Study on the prospects of a $t\bar{t}$ resonance search in events with one lepton at a High Luminosity LHC

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Abstract

A study on the prospects of a search for a new particle decaying to a top quark pair at the High Luminosity LHC using Monte Carlo simulations is presented. The proposed search will assume an integrated luminosity of 3000 fb$^{-1}$ of proton-proton collision data taken at $\sqrt{s} = 14$ TeV. Detector effects are accounted for using parameterised estimates of the performance of an upgraded ATLAS detector. The search is carried out by examining the $t\bar{t}$ invariant mass spectrum for localised excesses or deficits. A statistical analysis sets expected upper limits on the cross section of a $t\bar{t}$ resonance in a benchmark model for several signal masses. The mass reach of a search for a $Z'$ boson in the TopColour model at the HL-LHC is estimated to be 4 TeV. This is an increase of $\sim 1$ TeV relative to the estimated limit using 300 fb$^{-1}$ that is expected from the LHC prior to the upgrade.

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1 Introduction

This note documents a study carried out to investigate the prospects of a search for $t\bar{t}$ resonances at the High Luminosity LHC (HL-LHC). Several theories of physics beyond the Standard Model predict new particles with masses in the TeV scale that decay primarily to a $t\bar{t}$ pair. A $t\bar{t}$ resonance search is a benchmark analysis for evaluating physics prospects at the HL-LHC. The 14 TeV collision energy will increase the mass reach of the search over previous searches and the large increase in statistics will tighten the upper limits that, in the absence of signal, can be set on the cross sections of hypothesised heavy resonances. This study will estimate the impact of the increased statistics, collision energy and upgraded detector on the sensitivity of the search.

A $t\bar{t}$ resonance would cause a local excess or deficit in the $t\bar{t}$ mass spectrum as predicted by the Standard Model. A search for such a deviation is performed on $t\bar{t}$ pairs selected from events in Monte Carlo simulations of proton-proton collisions with a centre of mass energy of 14 TeV, over a total integrated luminosity of 3000 fb$^{-1}$. The search is performed in the semi-leptonic decay channel: both top quarks decay to a b quark and a $W$ boson; one $W$ decays to two quarks and the other decays to a lepton and a neutrino ($t\bar{t}\rightarrow WbWb\rightarrow lvbqq'b$). It is carried out as follows. The invariant mass of selected $t\bar{t}$ pairs in Monte Carlo simulation for signal and background is reconstructed and the expected $t\bar{t}$ mass spectrum is prepared under the signal-plus-background hypothesis and under the background-only hypothesis. The limit setting procedure [1] uses a likelihood model based on the binned mass spectrum to calculate the expected upper cross section limits for a benchmark signal model, for a range of resonance masses. The upper cross section limits are compared to the theoretical signal cross section to estimate the mass reach of the analysis. These results are compared to analogous results for 300 fb$^{-1}$, the amount of data anticipated from the LHC before the HL-LHC commences, to estimate the gain in sensitivity that can be expected from the HL-LHC data. The same detector configuration and pileup conditions are used for the 300 fb$^{-1}$ and 3000 fb$^{-1}$ results. The method of the search is independent of the signal model and can be adapted to test specific mass, resonance width and cross section predictions of different theoretical models. The effects of an upgraded ATLAS detector are taken into account by applying energy smearing, efficiencies and fake rates to truth level quantities, following parameterisations based on detector performance studies with full simulation and HL-LHC conditions.

Each step in this analysis, including object selection, event selection, mass reconstruction and statistical analysis, follows what was done in ATLAS Run 1 and 2 $t\bar{t}$ resonance searches, although the procedures are largely simplified. A similar analysis carried out in 2013 [2] estimated the increase in sensitivity to heavy $t\bar{t}$ resonances when the total integrated luminosity collected by ATLAS at 14 TeV is increased from 300 fb$^{-1}$ to 3000 fb$^{-1}$. A full search carried out on 20.3 fb$^{-1}$ of $\sqrt{s} = 8$ TeV Run 1 data found no evidence of $t\bar{t}$ resonances and placed 95% confidence level upper limits on the production of a $t\bar{t}$ resonance as predicted by a set of benchmark models [3]. The search excluded a narrow leptophobic Topcolour $Z'$ boson with mass $< 1.8$ TeV. The strongest mass limit on this resonance is currently 2.1 TeV [3].

2 Monte Carlo Samples

Background and signal samples are generated using Monte Carlo techniques.

