

**Discovery potential for heavy $t\bar{t}$ resonances in dilepton+jets final states in pp collisions at
 $\sqrt{s} = 14$ TeV
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We examine the prospects for probing heavy top quark-antiquark ($t\bar{t}$) resonances at the upgraded LHC in pp collisions at $\sqrt{s} = 14$ TeV. Heavy $t\bar{t}$ resonances (Z' bosons) are predicted by several theories that go beyond the standard model. We consider scenarios in which each top quark decays leptonically, either to an electron or a muon, and the data sets correspond to integrated luminosities of $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$ and $\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$. We present the expected 5σ discovery potential for a Z' resonance as well as the expected upper limits at 95% C.L. on the Z' production cross section and mass in the absence of a discovery.

I. INTRODUCTION

An important goal of the LHC research programs is to deepen our understanding of electroweak symmetry breaking. Electroweak symmetry breaking in the standard model (SM) is closely associated with the existence of a neutral Higgs boson. Therefore, the discovery of a new boson [1, 2] with properties consistent with those of the SM Higgs boson is clearly a monumental development. However, the top quark, by far the heaviest known fundamental particle, has a mass close to the electroweak scale, which suggests that it too may play a role in electroweak symmetry breaking. This alone provides ample motivation for the continued intense scrutiny of the top quark in all of its manifestations.

A generic prediction of many models that go beyond the standard model (BSM) is the existence of at least one heavy neutral boson, referred to generically as a Z' , that preferentially decays to a $t\bar{t}$ pair and that appears as a resonant structure superimposed on the SM $t\bar{t}$ continuum production. These models include coloron models [3–6], models based on extended gauge theories with massive color-singlet Z-like bosons [7–9], and models in which a pseudoscalar Higgs boson may couple strongly to top quarks [10]. Furthermore, various extensions of the Randall-Sundrum model [11] with extra dimensions predict Kaluza-Klein excitations of gluons [12], or gravitons [13], both of which can have enhanced couplings to $t\bar{t}$ pairs. The recent observation of forward-backward asymmetry in $t\bar{t}$ production at the Tevatron [14–17] has inspired new models [18–22] that explain the observation by positing new physics at the TeV scale. The latter can manifest itself as a broad enhancement over the SM $t\bar{t}$ production at high invariant mass. The top quark, and $t\bar{t}$ production in particular, is a powerful probe of potential new physics.

Direct searches for heavy $t\bar{t}$ resonances have been performed at the Tevatron and the LHC. No such resonances have been found. The Tevatron experiments probed the mass range up to ~ 900 GeV [23, 24], while the LHC experiments have set sub-pb limits on the $t\bar{t}$ resonance production cross section in the mass range of 1–3 TeV depending on the Z' width, and have excluded the existence of a narrow width Z' ($\Gamma_{Z'} = 0.012M_{Z'}$) below $M_{Z'} = 2.1$ TeV at 95% C.L. [25–30].

The null results indicate that $t\bar{t}$ resonances, if they exist, must have masses in the TeV range or higher. In this paper, we examine how high a mass can be expected to be probed using $Z' \rightarrow t\bar{t} \rightarrow W^+b W^- \bar{b}$ production in pp collisions at the upgraded LHC operating at $\sqrt{s} = 14$ TeV. We consider final states in which both W bosons decay to leptons (electron or muon), that is, final states comprising two high p_T leptons of opposite charge (e^+e^- , $\mu^+\mu^-$, or $e^\pm\mu^\mp$), at least two jets from the hadronization of b/\bar{b} quarks, and missing transverse momentum due to escaping neutrinos. Top quarks from the decay of a heavy Z' are expected to be highly boosted leading to decay products that may not be spatially well separated. Consequently, we expect events would contain a non-isolated lepton from $W \rightarrow \ell\nu$ decay that is partially or fully overlapped with the b-quark jet from $t \rightarrow Wb$ decay.

