Search for New Resonances Decaying into Top-Quark Pairs Using Lepton-Plus-Jets Events in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector

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Abstract

A search for new resonances that decay into top-quark pairs is performed using data collected from proton-proton collisions at a centre-of-mass energy of 13 TeV by the ATLAS detector at the Large Hadron Collider. The integrated luminosity of the data sample is 36.1 fb^{-1}. Events consistent with top-quark pair production are selected by requiring a single isolated charged lepton, missing transverse momentum and jet activity compatible with a hadronic top-quark decay. The invariant mass spectrum of the candidate top-quark pairs is examined for excesses above the background expectation. No significant deviations from the Standard Model predictions are found.

Keywords: BSM, exotics, heavy flavours, top quark, new resonance, ATLAS, LHC
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1. INTRODUCTION

The Large Hadron Collider (LHC) [1] is the largest, and most powerful proton-proton (pp) accelerator in the world hosted in the CERN laboratory near the Swiss-France border. The collider tunnel consist on four major experiments with circumstance of 27 Km and 100 m underground. ATLAS [2] is one of the general-purpose detectors at the LHC. It is a 46 m long, a 25 m diameter and a mass of 7000 tons. It consists of multiple sub-detectors layers surrounding the interaction point. This proceedings presents, in a way that is model-independents as much as possible, the experimental sensitivity in ATLAS to new resonances in the $t\bar{t}$ invariant mass distribution. This is done in a scenario of the integrated luminosity of 36.1 fb^{-1} collected by the ATLAS detector from LHC proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 13$ in 2015 and 2016.

2. PHENOMENOLOGY OF SEARCHES FOR $T\bar{T}$ RESONANCES

Searches for heavy particles whose produce resonances in the top-anti top ($t\bar{t}$) mass spectrum are of high-rise interest at the LHC due to the key role played by the top quark in several exotic models beyond the SM (BSM). The top quark is the heaviest of all known fundamental particles, which lead to a large Yukawa coupling to the Higgs Boson. Therefore, many models that advance alternative mechanisms for electroweak symmetry breaking (EWSB), integrate new heavy particles with a strong coupling to the third-generation quarks than to lighter quarks. Different benchmark scenarios are explored in this search, a first possible extension to the SM produces spin-1 leptophobic boson denoted Z'_{TC2} conformed to the topcolor-assisted technicolour (TC2) [3]. This boson couples preferentially to the top quark also is characterised by three parameters (cot θ_H, f_1, f_2) controlling the width and the branching ratio to $t\bar{t}$ final states. The second category of benchmarks adapt spin-1 colour-octet vector boson as postulated by Randall-Sundrum (RS) models with a single warped extra dimension [4]. It is a heavy Kaluza-Klein gluon, denoted g_{KK} with nominal widths varying between 10% and 40% of its mass. The strong coupling of these gluon excitations to light quarks is set to $g_q = -0.2g_s$, where g_s is the SM gluon coupling. The third benchmark forms spin-2 colour singlet bosons, such as Kaluza-Klein excitations of the graviton (G_{KK}), commonly referred to as a "Bulk" Randall-Sundrum graviton [5]. The G_{KK} width varies from 3% to 6% in the mass range 0.4-3 TeV. The branching ratio of the G_{KK} decay into a $t\bar{t}$ pair increases rapidly from 18% to 50% for masses between 400 and 600 GeV, plateauing at 68% for masses larger than 1 TeV.