Signal A Topcolour model containing a spin-1 $Z'$ boson is used as the signal in this study [4–6]. The signal simulation $pp \rightarrow Z' \rightarrow t\bar{t}$ was done with Pythia 8 [7] and assuming a signal width of 1.2%.
Samples at $m_{Z'} = 1$-7 TeV were generated, using the A14NNPDF23LO PDF set. Leading order cross sections are used for each signal sample, multiplied by a k-factor of 1.3 to account for NLO effects [8]. The interference between the signal and $t\bar{t}$ background, which can have a large impact on the shape at low mass, is neglected.

**Standard Model Backgrounds**

The main background is Standard Model $t\bar{t}$ production (in the single lepton decay channel), which was generated using Powheg+Pythia [9], using the CT10 PDF set and setting the hdamp parameter to the top mass. NNLO cross sections were used [10]. $W$+jets and $Z$+jets were generated with Sherpa (merged Matrix Element+Parton shower, matched and merged for 0-4 additional QCD partons in LO), using CT10 PDF set [11]. Single top production was generated by AcerMCPythia [12]. The cross sections were scaled to NNLO except single top which was NLO [13, 14].

3 Detector Effects and Object Selection

Studies on the performance of the upgraded phase-II ATLAS detector at the HL-LHC are documented in Ref. [15]. The performance studies assume a centre of mass energy of $\sqrt{s} = 14$ TeV, instantaneous luminosities of up to $7.4\times10^{34}$ cm$^{-2}$s$^{-1}$ and an average of 200 proton-proton interactions per bunch crossing. The upgraded detector is fully simulated. The results of these studies were used to derive functions that provide parameterised estimates of detector performance for different objects. These functions are $p_T$ and $\eta$ dependent and are applied to truth quantities to emulate energy resolution, efficiencies and fake rates. Efficiencies are implemented for each object by generating a uniformly distributed random number, $n_{\text{rand}}$, between 0 and 1 and comparing the random number to the estimated efficiency for the object, $n_{\text{eff}}$. The object is kept if $n_{\text{rand}} < n_{\text{eff}}$, otherwise it is discarded. Efficiency functions are available for electron identification, muon identification and $b$-tagging. Fake rates are implemented as follows. If there is a probability that an object of type A will be mis-identified as an object of type B, then, for each type A object, a uniform random number, $n_{\text{rand}}$, is compared to the estimated fake rate for the object, $n_{\text{fake}}$. If $n_{\text{rand}} < n_{\text{fake}}$ then the object is moved from the list of type A objects to the list of type B objects. Otherwise, it remains a type A object. There are fake rate functions for jets (sometimes mis-identified as electrons [16]) and $b$-tagging (light and pileup jets can be mis-tagged as $b$-jets) [15]. Energy resolution functions alter the four-momentum of truth-level objects by a random amount that on average reflects the expected resolution of the detector; this is referred to as energy smearing [15]. The object selection criteria are applied to smeared quantities.

**Leptons**

Truth level electrons and muons are required to be isolated by requiring the sum of other final state charged particles’ $p_T$, within $\Delta R(\ell, \text{object}) = 10$ GeV/$p_T, \ell$, less than 6% of the lepton $p_T$. The two dimensional radial distance between objects observed in ATLAS is measured in $(\eta, \phi)$ space:

$$\Delta R(\ell, \text{object}) = \sqrt{\Delta \eta(\ell, \text{object})^2 + \Delta \phi(\ell, \text{object})^2} \quad (1)$$

Lepton identification efficiencies are applied to isolated electrons and muons. These efficiencies depend on the criteria that a lepton candidate must pass in order to be identified as a lepton [15]. There are three possible sets of criteria that can be used, referred to as loose, medium and tight. In this analysis electrons and muons are required to pass the tight criteria, which rejects the most background. Once identification efficiencies are applied, the energies of the remaining leptons are smeared according to the expected detector resolution. Fake rates for jets faking electrons [16] are applied it all truth anti-$k_T$, R=0.4 jets, identifying a small fraction of jets that are moved to the list of electrons, with their energy smeared.
to the appropriate fake electron energy. Jets faking electrons are not required to pass the lepton isolation criteria. Electrons and muons are then required to have \( p_T > 30 \) GeV and \( p_T > 25 \) GeV respectively. Leptons must also have \( \eta \) within the acceptance of the inner detector (\( 1.37 < |\eta| < 2.47 \) for electrons and \( |\eta| < 2.5 \) for muons).