The dominant (irreducible) background is the $t\bar{t}$ continuum production. Other SM processes contributing to the background are the production of single top quarks, $Z/\gamma^*/W$ +jets, and dibosons (WW, WZ, and ZZ). We consider two potential data sets, one corresponding to $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$ and the other to $\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$, as anticipated by the end of Run 2 of the upgraded LHC and by the end of the High Luminosity LHC (HL-LHC) runs, respectively.

II. SIGNAL AND BACKGROUND SAMPLES

This study considers four different Z' mass hypotheses, $M_{Z'} = 2, 3, 4$ and 5 TeV, and assumes a resonance width of $\Gamma_{Z'} = 0.012M_{Z'}$. For each mass hypothesis, signal event samples are generated using the PYTHIA program [37]. The expected signal yields are computed using the leading-order (LO) cross sections for a leptophobic Z' [6] scaled by a K-factor of 1.3 [39] to approximate the cross section at next-to-leading-order (NLO). The SM background samples are generated using the MADGRAPH event generator [33] and higher-order and non-perturbative effects are approximated using PYTHIA through its parton showering and hadronization models. The LO cross sections for the background processes are obtained from the event generator and corrected for NLO effects [35]. The detector response to the simulated events is computed using the ‘‘Combined Snowmass LHC detector’’ [34], which is implemented in the DELPHES-3 fast simulation program [36]. The DELPHES-3 program can be used to model (to an accuracy of about 10 – 20%) the projected performance of future ATLAS [31] and CMS [32] detectors at the upgraded LHC. The program also supports the simulation of additional pp interactions per bunch crossing (that is, in-time pile-up). We use samples that correspond to two different luminosity and pile-up (PU) scenarios at $\sqrt{s} = 14$ TeV: $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$, with an average number of pile-up events of $\langle \text{PU} \rangle = 50$ events per bunch crossing (LHC Run 2), and $\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$, with $\langle \text{PU} \rangle = 140$ events per bunch crossing (HL-LHC).

III. EVENT SELECTION AND YIELDS

We select $Z' \rightarrow t\bar{t} \rightarrow 2\ell + 2\nu + b\bar{b}$ candidate events by requiring two oppositely charged leptons, each with $p_T > 20$ GeV and pseudorapidity $|\eta| < 2.4$, and at least two jets within $|\eta| < 2.4$ and with $p_T > 30$ GeV. In addition, events are required to have $E_T > 30$ GeV and at least one b-tagged jet, where the b-tagging efficiency is assumed to be $\sim 65\%$ [35]. In order to reduce the background from low-mass dilepton resonances, events are rejected if the dilepton mass $M_{\ell\ell} < 12$ GeV. The remaining events are split into three disjoint categories depending on the lepton flavors, the ee , $\mu\mu$, and $e\mu$ channels. In the ee and $\mu\mu$ channels, the contribution from Z+jets production is suppressed by vetoing events with $76 < M_{\ell\ell} < 106$ GeV. We refer to the sample at this stage as the “pre-selected” sample.

Starting with the pre-selected sample, selection cuts are optimized using the Random Grid Search (RGS) method [38] and the signal significance measure S/\sqrt{B} , where S is the expected number of Z' signal events with $M_{Z'} = 2$ TeV, and B is the total expected background. Since the signal-to-background separation power increases with the hypothesized Z' mass, the set of cuts optimized for $M_{Z'} = 2$ TeV also yields good discrimination between signal and background for higher $M_{Z'}$ values. The selection optimization is performed separately for the $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$ and $\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$ scenarios.

The kinematic variables used in the RGS procedure are the transverse momenta of the two leading leptons and the two leading jets, and the missing transverse momentum. In addition, we use two highly discriminating variables. The first is the separation between the lepton and the closest jet in the space $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$, where $\Delta\eta$ and $\Delta\phi$ are the pseudorapidity and the azimuthal angle differences, respectively, between the lepton and jet. The boosted top quarks from the decay of a heavy Z' produce a lepton and b-quark that are close together in space. We therefore expect ΔR to be smaller on average for the signal than for the background processes, which, unlike the signal, do not contain highly boosted particles. Figure 1 shows an example of the distribution of the ΔR between the leading lepton and the closest jet in the ee channel in the pre-selected sample.