3. SEARCH FOR $T\bar{T}$ RESONANCES IN THE LEPTON + JETS FINAL STATE

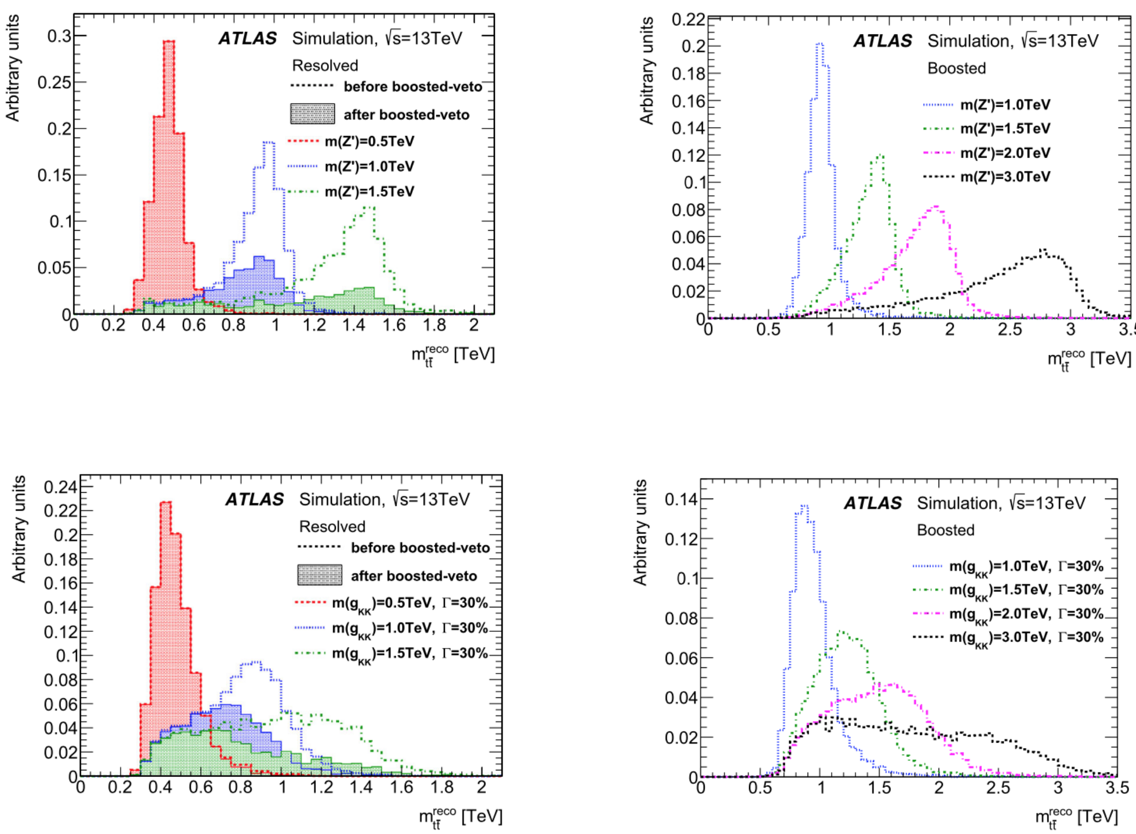
The search for new particles in the $t\bar{t}$ production is performed in [6] in the lepton+jets topology, using a single muon or electron (indicated with ℓ) as a trigger. The signature is a deviation from the $t\bar{t}$ mass spectrum predicted by the SM. The selection requires a single isolated ℓ with $p_T > 25$ GeV, large missing transverse momentum (E_T^{miss}) , and hadronic jets. At least one of the jets must be identified as a b-jet. Four categories have been considered and are as follows: Category 0 considers only events with no b-tagged jet matching to the hadronic- nor leptonic-top candidates, while categories 1 and 2 consider events with only the leptonic and hadronic top candidate that have a matching b-tagged jet, respectively. Category 3 contains events with both the hadronic-top and the leptonic-top candidates that have a matching b-tagged jet. Based on the hadronic activity, the event is calssified as Boosted or Resolved. The reconstruction of the event is based on three types of jets, all using the anti-k_t algorithm: the small-R jets are the standard, calorimeter-based jets, reconstructed with a radius parameters R=0.4; with $p_T > 25$ GeV and $|\eta| < 2.5$. The large-R jets, with $p_T > 300$ GeV and $|\eta| < 2.0$, are reconstructed with R=1.0, but also have a "trimming" process, to discard low-energy sub-jet components, which are due to event pile-up. The track-jets are reconstructed from charged tracks, with R=0.2, $p_T > 10$ GeV and $|\eta| < 2.5$. A lepton p_T-dependent isolation cut is also used. An event passes the Boosted selection if meets the following critaria: A small-R jet (Jsel), with no specific b-tagging is required to be near to the lepton, at $\Delta R(jet - \ell) < 1.5$ ($\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$). The large-R jet is required to be at a large azimuthal angle from both the lepton ($\Delta\phi_l > 2.3$ rad) and from Jsel ($\Delta\phi_l > 1.5$ rad). Events that fail any of these Boosted selection requirements are classified as passing the Resolved selection if there are at least 4 small-R jets with $p_T > 25$ GeV and if the $\chi 2$ algorithm for the reconstructing $t\bar{t}$ system [7] yields a value of $log_{10}(\chi 2) < 0.9$. Cuts on E_T^{miss} are also required: $E_T^{miss} > 20$ GeV and $E_T^{miss} + m_T^W > 60$ GeV.