**Small-R jets** The anti-\( k_t \) algorithm with a radius parameter of \( R = 0.4 \) is used to create small-R jets. As mentioned previously, a fraction of jets misidentified as electrons are removed from the list of truth jets by applying a fake rate [15]. Pileup jets are included from a pileup library built assuming an average of 200 proton-proton interactions per bunch crossing (\( \langle \mu \rangle = 200 \)). It is known at truth level whether a jet is a \( b \)-jet (i.e. contains a \( b \)-hadron). Flavour tagging efficiencies are applied to truth \( b \)-jets, identifying a fraction that are successfully \( b \)-tagged by the MV1 \( b \)-tagging algorithm, which is set to a working point of 70% [15]. Flavour tagging fake rates are also applied to light and pileup jets to identify jets which do not contain a \( b \)-hadron, but are mis-tagged as \( b \)-jets. Track confirmation algorithms are used to mitigate pileup by selecting jets with tracks that can be traced back to the primary vertex; track confirmation efficiencies are applied to hard-scatter and pileup jets. The energies of the remaining small-R truth jets that pass track confirmation are smeared. All small-R jets must have \( p_T > 25 \) GeV and \( |\eta| < 2.5 \).

**Large-R jets** The anti-\( k_t \) algorithm with a radius parameter of \( R = 1.0 \) is used to create large-R jets. The large-R jets are trimmed with trimming parameters \( p_T \) fraction = 0.05 and \( R = 0.2 \). No top-tagging efficiencies are applied to the large-R jets, which are candidates for boosted hadronic top quark decays. The \( p_T \) of the large-R jets is smeared by using a Gaussian of width 5%. Large-R jets must have \( p_T > 300 \) GeV and \( |\eta| < 2.0 \).

**Missing transverse momentum** The missing transverse momentum is determined from the vector sum of interacting truth particles within the detector acceptance. The values of missing \( p_x \) and missing \( p_y \) are smeared; the smeared values are used to obtain the total missing transverse energy in the event [17].

**Overlap removal** Electron energy deposits in the calorimeter can be clustered by a jet algorithm, resulting in electrons being double counted as jets. In this analysis, the truth jets are made with all final state particles, including electrons. To avoid the double counting of electrons, the nearest small-R jet to an electron is removed from the list of jets if \( \Delta R(electron,jet) < 0.2 \). Next, any electron within \( \Delta R = 0.4 \) of a remaining jet is assumed to be a decay product of a \( b \)-jet and is removed from the list of electrons. To mitigate muon-jet overlap, muons within \( \Delta R = 0.04 + (10 \text{GeV}/p_T,\mu) \) are removed. Additionally, small-R jets within \( \Delta R = 1.0 \) of large-R jets are removed from the list of jets.

### 4 Event Selection

#### 4.1 Preselection

Events are required to have exactly one lepton passing object selection. Single lepton trigger efficiencies are applied to these events [15]. There must be missing transverse energy \( E_{T\text{miss}} > 20 \) GeV and \( E_{T\text{miss}} + m_{W}^{\ell} > 60 \) GeV. Events must contain at least one jet that was identified as containing a \( b \)-hadron by the MV1 \( b \)-tagging algorithm. These cuts are applied with the aim of suppressing the non-irreducible backgrounds, the largest of which is \( W \)+jets. Events are separated into topological decay channels: boosted and resolved. The top quark which decays leptonically (\( t \rightarrow Wb \rightarrow l\nu b \)) is referred to as \( t_{\text{lep}} \), and the top quark which decays hadronically (\( t \rightarrow Wb \rightarrow q\bar{q}b \)) is referred to as \( t_{\text{had}} \). In a boosted event, all the decay products \( t_{\text{had}} \) are detected inside one large-R jet. In a resolved event, the jet decay products of \( t_{\text{had}} \) and \( t_{\text{lep}} \) are detected
as well separated small-R jets. Events are further separated into four channels depending on whether the single lepton is an electron or a muon. Thus the four channels are boosted electron, resolved electron, boosted muon and resolved muon, and are recombined for the limit setting procedure.