The other highly discriminating variable is a mass variable M . The mass variable M is computed from the four-momenta of the two leading leptons, the two leading jets and a four-momentum formed from the p_x and p_y components of the missing transverse momentum with the p_z set to zero. The distributions of the mass variable for the backgrounds and for the signal with Z' masses of 2 TeV and 3 TeV, after *all* selections, are shown in Figs. 2 and 3 for the $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$ and 3000 fb^{-1} scenarios, respectively. A heavy Z' produces higher values of M than the background processes. Table I summarizes the final selection cuts obtained from the RGS for the two luminosity scenarios. The expected event yields are given in Table II.

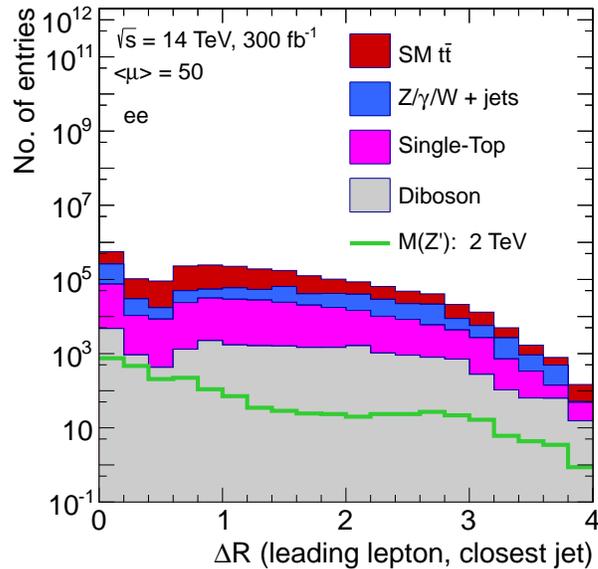


FIG. 1: Distribution of ΔR between the leading lepton and closest jet in the ee channel in the pre-selected cuts sample. Shown are contributions from the SM background processes and the Z' signal assuming $M_{Z'} = 2$ TeV and $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$ luminosity.

TABLE I: Summary of the final selection cuts obtained from the RGS for the two LHC luminosity scenarios at $\sqrt{s} = 14$ TeV.

LHC luminosity scenario	$\int \mathcal{L}dt = 300 \text{ fb}^{-1}$	$\int \mathcal{L}dt = 3000 \text{ fb}^{-1}$
Leading lepton $p_T >$	100 GeV	100 GeV
Second leading lepton $p_T >$	30 GeV	20 GeV
Leading jet $p_T >$	175 GeV	550 GeV
Second leading jet $p_T >$	150 GeV	100 GeV
$E_T >$	95 GeV	35 GeV
$\Delta R(\text{lepton, closest jet}) <$	0.6	1.2
$M >$	1500 GeV	–

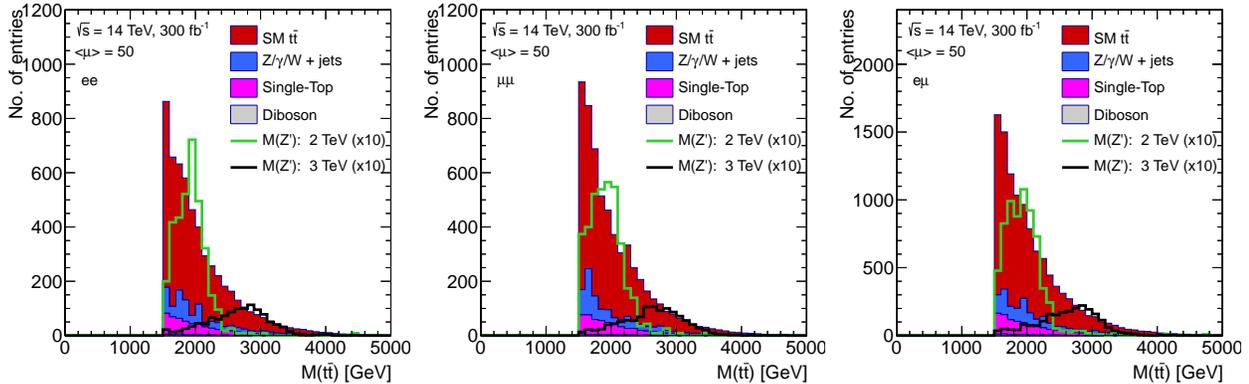
TABLE II: Summary of the expected signal and the background event yields for the two LHC luminosity scenarios at $\sqrt{s} = 14$ TeV.

