Boosted top quark techniques and searches for $t \bar{t}$ resonances at the LHC

S Fleischmann  
On behalf of the ATLAS and CMS Collaborations  
Bergische Universität Wuppertal, Wuppertal, Germany  
E-mail: Sebastian.Fleischmann@cern.ch

Abstract. In many models of beyond the Standard Model physics (BSM) the top quark plays a special role. The ATLAS and CMS experiments at the Large Hadron Collider (LHC) have performed dedicated searches for resonances decaying into top quark pairs, which may occur in BSM models. Especially at high $t \bar{t}$ masses the top quarks can have strongly boosted decay products. In recent years many new techniques have been developed to reconstruct and identify such decays. Both ATLAS and CMS use jet substructure to identify hadronic $W$ boson and top quark decays. Some of those techniques are summarised in this article and the recent results of searches for $t \bar{t}$ resonances are presented. In the lepton+jets channel a leptophobic top-colour $Z'$ with a small width is excluded at the 95% CL in the range $0.5 \text{ TeV} < m_{Z'} < 1.7 \text{ TeV}$ as a benchmark scenario. Kaluza-Klein gluons and $Z'$ bosons with larger widths are excluded in similar mass ranges.

1. Introduction

In 2011 the ATLAS [1] and CMS [2] experiments both recorded about $5 \text{fb}^{-1}$ of pp collisions at a centre-of-mass energy of $\sqrt{s} = 7 \text{ TeV}$. This data set allowed one to start to explore the multi-TeV regime. The top quark plays a special role in many models of physics beyond the Standard Model (BSM), therefore top quark pairs with high invariant mass can be sensitive probes of new physics. Both experiments performed searches for deviations from the Standard Model in the $t \bar{t}$ mass spectrum. The results are usually interpreted in terms of benchmark scenarios for $t \bar{t}$ resonances which differ in width and spin.

Experimentally, the width of the resonance compared to the experimental resolution of the invariant $t \bar{t}$ mass has a big impact on the obtained sensitivity of the searches. The spin of the resonance on the other hand plays only a minor role experimentally. Two benchmark scenarios are used by the LHC experiments. A leptophobic topcolour $Z'$ boson [3] is used as an example for a resonance with width below or of the order of the experimental $m_{t \bar{t}}$ resolution of about 10%. Kaluza-Klein excitations of gluons are predicted by models with warped extra dimensions and used as a benchmark model with $\Gamma/m$ larger than the experimental resolution [4].

One can estimate the angular separation in $\eta$-$\phi$ space of decay products from heavy particle (2-body) decays by $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} \approx \frac{2p_T}{M}$, where $M$ is the mass of the decaying particle and $p_T$ its transverse momentum. For example, the $W$ and the $b$-quark from the top decay ($t \to bW$) are usually separated by $\Delta R(W, b) < 1.0$ for $p_T > 350 \text{ GeV}$. Correspondingly, the hadronic decays of $W$ bosons ($t \to bW \to bq\bar{q}$) may not be fully resolved anymore by usual jets with a radius parameter of $R = 0.4$ or $R = 0.5$, if the transverse momentum $p_T^W$ of the...
$W$ boson is larger than about 200 GeV [5]. As a consequence, the top decay products start to merge and parton-level objects cannot be identified with individual jets.

One can use a different approach in the case of overlapping decay products from decays of heavy particles. Instead of using several narrow ($R = 0.4$ or $R = 0.5$) jets and constructing the hadronic decay of the top quark from them, one can use a single large radius jet (e.g. $R = 1.0$ or $R = 1.5$) and investigate its substructure. Several different methods have been proposed recently [6, 7] and section 2 will summarise a few of them. In section 3 the searches for $tt$ resonances in different channels using 7 TeV data are presented. Finally, section 4 summarises the results.

2. Jet substructure techniques

The usage of jets with large radii (e.g. $R = 1.0$ or $R = 1.5$), so-called fat jets, instead of many fixed-size, narrow jets has the advantage that the fat jet can be decomposed into subjets of varying sizes and more information about the substructure of the fat jet can be taken into account. However, fat jets suffer more than narrow jets from contamination by the underlying event, initial/final state radiation and pile-up. These additional energy deposits do not only introduce larger systematic uncertainties in the jet energy and jet mass scales, but also dilute the substructure from the decays of heavy particles. Therefore, grooming techniques have been developed, which allow one to remove contributions from soft radiation. The most commonly used grooming techniques are filtering [8], pruning [9] and trimming [10]. The CMS collaboration applies jet pruning in their searches for $tt$ resonances [11, 12]. The ATLAS collaboration has performed extensive comparisons of filtering, pruning and trimming including validations of these methods with data at $\sqrt{s} = 7$ TeV [5]. The impact of pile-up on groomed jets was evaluated in data and good performance of grooming was observed [13].