4.2 Boosted Channel

Events passing the preselection are initially tested against the boosted selection. A boosted event must contain at least one small-R jet such that $\Delta R(\text{jet, lepton}) < 1.5$. If there is more than one jet that meets this criteria then the highest $p_T$ jet is chosen as the candidate for the $b$-jet decaying from the leptonic top. This jet is referred to as the selected jet, $j_{sel}$. Additionally, boosted events must contain at least one large-R jet such that:

- $\Delta R(\text{large-R jet, } j_{sel}) > 1.5$
- $\Delta \phi(\text{large-R jet, lepton}) > 2.3$

If more than one large jet satisfies these requirements, the highest $p_T$ jet is chosen and is taken to comprise the decay products of $t_{\text{had}}$.

4.3 Resolved Channel

Events are tested against the resolved selection only if they fail the boosted selection, to ensure exclusive channels. Resolved events must contain at least four small-R jets. A $\chi^2$ algorithm, detailed in section 5, is used to iteratively test each four-jet combination in the event and choose the optimal combination, matching them to the decay products of the top quarks. Resolved events must have $\chi^2 < 10$. Event yields after each cut in the electron and muon channel are shown in Tables 1 and 2 respectively.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$tt$</th>
<th>$W+$jets</th>
<th>$Z+$jets</th>
<th>single top</th>
<th>$Z'$ (3 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>1.37e+09</td>
<td>3.9e+08</td>
<td>9.3e+08</td>
<td>2.35e+08</td>
<td>2.97e+04</td>
</tr>
<tr>
<td>Electron ($e$)</td>
<td>2.15e+08</td>
<td>5.5e+07</td>
<td>1.39e+08</td>
<td>2.85e+07</td>
<td>4.9e+03</td>
</tr>
<tr>
<td>$E_T^{\text{miss}} &gt; 20$ GeV ($e$)</td>
<td>2.05e+08</td>
<td>5.2e+07</td>
<td>1.26e+08</td>
<td>2.70e+07</td>
<td>4.8e+03</td>
</tr>
<tr>
<td>$E_T^{\text{miss}} + m_W &gt; 60$ GeV ($e$)</td>
<td>1.97e+08</td>
<td>5.0e+07</td>
<td>1.17e+08</td>
<td>2.57e+07</td>
<td>4.7e+03</td>
</tr>
<tr>
<td>$\geq 1$ $b$-tag ($e$)</td>
<td>1.42e+08</td>
<td>1.50e+07</td>
<td>2.90e+07</td>
<td>1.50e+07</td>
<td>3.41e+03</td>
</tr>
<tr>
<td>Resolved ($e$)</td>
<td>9.5e+07</td>
<td>6.6e+06</td>
<td>1.36e+07</td>
<td>8.2e+06</td>
<td>3.13e+02</td>
</tr>
<tr>
<td>Boosted ($e$)</td>
<td>2.99e+06</td>
<td>1.68e+03</td>
<td>5.6e+04</td>
<td>3.48e+04</td>
<td>2.11e+03</td>
</tr>
</tbody>
</table>

Table 1: Event yields in the electron channel after each selection cut for 3000 fb$^{-1}$.

5 Event Reconstruction

The invariant mass of $t\bar{t}$ pairs is reconstructed for events selected as consistent with semi-leptonic $t\bar{t}$ decay.
<table>
<thead>
<tr>
<th>Sample</th>
<th>$tt$</th>
<th>$W+$jets</th>
<th>$Z+$jets</th>
<th>single top</th>
<th>$Z'$ (3 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>1.37e+09</td>
<td>3.9e+08</td>
<td>9.3e+08</td>
<td>2.35e+08</td>
<td>2.97e+04</td>
</tr>
<tr>
<td>Muon ($\mu$)</td>
<td>2.96e+08</td>
<td>7.2e+07</td>
<td>1.29e+08</td>
<td>4.4e+07</td>
<td>4.5e+03</td>
</tr>
<tr>
<td>$E_T^{\text{miss}} &gt; 20$ GeV ($\mu$)</td>
<td>2.83e+08</td>
<td>6.9e+07</td>
<td>1.18e+08</td>
<td>4.2e+07</td>
<td>4.4e+03</td>
</tr>
<tr>
<td>$E_T^{\text{miss}} + m_T^W &gt; 60$ GeV ($\mu$)</td>
<td>2.72e+08</td>
<td>6.6e+07</td>
<td>1.09e+08</td>
<td>4.0e+07</td>
<td>4.4e+03</td>
</tr>
<tr>
<td>$\geq 1$ b-tag ($\mu$)</td>
<td>1.94e+08</td>
<td>1.85e+07</td>
<td>2.45e+07</td>
<td>2.26e+07</td>
<td>3.28e+03</td>
</tr>
<tr>
<td>Resolved ($\mu$)</td>
<td>1.34e+08</td>
<td>8.5e+06</td>
<td>1.02e+07</td>
<td>1.28e+07</td>
<td>2.34e+02</td>
</tr>
<tr>
<td>Boosted ($\mu$)</td>
<td>3.45e+06</td>
<td>1.94e05</td>
<td>4.2e04</td>
<td>3.8e+04</td>
<td>2.34e+03</td>
</tr>
</tbody>
</table>