LHC luminosity scenario	$\int \mathcal{L}dt = 300 \text{ fb}^{-1}$	$\int \mathcal{L}dt = 3000 \text{ fb}^{-1}$
Signal Event Yields		
Z' $M_{Z'} = 2 \text{ TeV}$	1395	22534
Z' $M_{Z'} = 3 \text{ TeV}$	446	5955
Z' $M_{Z'} = 4 \text{ TeV}$	85.7	1118
Z' $M_{Z'} = 5 \text{ TeV}$	14.5	184
Background Event Yields		
$t\bar{t}$	17599	427058
single top	2044	50545
$W/Z/\gamma^* + \text{jets}$	2545	81740
Diboson	163	6384
Total background	22351	565727

IV. EXPECTED DISCOVERY REACH AND LIMITS

In order to quantify the expected 5σ discovery or 95% C.L. exclusion limit for a Z' resonance, we use the Bayesian method [41] implemented in the statistical software package THETA [40]. A multi-Poisson likelihood, constructed from the binned mass distributions of all three channels (ee , $\mu\mu$, and $e\mu$), is combined with a flat prior for the signal cross section. The following systematic uncertainties are accounted for in the signal and background models, assuming full correlation across channels: 10% in the cross section normalization for each background process, 10% in the b-tagging efficiency, and 2% in the jet-energy scale.

Figure 4 (left) shows the Z' production cross section times the branching fraction to $t\bar{t}$ ($\sigma_{Z'}\mathcal{B}$), as a function of $M_{Z'}$,

FIG. 2: Distributions of the mass variable M for the ee , $\mu\mu$, and $e\mu$ channels for 300 fb^{-1} after selection cuts are applied.

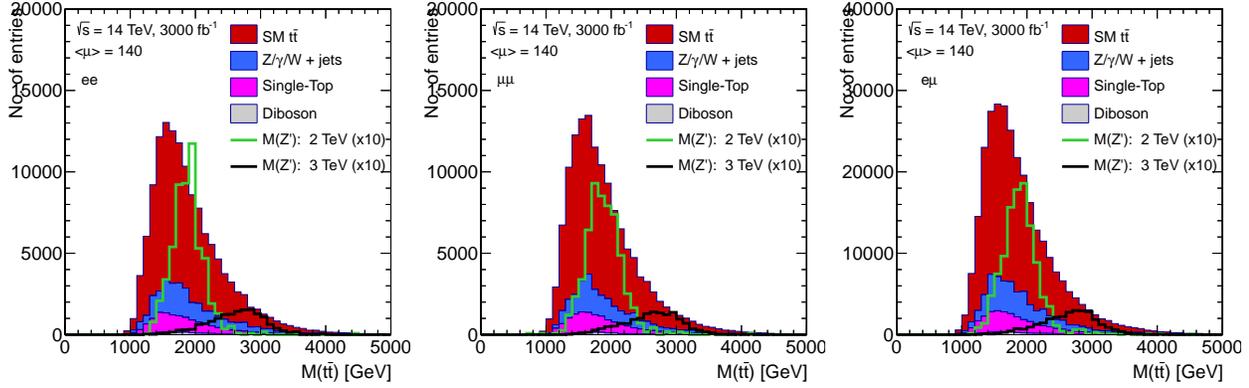


FIG. 3: Distributions of the mass variable M for the ee , $\mu\mu$, and $e\mu$ channels for 3000 fb^{-1} after selection cuts are applied.

that would yield a signal with a statistical significance of 5σ at $\sqrt{s} = 14 \text{ TeV}$, that is, a discovery, with integrated luminosities $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$ and $\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$. The cross section times branching fraction, $\sigma_{Z'} \mathcal{B}$, ranges from 6 – 300 (2 – 60) fb with $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$ ($\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$) for the mass range 2–5 TeV. Comparing these with the theoretical prediction for the production cross section of a leptophobic Z' yields the expected Z' discovery mass reach of 2.8 TeV with $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$ and 4.1 TeV with $\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$.