4. $T\bar{T}$ INVARIANT MASS RECONSTRUCTION

Following the event selection, an observable $m_{t\bar{t}}^{reco}$ is constructed from the physics objects to approximate the invariant mass of the $t\bar{t}$ system. For events passing the boosted selection, the $m_{t\bar{t}}^{reco}$ is reconstructed by summing up the four transverse momentum of: selected jet, charged lepton, neutrino and top tagged Large-R jet. For events passing the resolved selection, a $\chi 2$ minimization algorithm is employed to select the right jets combination (that minimise the $\chi 2$ value) assigned to the leptonic-top candidate and hadronic-top candidate in order to reconstruct the $t\bar{t}$ system [6]. Using the four- momenta of the neutrino, lepton, and all small-R jets in the event, a $\chi 2$ is defined using the expected top-quark and W boson masses:

$$\chi^2 = \left[\frac{m_{jj} - m_W}{\sigma_W}\right]^2 + \left[\frac{m_{jjb} - m_{jj} - m_{th-W}}{\sigma_{th-W}}\right]^2 + \left[\frac{m_{j\ell\nu} - m_{tl}}{\sigma_{t\ell}}\right]^2 + \left[\frac{(p_{\mathrm{T},jjb} - p_{\mathrm{T},j\ell\nu}) - (p_{\mathrm{T},th} - p_{\mathrm{T},t\ell})}{\sigma_{diffp\mathrm{T}}}\right]^2. \quad (1)$$

The resulting $m_{t\bar{t}}^{reco}$ distributions for several signal masses $t\bar{t}$ are shown in Figure [1], where all events satisfying the selection criteria are considered.



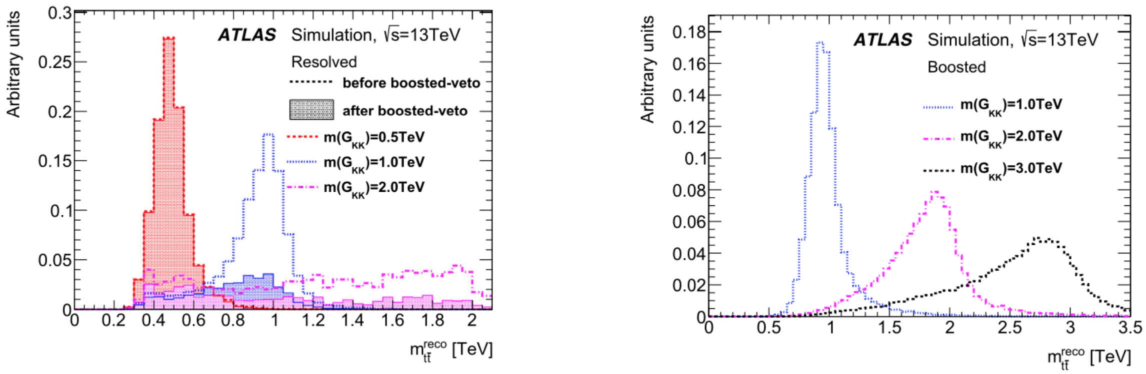


FIGURE 1: Reconstructed invariant masses for the resolved (left) and boosted (right) selections for the Z'_{TC2} (top), g_{KK} (middle) and G_{KK} (bottom) signals. [6]

5. MULTI-JET BACKGROUND ESTIMATION USING DATA

The multi-jet background consists mainly of events that have a jet that is mis-reconstructed as a lepton. The normalisation, kinematic distributions, and statistical and systematic uncertainties associated with the multi-jet background are estimated from data using a technique known as a matrix method. This method boils down to solving a set of two equations. Those equations are built from a two-stage event selection process. First a data sample is selected requiring the lepton to satisfy loose isolation criteria; this is thereafter referred to as the loose sample. Then a sub-sample is selected requiring the lepton to satisfy tight isolation criteria.

The tight criteria are chosen so that they match the final, analysis-optimised isolation criteria. This sample is thereafter referred to as the tight sample. Given those two samples, the following system of equations can be constructed:

$$N_{\rm L} = N_{\rm prompt} + N_{\rm QCD} \quad (2)$$

$$N_{\rm T} = \epsilon N_{\rm prompt} + f N_{\rm QCD} \quad (3)$$

where $N_{\rm L}(N_{\rm T})$ is the number of data events in the loose (tight) sample passing the selections, $N_{\rm prompt}$ is the number of signal-like leptons originating from the W decay and $N_{\rm QCD}$ the number of misidentified QCD leptons. The quantity ϵ, also referred to as signal efficiency, denotes the fraction of loose signal- like leptons subsequently passing the tight cut; f, also referred to as fake rate, denotes the fraction of loose QCD leptons passing the tight cut. Since every event passing the tight selection must also pass the loose selection, selection efficiencies for real and fake leptons can be defined as:

$$\epsilon = \frac{N_{\rm prompt}}{N_{\rm QCD}} \quad (4)$$

$$f = \frac{N_{\rm prompt}}{N_{\rm QCD}} \quad (5)$$

Since the tight selection criteria are the same as those used in the final analysis, the number of fake leptons passing the tight selection, can be calculated solving the Equations 2 and 3 for $N_{\rm prompt}$ and $N_{\rm QCD}$.