Jet trimming takes the constituents of a fat jet and applies a $k_\perp$ jet algorithm with smaller radius $R_{\text{sub}}$ to obtain sub-jets of the original jet. All constituents belonging to sub-jets that carry only a transverse momentum fraction $p_T^{\text{subject}}/p_T^{\text{fat jet}}$ below a given cut value are discarded in the trimmed jet. Trimming significantly improves the mass resolution for heavy particles and pushes the mass for jets from light quarks and gluons lower, therefore giving a better separation power between jets stemming from heavy particles and multi-jet background [5].

Similarly, pruning tries to discard soft particles and wide-angle radiation. In contrast to trimming, jet constituents are selected at each recombination step of a $k_\perp$ or Cambridge/Aachen ($C/A$) jet algorithm. When merging two constituents or proto-jets into a new proto-jet one requires the softer component to contribute a significant fraction of the transverse momenta to the merged proto-jet or to be close-by in $\Delta R$, otherwise the softer component is discarded.

In order to separate jets from heavy particle decays from the overwhelming background of jets induced by light quarks and gluons one takes variables into account which are sensitive to the substructure of the jets. The invariant mass of a jet is a very obvious variable. Another widely used class of variables are the last splitting scales of a $k_\perp$ jet algorithm. One defines the splitting scale $\sqrt{d_{12}} = \min(p_{T11},p_{T12})\Delta R_{12}$, where $p_{T11}$ and $p_{T12}$ are the transverse momenta of the last two proto-jets in the recombination process of the $k_\perp$ algorithm and $\Delta R_{12}$ their distance in $\eta-\phi$ space. One expects $\sqrt{d_{12}} \approx m_t/2$ for a jet containing all products of a hadronic top decay $t \to bW \to bq$.

Top tagging algorithms aim for the reconstruction and identification of hadronic top decays. The HEPTopTagger [13] is applied by the ATLAS collaboration and applies mass-drop filtering to remove contamination. It tries to reconstruct “tree level” decay products ($t \to bq$) and uses mass relations between those to identify top decays. For this purpose the fat jet is decomposed with a mass drop requirement, i.e. the jet clustering is run backward and at each step one requires the two subjets to have significantly lower mass than their combination. The jet is decomposed until all subjets have a mass less than 30 GeV. From those subjets three subjets are selected and their constituents investigated further. In the next step only the selected constituents are
clustered using the C/A algorithm with radius parameter \( R = \min(0.3, \min_{ij} \Delta R(j_i, j_j)/2) \). The five hardest subjets of this step are processed further and exactly three subjets are built from their constituents, which are then interpreted as the tree-level objects.

The CMS top tagger \([11]\) is based on the Johns Hopkins tagger \([15]\) and decomposes the initial fat jet in two steps, where also grooming techniques are applied. This follows the decay chain \( t \rightarrow bW, W \rightarrow qq \). Afterwards top candidates are tagged using variables like the jet mass, the number of subjets found and the minimum pairwise mass of the three hardest subjets. CMS also uses a special \( W \) boson tagger which applies jet pruning and requires a mass drop of the last two subjets to account for the components of the heavy particle decays.

Figure 1 shows the mass distributions of hadronic top candidates for the \( t\bar{t} \) lepton+jets channel. A broad peak is obtained for the mass of large radius \((R=1.5)\) C/A jets when no grooming is applied (figure 1a). In this selection without \( b \)-tagging the fraction of \( t\bar{t} \) events is only about 50%. The dominant background consists of \( W \) + jets events, where the hadronic top candidate stems from additional light quarks or gluons. After applying the HEPTopTagger the background from \( W \) + jets events is already strongly reduced and the mass peak of the top quark is much more narrow (figure 1b). Background events can be further suppressed by applying a mass window cut, giving a fraction of \( t\bar{t} \) events of about 86% within 140 GeV < \( m_t \) < 200 GeV.

3. Searches for \( t\bar{t} \) resonances

The searches for \( t\bar{t} \) resonances are performed in all possible \( t\bar{t} \) decay channels. The all-jets channel, where both top quarks are considered to decay hadronically, mostly aims at high di-top masses \( m_{t\bar{t}} \). Only for significantly boosted top decays this final state can be distinguished from the overwhelming multijet background at the LHC. The di-lepton channel is considered for low \( m_{t\bar{t}} \). No analyses specifically designed for the high \( m_{t\bar{t}} \) regime have been performed so far by the ATLAS and CMS collaborations in this channel. The highest sensitivity for \( t\bar{t} \) resonances is reached in the lepton+jets channel, where a single electron or muon and additional jets are used as final state. Both ATLAS and CMS use distinct event selections optimised for the low and the high mass regime in this channel.