Figure 4 (right) shows expected 95% C.L. limits on $\sigma_{Z'} \mathcal{B}$ as a function of $M_{Z'}$ for the two luminosity scenarios. The expected limits range from 2 – 100 (1–20) fb with $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$ ($\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$) for the mass range 2–5 TeV. Comparing these with the predicted production cross section for a leptophobic Z' shows that we can expect to exclude the existence of a Z' with mass < 4.4 (4.7) TeV at 95% C.L. with $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$ ($\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$) should we fail to make a discovery.

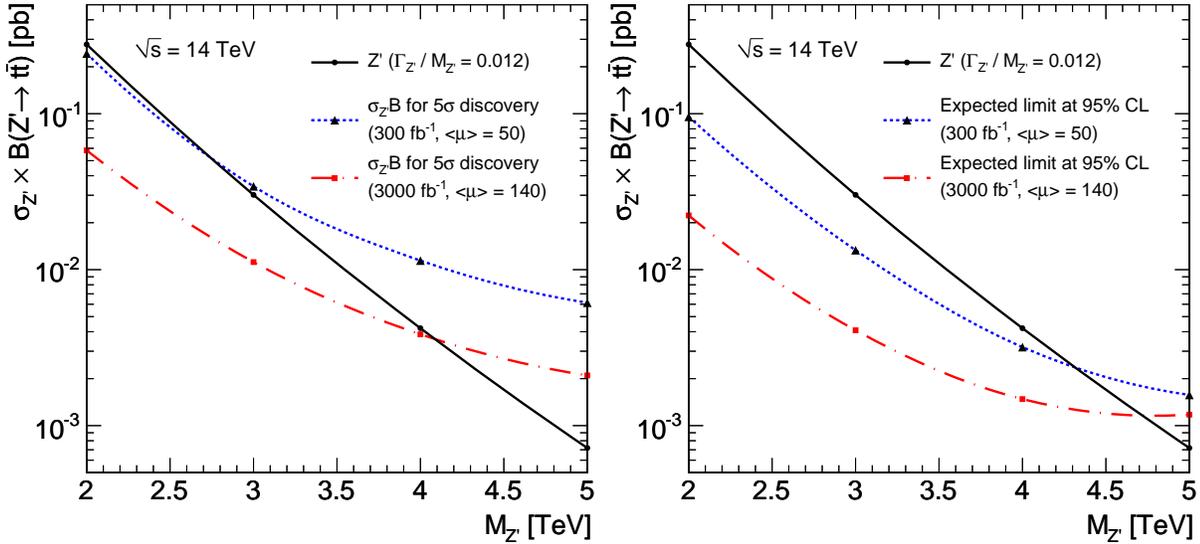


FIG. 4: Required $\sigma_{Z'} \mathcal{B}$ for a 5σ observation (left) and upper limits at 95% C.L. on $\sigma_{Z'} \mathcal{B}$ (right) as a function of $M_{Z'}$ for narrow-width, leptophobic Z' resonances. Also shown is the theoretical prediction for the Z' .

V. SUMMARY

We have assessed the potential for finding evidence of a leptophobic Z' boson in $Z' \rightarrow t\bar{t} \rightarrow 2\ell + 2\nu + b\bar{b}$ decays in pp collisions at $\sqrt{s} = 14 \text{ TeV}$. Two sets of hypothetical data, simulated using PYTHIA, MADGRAPH and DELPHES, have been analyzed assuming an integrated luminosity of $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$ with an average number of events per bunch crossing (pile-up) of $\langle \text{PU} \rangle = 50$, and $\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$ with $\langle \text{PU} \rangle = 140$. For the lower (higher)

integrated luminosity, our study indicates that it is possible to discover a Z' up to a mass 2.8 (4.1) TeV with a statistical significance of 5σ . Should we fail to make a discovery, the existence of a Z' with mass < 4.4 (4.7) TeV can be excluded at 95% C.L. using data associated with the lower (higher) integrated luminosity scenario.