Table 2: Event yields in the muon channel after each selection cut for 3000 fb$^{-1}$.

**Leptonically decaying $W$ ($W_{\text{lep}}$)** The missing $p_x$ and $p_y$ in an event are assumed to be the neutrino $p_x$ and $p_y$. The neutrino $p_z$ component is determined by imposing a $W$ boson mass (PDG value) constraint on the mass of the neutrino-lepton system. This yields a quadratic equation that is solved for the neutrino $p_z$. If the solution is complex, the real part is used as $p_z$. If there are two real solutions and the event is boosted, the one with the smallest absolute value is used as $p_z$. If there are two real solutions and the event is resolved, both solutions $p_z$ solutions are tested by the $\chi^2$ which is used to identify decay products in a resolved event.

**Boosted event** The leptonically decaying top quark, $t_{\text{lep}}$, is reconstructed from $W_{\text{lep}}$ and $j_{\text{sel}}$, and the hadronically decaying top quark, $t_{\text{had}}$, from the large-R jet.

**Resolved event** In a resolved event, one unique small-R jet is selected for each hadronic decay product (the $b$-jets decaying from $t_{\text{lep}}$ and $t_{\text{had}}$ and the two jets decaying from $W_{\text{had}}$) using a $\chi^2$ algorithm shown in equation 2. Each combination of four small-R jets is tested and the combination giving the smallest $\chi^2$ value is chosen. If there are two real solutions for $p_z$, each $W_{\text{lep}}$ scenario is also tested in the algorithm. The first three terms in the $\chi^2$ algorithm compare the expected reconstructed top quark and $W$ boson masses to the masses of the reconstructed tops and $W$ built from the candidate decay jets. The $\sigma$ terms in the denominator account for the expected mass resolution of the reconstructed tops and $W$s. (If a large spread in mass values is expected, then the constraint for the reconstructed mass to be near the expected mass is loosened). The expected mass and resolution values for $t_{\text{lep}}$ ($m_{1\ell}, \sigma_{1\ell}$), $t_{\text{had}} - W_{\text{had}}$ ($m_{th-W}, \sigma_{th-W}$) and $W_{\text{had}}$ ($m_W, \sigma_W$) are estimated by reconstructing the tops and $W$ in events where it is possible to select the correct decay jets using MC truth information and plotting the mass distribution for these events only. This yields a gaussian distribution, and the expected reconstructed mass and resolution are taken from the mean and $\sigma$ of the gaussian. The first $\chi^2$ term directly constrains the mass of the two jets matched to $W_{\text{had}}$ to be near the expected $W_{\text{had}}$ mass, and the third term does the same for $t_{\text{lep}}$. The second term indirectly constrains the mass of the reconstructed $t_{\text{had}}$ since $m_{\text{had}}$ and $m_{\text{Whad}}$ are highly correlated. The fourth term constrains $\Delta p_T(t_{\text{had}},t_{\text{lep}})$, favouring events where the two top quarks have similar $p_T$, which is expected in a resonance event. This method aims to optimise the proportion of successful decay product matches in a resolved event. A cut $\chi^2 < 10.0$ is applied to resolved events.

$$\chi^2 = \left[ \frac{m_{jj} - m_W}{\sigma_W} \right]^2 + \left[ \frac{m_{jjb} - m_{jj} - m_{th-W}}{\sigma_{th-W}} \right]^2 + \left[ \frac{m_{jj\ell} - m_{1\ell}}{\sigma_{1\ell}} \right]^2 + \left[ \frac{(p_{T, jjb} - p_{T, jj\ell}) - (p_{T, th} - p_{T, 1\ell})}{\sigma_{\Delta p_T}} \right]^2$$

