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 $\int L \, dt = 300$ fb$^{-1}$ and $\int L \, dt = 3000$ fb$^{-1}$. We present the expected $5\sigma$ 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 tt pair and that appears as a resonant structure superimposed on the SM tt 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 tt pairs. The recent observation of forward-backward asymmetry in tt 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 tt production at high invariant mass. The top quark, and tt production in particular, is a powerful probe of potential new physics.

Direct searches for heavy tt 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 Z′ 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′ (Γ_{Z′} = 0.012 M_{Z′}) below M_{Z′} = 2.1 TeV at 95% C.L. [25–30].

The null results indicate that tt 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′ → tt → W^+b W^−b production in pp collisions at the upgraded LHC operating at √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^−, μ^±μ^−, or e^±μ^±), at least two jets from the hadronization of b/¯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 → ℓν decay that is partially or fully overlapped with the b-quark jet from t→Wb decay.

The dominant (irreducible) background is the tt continuum production. Other SM processes contributing to the background are the production of single top quarks, Z/γ*/W+jets, and dibosons (WW, WZ, and ZZ). We consider two potential data sets, one corresponding to ∫ Lt = 300 fb−1 and the other to ∫ Lt = 3000 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 Γ_{Z′} = 0.012 M_{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 √s = 14 TeV: ∫ Lt = 300 fb−1, with an average number of pile-up events of <PU> = 50 events per bunch crossing (LHC Run 2), and ∫ Lt = 3000 fb−1, with <PU> = 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 $\int \mathcal{L} dt = 300$ fb$^{-1}$ and $\int \mathcal{L} dt = 3000$ 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 $\Delta R$ 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 $\Delta R$ 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 $\int \mathcal{L} dt = 300$ 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 $\Delta R$ 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 $\int \mathcal{L} dt = 300$ fb$^{-1}$ luminosity.](image-url)
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 5\( \sigma \) 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 \( t\bar{t} \) (\( \sigma_{Z'} B \)), 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 \( \text{ fb}^{-1} \) after selection cuts are applied.
with the theoretical prediction for the production cross section of a leptophobic $\ell\ell$ from $6 - 300 (2 - 60) \, \text{fb}$ with luminosities that would yield a signal with a statistical significance of $5\sigma$ 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, $\sigma_{Z'} B$, ranges from $6 - 300 (2 - 60) \, \text{fb}$ with $\int \mathcal{L} \, dt = 300 \, \text{fb}^{-1}$ ($\int \mathcal{L} \, dt = 3000 \, \text{fb}^{-1}$) for the mass range $2 - 5 \, \text{TeV}$. Comparing these with the theoretical prediction for the production cross section of a leptophobic $Z'$ yields the expected $Z'$ discovery mass reach of $2.8 \, \text{TeV}$ with $\int \mathcal{L} \, dt = 300 \, \text{fb}^{-1}$ and $4.1 \, \text{TeV}$ with $\int \mathcal{L} \, dt = 3000 \, \text{fb}^{-1}$.

Figure 4 (right) shows expected 95% C.L. limits on $\sigma_{Z'} B$ as a function of $M_{Z'}$ for the two luminosity scenarios. The expected limits range from $2 - 100 (1 - 20) \, \text{fb}$ with $\int \mathcal{L} \, dt = 300 \, \text{fb}^{-1}$ ($\int \mathcal{L} \, dt = 3000 \, \text{fb}^{-1}$) for the mass range $2 - 5 \, \text{TeV}$. 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 $< 4.4 (4.7) \, \text{TeV}$ 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 $\sigma_{Z'} B$ for a $5\sigma$ observation (left) and upper limits at 95% C.L. on $\sigma_{Z'} B$ (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 $< \text{PU} > = 50$, and $\int \mathcal{L} \, dt = 3000 \, \text{fb}^{-1}$ with $< \text{PU} > = 140$. 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 $5\sigma$. 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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