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- [1] S. Chatrchyan *et al.* [CMS Collaboration], “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC,” Phys. Lett. B **716**, 30 (2012) [arXiv:1207.7235 [hep-ex]].
- [2] G. Aad *et al.* [ATLAS Collaboration], “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC,” Phys. Lett. B **716**, 1 (2012) [arXiv:1207.7214 [hep-ex]].
- [3] C. T. Hill, “Topcolor: top quark condensation in a gauge extension of the standard model”, Phys. Lett. B, 266, 419 (1991)
- [4] C.T. Hill and S.J. Parke, “Top production: Sensitivity to new physics”, Phys. Rev. D, 49, 4454 (1994) arXiv:hep-ph/9312324
- [5] C.T. Hill, “Topcolor assisted technicolor”, Phys. Lett. B 345, 483 (1995) arXiv:hep-ph/9411426; Updates in arXiv:hep-ph/9911288
- [6] R. M. Harris and S. Jain, “Cross sections for leptophobic topcolor Z' decaying to top-antitop”, Eur. Phys. J. C, 72, 2072 (2012) arXiv:1112.4928
- [7] J.L. Rosner, “Prominent decay modes of a leptophobic Z' ”, Phys. Lett. B, 387, 113 (1996) arXiv:hep-ph/9607207
- [8] K.R. Lynch *et al.*, “Finding Z-prime bosons coupled preferentially to the third family at LEP and the Tevatron”, Phys. Rev. D, 63, 035006 (2001) arXiv:hep-ph/0007286
- [9] M.S. Carena *et al.*, “Z-prime gauge bosons at the Tevatron”, Phys. Rev. D, 70, 093009 (2004) arXiv:hep-ph/0408098
- [10] D. Dicus, A. Stange and S. Willenbrock, “Higgs decay to top quarks at hadron colliders”, Phys. Lett. B, 333, 126 (1994) arXiv:hep-ph/9404359
- [11] L. Randall and R. Sundrum, “Large Mass Hierarchy from a Small Extra Dimension”, Phys. Rev. Lett., 83, 3370 (1999)
- [12] K. Agashe *et al.*, “LHC Signals from Warped Extra Dimensions”, Phys. Rev. D, 77, 015003 (2008) arXiv:hep-ph/0612015
- [13] H. Davoudiasl, J.L. Hewwett and T.G. Rizzo, “Phenomenology of the Randall-Sundrum Gauge Hierarchy Model”, Phys. Rev. Lett., 84, 2080 (2000)
- [14] CDF Collaboration, “Forward-Backward Asymmetry in Top-Quark Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV”, Phys. Rev. Lett., 101, 202001 (2008) arXiv:1107.1473
- [15] D0 Collaboration, “Measurement of the Forward-Backward Charge Asymmetry in Top-Quark Pair Production”, Phys. Rev. Lett., 100, 142002 (2008) arXiv:0712.10851
- [16] CDF Collaboration, “Evidence for a mass dependent forward-backward asymmetry in top quark pair production”, Phys. Rev. D, 83, 112003 (2011) arXiv:1101.0034
- [17] , D0 Collaboration, “Forward-backward asymmetry in top quark-antiquark production”, Phys. Rev. D, 84, 112005 (2011) arXiv:1107.4995
- [18] Y. Bai *et al.*, “LHC Predictions from a Tevatron Anomaly in the Top Quark Forward-Backward Asymmetry”, JHEP 03, 003 (2011) arXiv:1101.5203
- [19] P.H. Frampton, J. Shu and K. Wang, “Axigluon as possible explanation for forward-backward asymmetry”, Phys. Lett. B, 683, 294 (2010) arXiv:0911.2955
- [20] M.I. Gresham, I.-W. Kim and K.M. Zurek, “On models of new physics for the Tevatron top AFB”, Phys. Rev. D, 83, 114027 (83) arXiv:1103.3501
- [21] O. Antuñano, J.H. Kühn and G. Rodrigo, “Top quarks, axigluons, and charge asymmetries at hadron colliders”, Phys. Rev. D, 77, 014003 (2008) arXiv:0709.1652
- [22] E. Álvarez *et al.*, “Phenomenology of a light gluon resonance in top-physics at Tevatron and LHC”, JHEP 09, 007 (2011) arXiv:1107.1473
- [23] T. Aaltonen *et al.*, “A Search for resonant production of $t\bar{t}$ pairs in 4.8 fb^{-1} of integrated luminosity of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV”, Phys. Rev. D, 84, 072004 (2011) arXiv:1107.5063
- [24] V. M. Abazov *et al.*, “Search for a narrow $t\bar{t}$ resonance in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV”, Phys. Rev. D, 85, 051101 (2012) arXiv:1111.1271
- [25] CMS Collaboration, “Search for anomalous $t\bar{t}$ production in the highly-boosted all-hadronic final state”, JHEP, 09, 029 (2012) arXiv:1204.2488
- [26] CMS Collaboration, “Search for resonant $t\bar{t}$ production in lepton+jets events in pp collisions at $\sqrt{s} = 7$ TeV”, JHEP, 12, 015 (2012) arXiv:1209.4397
- [27] CMS Collaboration, “Search for Z' resonances decaying to $t\bar{t}$ in dilepton+jets final states in pp collisions at $\sqrt{s} = 7$ TeV”, Phys. Rev. D, 87, 072002 (2013) arXiv:1211.3338
- [28] CMS Collaboration, “Searches for anomalous $t\bar{t}$ production in pp collisions at $\sqrt{s} = 8$ TeV”, Submitted to Phys. Rev. Lett., arXiv:1309.2030