(2)
The following values extracted from Monte Carlo studies are used for the mass and \( \sigma \) parameters. 
\[
\begin{align*}
  m_W &= 83.7 \text{ GeV}, \\
  m_{\text{th}-W} &= 91.2 \text{ GeV}, \\
  m_{t\bar{t}} &= 167.6 \text{ GeV}, \\
  \sigma_W &= 8.4 \text{ GeV}, \\
  \sigma_{\text{th}-W} &= 11.1 \text{ GeV}, \\
  \sigma_{t\bar{t}} &= 21.8 \text{ GeV}, \\
  p_T,_{\text{th}-p_T,_{t\bar{t}}} &= -0.0012 \text{ GeV} \text{ and } \sigma_{\Delta p_T} = 34.7 \text{ GeV}.
\end{align*}
\]

\( m_{jj}, m_{jjb}, m_{jj\nu}, p_{T,jjb}, \text{ and } p_{T,jj\nu} \) are variables reconstructed from the decay candidates in the iteration.

### 6 Results

A statistical analysis is performed using HistFactory [1] to determine the expected upper limits that can be set on the signal cross section in the absence of signal. The \( t\bar{t} \) invariant mass distribution is constructed for the background-only hypothesis and for signal-plus-background hypotheses with varying signal strength \( \mu \), where \( \mu = 0 \) corresponds to the background only model and \( \mu = 1 \) is the prediction of the signal model. A likelihood function based on the binned \( t\bar{t} \) mass spectrum is used to exclude values of \( \mu \) with 95% confidence. The expected upper limit set on the signal cross section is the greatest value of \( \mu \) that is not excluded with 95% confidence. This procedure is carried out for each signal mass. A luminosity uncertainty of 3% is included. A systematic uncertainty on the total signal and background yield in each channel is applied: 8.8% on the resolved signal channel, 18.0% on the boosted signal channel, 10.8% on the resolved background channel and 13.4% on the boosted background channel. The uncertainties are taken from the Run 1 analysis and reflect the average impact of the dominant systematic uncertainties on the yields and are treated as correlated across the channels [3]. Stacked \( t\bar{t} \) mass spectra for all included backgrounds and two signal points are shown for each channel in Figure 1. Most signal events fall into the boosted channels, where the excess of events is localised around the signal mass. The boosted channel dominates the limit setting. The expected upper limits set on the signal cross section \( \times \) branching ratio as a function of the signal mass are shown in Figure 2, with \( \int L = 300 \text{ fb}^{-1} \) and \( \int L = 3000 \text{ fb}^{-1} \). A line showing the theoretical cross section of the \( Z' \) boson at each mass indicates the mass reach of the search, which is estimated to be \( \approx 3 \text{ TeV} \) with 300 fb\(^{-1}\) and \( \approx 4 \text{ TeV} \) with 3000 fb\(^{-1}\) of p-p collisions, using the same detector configuration and pileup conditions. A factor of ten increase in the total integrated luminosity is expected to increase the sensitivity of the search to this benchmark signal by \( \approx 1 \text{ TeV} \).
Figure 1: The reconstructed mass spectrum of $t\bar{t}$ pairs selected from signal and background events with 3000 fb$^{-1}$ of simulated $\sqrt{s} = 14$ TeV p-p collisions. The background normalisations are obtained from the theoretical cross sections. Standard Model $t\bar{t}$, W+jets, Z+jets and single top events are included. The cross sections of the signal samples, $Z'$ (2 TeV) and $Z'$ (3 TeV), are multiplied by 50 for visibility and shown on the boosted channel plots. These signals are not visible in the resolved channel, so a $Z'$ (1 TeV) sample is shown on the resolved channel plots, with its cross section multiplied by 50.
Figure 2: The expected upper limits set on the cross section \( \times \) branching ratio of the Topcolour Z' boson for masses 1-7 TeV, with 300 fb\(^{-1}\) (a) and 3000 fb\(^{-1}\) (b) of simulated \( \sqrt{s} = 14\) TeV p-p collisions. The theoretical signal cross section intersects with the 300 fb\(^{-1}\) limits line at \( \approx 3\) TeV and with the 3000 fb\(^{-1}\) line at \( \approx 4\) TeV. We can expect to exclude this resonance for \( m_{Z'} < \sim 3\) TeV after Run 3 and \( m_{Z'} < \sim 4\) TeV after HL-LHC.
References


[17] ATLAS Collaboration, 
Jet/EtMiss performance studies for the High-Luminosity LHC for ECFA 2016 (),