 292 < 
mij < 339     | 549 < 
mij < 650 | 371 < 
mij < 608 | 628 < 
mij < 973 |
| Signal window eff.| 7.5%                 | 9.9%       | 11.9%      | 5.7%      |
| 
tt                | 18000 ± 3000        | 740 ± 160  | 270 ± 60   | 660 ± 150 | 60 ± 10   |
| W + jets          | 1700 ± 560          | 60 ± 30    | 30 ± 20    | 80 ± 40   | 8 ± 5     |
| Total             | 22000 ± 3700        | 820 ± 190  | 320 ± 80   | 780 ± 180 | 70 ± 20   |
| Observed          | 22731               | 970        | 343        | 923       | 77        |
| Signal region yield | 560 ± 120          | 98 ± 24    | 410 ± 100  | 20 ± 6    |
| Signal σ          | 19.0 pb             | 1.55 pb    | 7.9 pb     | 0.67 pb   |
control region with five or more jets, vetoing events with 
\(b\)-tagged jets. The requirement of zero \(b\)-tagged jets 
reduces both signal and \(t\)/\(C22\) contamination. The distribution 
in Fig. 3 shows good agreement between data and the 
prediction within uncertainties. Table I summarizes the 
expected and observed yields in the control regions. 

Figure 4 shows the expected and observed \(m_{jj}\) and \(m_{ij}\) 
distributions in the signal region. The data are found to be 
consistent with the SM expectation. A variety of potential 
systematic effects are evaluated for the predicted signal 
and the background rates and shapes. The dominant sys-
tematic effects of the jet energy scale [21] and resolution

\[
W' \text{ mass [GeV]} \quad 500 \quad 1000 \quad 1500 \quad 2000 \quad 2500
\]

\[
\text{Cross-section [pb]} \quad 10^0 \quad 10^1 \quad 10^2 \quad 10^3 \quad 10^4 \quad 10^5 \quad 10^6 \quad 10^7 \quad 10^8 \quad 10^9 \quad 10^{10}
\]

\[
\int L \, dt = 4.7 \, \text{fb}^{-1} \quad \sqrt{s} = 7 \, \text{TeV}
\]

\[g_{R_0} = 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5\]

\(\text{Expected exclusion}\)

\(95\% \text{ C.L. exclusion}\)

\(\text{CDF exclusion}\)

\(\text{(M. Gresham et al.)}_{tt}\)

\(\text{Favored by Tevatron A}_{FB}\) and \(\sigma_{ij}\) 

\(\text{ATLAS}\)

\[\int L \, dt = 4.7 \, \text{fb}^{-1} \quad \sqrt{s} = 7 \, \text{TeV}\]

\(\phi\) mass [GeV] 

\(\text{Expected exclusion}\)

\(95\% \text{ C.L. exclusion}\)

\(\text{CDF exclusion}\)

\(\text{Favored by Tevatron A}_{FB}\) and \(\sigma_{ij}\) 

\(\text{(M. Gresham et al.)}_{tt}\)

\(\text{Favored by Tevatron A}_{FB}\) and \(\sigma_{ij}\) 

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\[\int L \, dt = 4.7 \, \text{fb}^{-1} \quad \sqrt{s} = 7 \, \text{TeV}\]

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\(\text{(M. Gresham et al.)}_{tt}\)

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\[\int L \, dt = 4.7 \, \text{fb}^{-1} \quad \sqrt{s} = 7 \, \text{TeV}\]

\(\phi\) mass [GeV] 

\(\text{Expected exclusion}\)

\(95\% \text{ C.L. exclusion}\)

\(\text{CDF exclusion}\)

\(\text{Favored by Tevatron A}_{FB}\) and \(\sigma_{ij}\) 

\(\text{(M. Gresham et al.)}_{tt}\)

\(\text{Favored by Tevatron A}_{FB}\) and \(\sigma_{ij}\)
assessed using $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ data, which lead to systematic uncertainties of a few percent. Other potential systematic effects considered are the size of the small multijet background (assigned 100% uncertainty); $t\bar{t}$ generator uncertainties (evaluated by comparing different results using the MC@NLO and POWHEG generators, 1–10%); $t\bar{t}$ showering and fragmentation uncertainties (evaluated by comparing samples using both PYTHIA and HERWIG, 1%–6%); an uncertainty on the total integrated luminosity (3.9%) \cite{13,14}; and the amount of QCD radiation for the signal and the $t\bar{t}$ background (approximately 10%, evaluated using AcerMC). Total cross section uncertainties of 10% (55%) are used for the $t\bar{t}$ ($W$ + jets) backgrounds.