Standard Model \( t\bar{t} \) production is obviously an irreducible background to all searches for \( t\bar{t} \) resonances and the signal only occurs as deviations in the invariant mass spectrum. \( W \) boson production with additional jets is the dominant non-\( t\bar{t} \) background in the lepton+jets channel. The normalisation of the Monte Carlo prediction for \( W \) + jets events is usually estimated directly from data, e.g. using the charge asymmetry. \( Z/\gamma \) bosons yield an important background in the...
di-leptonic channel and are usually also estimated by data driven methods in this channel. Diboson production (WW, WZ) is only relevant in the di-leptonic channel. Especially in the all-jets channel multijet events are an important background which needs to be estimated with data.

In the searches all important systematic uncertainties which affect the shape of the \(m_{tt}\) spectrum or give yield variations are taken into account. Prominent examples are the jet energy scale and resolution. Furthermore, reconstruction and identification efficiencies play an important role. Especially \(b\)-tagging uncertainties can be very large for high-\(p_T\) jets.

3.1. All-jets channel
While the ATLAS collaboration uses rather large C/A jets with radius \(R = 1.5\) in combination with the HEPTopTagger [16], the CMS analysis [12] takes C/A jets with radius \(R = 0.8\), but distinguishes two different types of top decays: Type-1 decays are top decays where all products of the hadronic top decay are included in a jet tagged by the CMS top tagger, while type-2 decays include only the hadronic \(W\) decay in the fat jet while the additional jet from the \(b\)-quark is separated from it. The analysis considers events with two type-1 top tagged jets and events with one type-1 and one type-2 decay, where one top tag as well as a \(W\)-tag and an additional jet is required.

Figure 2a shows the \(t\bar{t}\) invariant mass spectrum obtained by the ATLAS collaboration in the all-jets channel. Both ATLAS and CMS do not observe any significant excess in the \(m_{tt}\) distributions and set limits for the benchmark scenarios (table 1).

3.2. Di-leptonic channel
The di-leptonic channel has only low non-\(t\bar{t}\) background, but suffers from the two neutrinos in the final state, which complicate the reconstruction of the invariant di-top mass. In the ATLAS analysis [17] \(H_T + E_T^{\text{miss}}\) with \(H_T = \sum p_T^\ell + \sum p_T^j\) (\(\ell = e^\pm, \mu^\pm\)) is used as a proxy for \(m_{tt}\) and the search for deviations from the Standard Model prediction is done in this variable. In simulation one finds a decent correlation between this variable and the simulated true \(t\bar{t}\) mass. The corresponding CMS analysis [18] simply estimates \(m(2j2\ell2\nu)\) by setting the \(z\)-component of the neutrinos to zero. In addition to a bump hunting in the \(m(2j2\ell2\nu)\) spectrum a Bayesian neural network is used for a multivariate event selection to obtain a better discrimination power between Standard Model \(t\bar{t}\) production and the signal. Kinematic variables like the momenta of
the leptons and jets as well as various angles between them and the missing transverse momentum \( E_T^{\text{miss}} \) are used.

### 3.3. Lepton+jets channel

In the lepton+jets channel one assumes a final state with only one neutrino which allows one to estimate the longitudinal component \( p_T^z \) of the neutrino momentum by applying a \( W \) boson mass constraint on the lepton+\( E_T^{\text{miss}} \) system by different methods. In the event selection and the reconstruction of the \( t\bar{t} \) system both ATLAS and CMS use specialised analyses for the “resolved” case, where the hadronically decayed top is reconstructed as three (or two) narrow jets and the “boosted” case, where the decay products merge. This affects not only the hadronic top decay, but also the leptonic decay, such that the isolation criteria of leptons need to be adapted.

The CMS analysis [19] uses narrow \((R = 0.5)\) jets. In the resolved case leptons with standard isolation criteria are used. The boosted selection replaces isolation by a cut on \( p_T^{\text{clus}}(\ell, j) \), defined as the lepton momentum perpendicular to the closest jet axis. This allows for a certain overlap of leptons and jets, while keeping the multijet background from fake leptons low. In both cases a \( \chi^2 \) method including kinematic constraints on the leptonic and hadronic top decay is applied to find the most likely combination of jets for the calculation of the \( t\bar{t} \) mass. The \( m_{t\bar{t}} \) spectrum for the boosted selection with \( b \)-tagging is shown in figure [21]. In the calculation of exclusion limits the resolved analysis is used at low \( m_{t\bar{t}} \) and the boosted selection at high \( m_{t\bar{t}} \) (figure [3a]).