Technically, the estimation is implemented by applying per-event weights, $w_{\rm QCD}(N_{\rm T}, N_{\rm A})$, to the data events passing the loose selection:

$$w_{\rm QCD}(N_{\rm T}, N_{\rm A}) = f N_{\rm QCD} = \frac{\epsilon - 1}{\epsilon - f} N_{\rm T} + \frac{\epsilon f}{\epsilon - f} N_{\rm A} \quad (6)$$

Where $N_{\rm T}$ is the number of events with a tight lepton, and $N_{\rm A}$ is the number of events with anti-tight lepton (i.e. a loose lepton which failed the tight cuts). This result however cannot be used directly as the parameters ϵ and f can depend on event kinematics and have to be modelled accordingly. In order to take those dependencies into account, an unbinned method is used in which a weight is constructed. With this method, all the events are used in the background estimation, as the event weight is calculated differently for a loose event and for a tight event. In the expression of the weight $w_{\rm QCD}(N_{\rm T}, N_{\rm A})$, $N_{\rm T}$ $(N_{\rm A})$ is equal to 1 if the event satisfies both the loose and tight criteria and 0 if the event satisfies only the loose criteria. The QCD prediction in the final sample is therefore the sum of weights calculated over the loose sample.

6. RESULTS

The final discriminating observables used to search for a massive resonance are the $m_{t\bar{t}}^{reco}$ spectra from the two selections. the $t\bar{t}$ system is reconstructed from both kinematic regimes, Boosted and Resolved. The simulation agrees well with the data, within the systematic uncertainties, and a statistical fit is performed to the invariant $t\bar{t}$ mass spectra (as shown in Figure [2]) using the

BumpHunter algorithm, with nuisance parameter profile fit. The main systematic uncertainties are related to the large-R jet energy scale. From the fit, using various hypotheses for the mass and width, it is possible to establish limits on the cross section times the branching ratio to top quark pairs.