Expected and observed upper limits on the signal cross section are computed at discrete mass points as follows. For each benchmark signal mass point under consideration, a signal region is defined in the $m_{tj}$-$m_{ij}$ plane. When setting limits for the $W'$ ($\phi$) model, the $m_{tj}$ ($m_{ij}$) window is significantly wider than the $m_{tj}$ ($m_{ij}$) window to account for the fact that the resonance is predominantly in the $m_{tj}$ ($m_{ij}$) system. The windows are optimized to maximize sensitivity, accounting for the full effect of systematic uncertainties. Typical mass windows are shown in Table II. For each mass window, 95% confidence level (C.L.) upper limits on the signal cross section (times the branching ratio to $t\tau$ or $t\bar{t}$) are computed using a single bin frequentist CLs method \cite{41}. No shape information is used within the mass windows. Table II shows the expected and observed event yields in several of the signal region windows. Expected and observed 95% C.L. lower limits on the signal mass are derived, assuming a coupling of $g_R = 1$ and $g_R = 2$, and are shown in Fig. 5. Assuming that the cross section scales as $g_R^2$, the exclusion in the mass-coupling plane is shown in Fig. 6. As shown, most of the parameter space in this model, which was favored by the Tevatron forward-backward asymmetry and cross section measurements \cite{42}, has been excluded.

In conclusion, this paper presents a search for a new heavy particle $R$ in the $t\bar{t}$ or $t\bar{t}$ system of $t\bar{t}$ plus extra jet events with the ATLAS detector. Such new particles have been proposed as a potential explanation of the difference from the SM values of the forward-backward asymmetries measured in top quark pair production at the Tevatron. The full 2011 ATLAS $p\bar{p}$ data set ($4.7 \text{ fb}^{-1}$) is used in the search. Assuming unit coupling, the expected 95% C.L. lower limit on the mass of the new particle is 500 (700) GeV in the $W'$ ($\phi$) model. No significant excess of data above SM expectation is observed, and 95% C.L. lower limits of 430 GeV for both the $W'$ and $\phi$ models are set. At $g_R = 2$, the limits are 1.10 (1.45) TeV for the $W'$ ($\phi$) model, with expected limits of $0.93$ ($1.30$) TeV. These are the most stringent limits to date on such models. Most of the regions of parameter space for these models that are more consistent with the Tevatron forward-backward asymmetry and $t\bar{t}$ cross section measurements than the SM are excluded at 95% C.L. by these results.

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC, and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST, and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR, and VSC CR, Czech Republic; DNRF, DNSRC, and Lundbeck Foundation, Denmark; EPLANET and ERC, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG, and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP, and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERSYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF, and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, USA. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular, from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK), and BNL (USA) and in the Tier-2 facilities worldwide.


[12] There are several differences between the models in Refs. [3,4]. The Lagrangian in the former (used in this paper) includes a factor of $1/\sqrt{2}$, and the one in the latter (used by CMS) does not. In addition, Ref. [4] includes additional nonresonant diagrams with cross section that scale as $g_s^5$. Such diagrams are not included in Ref. [3].


[16] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the center of the detector and the z axis along the beam pipe. The x axis points from the interaction point to the center of the LHC ring, and the y axis points upward. Cylindrical coordinates $(r, \phi)$ are used in the transverse ($x$-$y$) plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$.


[42] This region simultaneously satisfies the observed high-$mt\ell\tau$ and low-$mt\ell\tau$ observed at the Tevatron. Mathematically it is defined as the region with $\chi^2 < 2.8$, where $\chi^2$ is defined in Eq. (22) in M. Gresham, I.-W. Kim, and K. Zurek, Phys. Rev. D 85, 014022 (2012). The $\chi^2$ for the Standard Model is 2.8.
RAPID COMMUNICATIONS

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