In the ATLAS search [20] the default lepton isolation was replaced by a definition with a shrinking cone size of the isolation region. Tracks in a cone with size \( \Delta R(\ell, \text{track}) \) proportional to \( 1/p_T^{\text{clus}} \) are used in the isolation criteria. This gives a strong improvement in the selection efficiency for leptons from boosted top quarks compared to isolation criteria with fixed cone sizes. In the resolved selection a single lepton trigger is used and a \( \chi^2 \) method is applied on narrow jets to find the best jet combination for the \( m_{t\bar{t}} \) calculation. The boosted selection uses a dedicated fat jet trigger on jets with \( R = 1.0 \). For high \( t\bar{t} \) masses this trigger has a much better efficiency of nearly 100% than the single lepton triggers. Fat jets with a high \( p_T \) threshold and cuts on their mass and \( k_T \)-splitting scale \( \sqrt{d_{12}} \) represent the hadronic top decay products in the reconstruction of the \( t\bar{t} \) system. However, both selection strategies are not used exclusively in the limit calculation at a certain \( t\bar{t} \) mass, but events from both are taken into account, where the boosted reconstruction is used, if a single event is selected by the boosted and the resolved strategy (figure [3b]).

![Figure 3(a)](image1)

(a) \( Z' (\Gamma_{Z'}/m_{Z'} = 10\%) \) [19]

![Figure 3(b)](image2)

(b) Kaluza-Klein gluons [20]

Figure 3: 95% CL expected and observed upper limits on the cross section times the \( t\bar{t} \) branching fraction \((a)\) for a medium width \( Z' (\Gamma_{Z'}/m_{Z'} = 10\%) \) and \((b)\) for Kaluza-Klein gluons \((\Gamma_{gKK}/m_{gKK} = 15.3\%) \) obtained in the lepton+jets channel.
4. Results and Summary

Many new techniques to reconstruct and identify boosted top decays were developed in recent years. Both ATLAS and CMS could show their feasibility at the LHC and improve their searches for $t\bar{t}$ resonances especially at high $m_{t\bar{t}}$ by their application. Boosted techniques are expected to gain even more importance with higher centre-of-mass energies and more integrated luminosity as higher mass scales get accessible. Grooming techniques can help to reduce the pile-up dependence and effects from the underlying event on jets with large radii.

In none of the channels any significant excess in the $t\bar{t}$ mass spectra was observed. Therefore, exclusion limits for certain benchmark scenarios were set. The expected and observed mass limits for the three different benchmark models considered by the ATLAS and CMS collaborations are summarised in table 1. The lepton+jets channel has the highest sensitivity and a leptophobic top-colour $Z'$ with a small width of $\Gamma_{Z'}/m_{Z'} = 1.2\%$ is excluded at the 95% CL in the range $0.5 \text{ TeV} < m_{Z'} < 1.7 \text{ TeV}$ by the ATLAS experiment. $Z'$ bosons with larger widths (figure 3a) and Kaluza-Klein gluons (figure 3b) are excluded in similar mass ranges.

Table 1: Summary of the observed and expected exclusion ranges at 95% CL of the resonance mass in TeV for three different benchmark models.

|                  | $Z'$ ($\Gamma_{Z'}/m_{Z'} = 1.2\%$) | $Z'$ ($\Gamma_{Z'}/m_{Z'} = 10\%$) | $g_{KK}$ ($\Gamma_g/m_g = 15.3\%$) |
|------------------|-----------------------------------|-----------------------------------|-----------------------------------|
|                  | obs.    | exp.     | obs.    | exp.     | obs.    | exp.     |
| ATLAS $\ell$+jets| 0.5—1.7 | 0.5—1.6  | 0.7—1.9 | 0.7—1.9  | 1.3      |
| CMS $\ell$+jets  | 0.5—1.5 | 0.5—1.5  | 0.5—2.0 | 0.5—2.0  | 1.0—1.8  | 1.0—1.8  |
| ATLAS all-jets   | 0.7—1.0 | 0.7—1.2  | 0.7—1.5 | 0.7—1.5  | 1.0—1.5  | 1.0—1.5  |
| CMS all-jets     | 1.0     | 1.0—2.0  | 1.0     | 1.0—2.0  | 1.0      | 1.0—1.5  |
| ATLAS $\ell\ell$ | 0.5—1.1 | 0.5—1.1  | 0.5—1.1 | 0.5—1.1  | 1.3—1.5  | 1.4—1.5  |
| CMS $\ell\ell$   | 0.5—1.1 | 0.5—1.1  | 1.3—1.5 | 1.4—1.5  | 0.5—1.1  | 0.5—1.1  |

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