- [29] ATLAS Collaboration, “A search for $t\bar{t}$ resonances in lepton+jets events with highly boosted top quarks collected in pp collisions at $\sqrt{s}=7$ TeV with the ATLAS detector”, JHEP, 09, 041 (2012) arXiv:1207.2409
- [30] ATLAS Collaboration, “Search for $t\bar{t}$ resonances in the lepton plus jets final state with ATLAS using 4.7 fb^{-1} of pp collisions at $\sqrt{s}=7$ TeV”, Phys. Rev. D., 88, 012004 (2013) arXiv:1305.2756
- [31] ATLAS Collaboration, “The ATLAS experiment at the CERN Large Hadron Collider”, JINST 3 S08003 (2008)
- [32] CMS Collaboration, “The CMS experiment at the CERN Large Hadron Collider”, JINST 3 S08004 (2008)
- [33] A. Avetisyan *et. al.*, “Methods and results for SM event generation at $\sqrt{s}=14$ TeV, 33 TeV, and 100 TeV proton colliders”, A Snowmass whitepaper (2013), arXiv:1308.1636
- [34] J. Anderson *et. al.*, “Snowmass Energy Frontier Simulations”, Snowmass whitepaper (2013), arXiv:1309.1057
- [35] http://www.snowmass2013.org/tiki-index.php?page=Energy_Frontier_FastSimulation
- [36] S. Oryn, X. Rouby, V. Lemaitre, “Delphes, a framework for fast simulation of a generic collider experiment”, arXiv:0903.2225
- [37] T. Sjöstrand, S. Mrenna, P. Skands, “A brief introduction to PYTHIA 8.1”, Comput. Phys. Commun. 178, 852 (2008) arXiv:0710.3820
- [38] N. Amos *et. al.*, Proceedings of the Computing in High Energy Physics Conference, Rio de Janeiro, Brazil (1995)
- [39] Gao, J. and Li, C. S. and Li, B. H. and Zhu, H. X. and Yuan, C.-P., “Next-to-leading order QCD corrections to a heavy resonance production and decay into top quark pair at the LHC”, Phys. Rev. D 82, 014020 (2010) arXiv:1004.0876
- [40] “theta—a framework for template-based modeling and inference”
<http://www-ekp.physik.uni-karlsruhe.de/~ott/theta/testing/html>
- [41] G. Cowan, “PDG Review on statistics” (chapter 33), JPG 37, 075021, (2010)