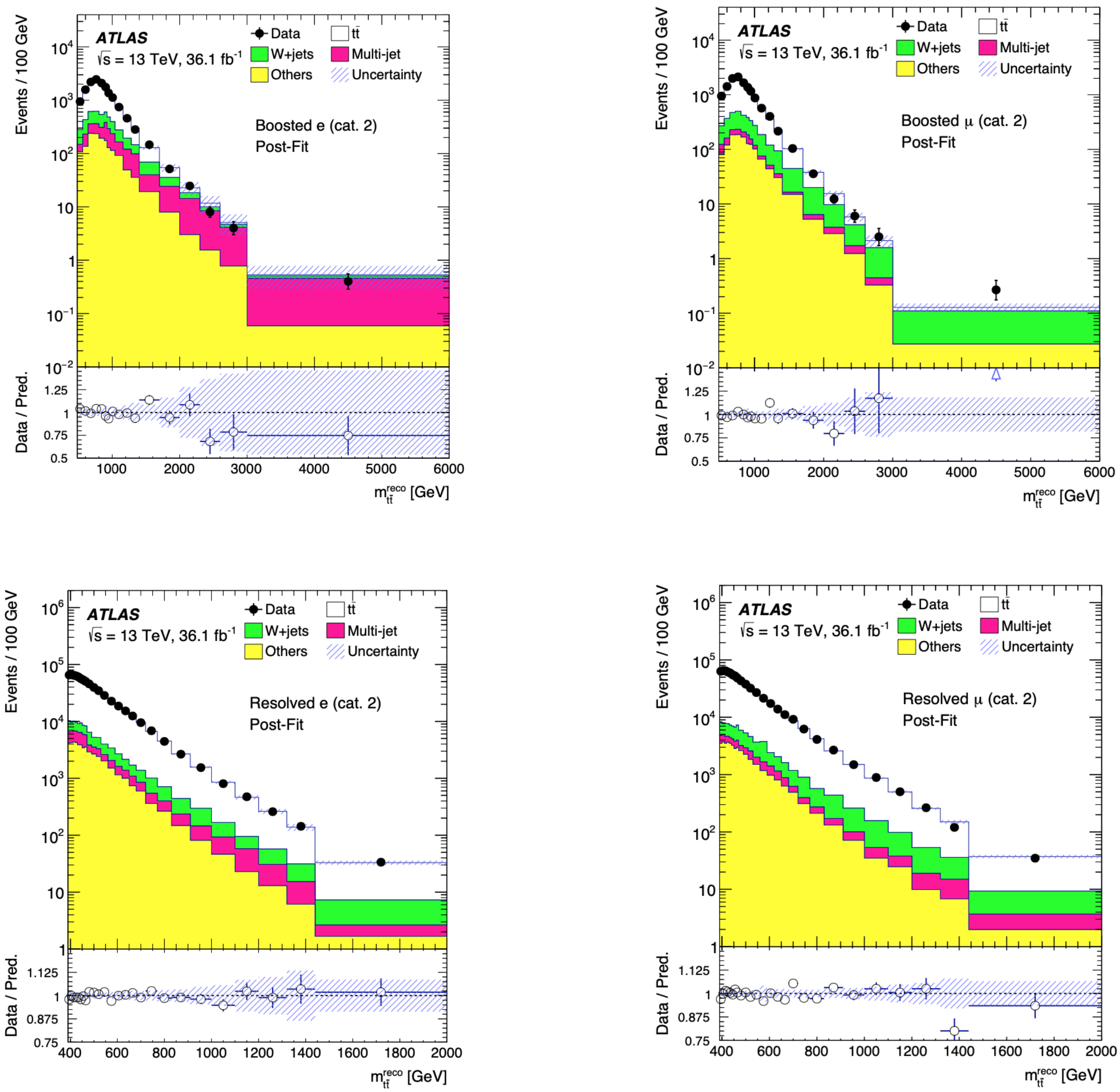


FIGURE 2: $m_{t\bar{t}}$ distributions after the profiling of the nuisance parameters in the boosted regime (top) and resolved regime (bottom) for the electron (left) and muon (right) channels [6]

The sensitivity of the search is tested new colour-singlet/octet bosons with spin 1/2 and masses from 0.4 to 5 TeV. The resulting constraints on the mass at 95% C.L.; a Topcolour-assisted Technicolour, Z'_{TC2} , with a width of 1% is excluded for masses $Z'_{TC2} <$ 3.0 TeV. The search allowed to exclude at 95% C.L. Kaluza-Klein (KK) gravitons in the range 0.45 TeV $< m_{G_{KK}} <$ 0.65 TeV , while a KK gluon of width 15% is excluded for $m_{g_{KK}} <$ 3.8 TeV as shown in Figure [3].

7. CONCLUSION

A search for heavy particles decaying into $t\bar{t}$ in the lepton+jets decay channel with the ATLAS experiment at the LHC was carried out. The seach has been done using data corresponding to a luminosity of 36.1 fb^{-1} of proton-proton collisions at a centre-of-mass energy of 13 TeV. No obvious deviation from SM prediction has been found so far in the $t\bar{t}$ invariant mass spectra. Upper limits on the cross-section x branching ratio are set for Z'_{TC2} , g_{KK} and G_{KK} signal models.

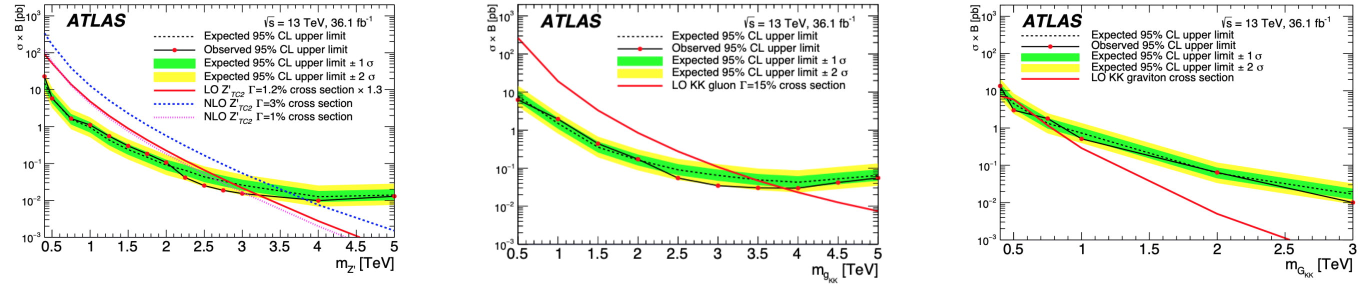


FIGURE 3: Cross-section 95% CL upper limits on the Z'_{TC2} signal (left), kk gluon (middle), and kk graviton (right) [6]

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