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Search for heavy bottom-like quarks in 4.9 fb^{-1} of pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$

The CMS Collaboration*

Abstract

Results are presented from a search for heavy bottom-like quarks, pair-produced in pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$, undertaken with the CMS experiment at the LHC. The b′ quarks are assumed to decay exclusively to tW. The $\mathrm{b}'\overline{\mathrm{b}}' \rightarrow \mathrm{tW}^{-}\bar{\mathrm{t}}\mathrm{W}^{+}$ process can be identified by its distinctive signatures of three leptons or two leptons of same charge, and at least one b-quark jet. Using a data sample corresponding to an integrated luminosity of 4.9 fb^{-1}, observed events are compared to the standard model background predictions, and the existence of b′ quarks having masses below 611 GeV/c^2 is excluded at 95% confidence level.

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*See Appendix A for the list of collaboration members

1 Introduction

The total number of fermion generations is assumed to be three in the standard model (SM), though the model does not provide an explanation of why this should be the case. Thus the possible existence of a fourth generation remains an important subject for experimental investigation. Adding a fourth generation of massive fermions to the model may strongly affect the Higgs and flavour sectors [1–5]. A fourth generation of heavy quarks would enhance the production of Higgs bosons [6], while the indirect bound from electroweak precision data on the Higgs mass would be relaxed [7, 8]. Additional massive quarks may provide a key to understanding the matter-antimatter asymmetry in the universe [9].

Various searches for fourth-generation fermions have already been reported. Experiments have shown that the number of light neutrino flavours is equal to three [10–13], but the possibility of additional heavier neutrinos has not been excluded. A search for pair-produced bottom-like quarks (b') by the ATLAS collaboration excludes a b'-quark mass of less than 480 GeV/c^2 [14]. Earlier studies setting mass limits on possible fourth-generation quarks, from experiments at the Tevatron and the Large Hadron Collider (LHC), can be found in Ref. [15–21].

Using the Compact Muon Solenoid (CMS) detector, we have searched for a heavy b' quark that is pair-produced in pp collisions at a centre-of-mass energy of 7 TeV at the LHC. We assume that the mass of the b' quark ($M_{\mathrm{b}'}$) is larger than the sum of the top quark and the W-boson masses. If the b' quark couples principally to the top quark, the decay chain $\mathrm{b}'\overline{\mathrm{b}}' \rightarrow \mathrm{tW}^-\overline{\mathrm{t}}\mathrm{W}^+ \rightarrow \mathrm{bW}^+\mathrm{W}^-\overline{\mathrm{b}}\mathrm{W}^-\mathrm{W}^+$ will dominate [22]. Given the 11% branching fraction for a W-boson to each lepton, distinctive signatures of $\mathrm{b}'\overline{\mathrm{b}}'$ production are expected, specifically those of two isolated leptons with the same charge ("same-charge dileptons") or three isolated leptons ("trileptons"). Although occurring very rarely in the standard model, these two signatures may be present in 7.3% of the $\mathrm{b}'\overline{\mathrm{b}}'$ events. An earlier search by CMS [17] in the same-charge dilepton and the trilepton channels, utilizing a data set corresponding to an integrated luminosity of 34 pb^{-1}, set a lower limit on the mass of the b' quark of 361 GeV/c^2 at the 95% confidence level (CL). Here we present an update of this search using a much larger data set, corresponding to an integrated luminosity of 4.9 fb^{-1}.

2 CMS detector and trigger

This analysis is based on the data recorded by the CMS experiment in 2011. The central feature of the CMS detector is a superconducting solenoid, 13 m in length and 6 m in diameter, which provides an axial magnetic field of 3.8 T. Charged-particle trajectories are determined using silicon pixel and silicon strip tracker measurements. A crystal electromagnetic calorimeter, including lead-silicon preshower detectors in the forward directions, together with a surrounding brass/scintillator hadronic calorimeter, encloses the tracking volume and provides energy measurements of electrons and hadronic jets. Muons are identified and measured in the tracker and in gas-ionization detectors embedded in the steel return yoke outside the solenoid. The detector is nearly hermetic, providing measurements of any imbalance of momentum in the plane transverse to the beam direction. A more detailed description of the CMS detector can be found in Ref. [23].

A two-level trigger system [24] selects events for further analysis. The events analyzed in this search are collected with the requirement that the trigger system detects at least two lepton candidates. Efficiencies for these dilepton triggers are determined using events that pass a jet trigger, have two reconstructed electrons or muons, and that also pass the full selection criteria described in the next section. For these selected events, the dilepton trigger efficiencies are estimated to be 91%, 96%, and >99%, for events with two muons, one electron and one muon, and two electrons, respectively.

3 Selection criteria

The use of the CMS particle-flow global event reconstruction procedure [25–28] has been extended beyond its application in Ref. [17]. In the present analysis, all physics objects – leptons, jets, and missing transverse energy - are reconstructed with this procedure. The reconstruction and selection criteria for each physics object used in this analysis are described below.

Candidate muons are reconstructed through a global fit to trajectories, using hit signals in the inner tracker and in the muon system. Muons are required to have transverse momenta $p_T > 20\,\text{GeV}/c$ and $|\eta| < 2.4$, where the pseudorapidity $\eta = -\ln[\tan\theta/2]$ and θ is the polar angle relative to the anticlockwise beam direction. The muon candidate must be associated with hits in the silicon pixel and strip detectors, have segments in the muon chambers, and provide a high-quality global fit to the track segments. The efficiency for these muon selection criteria is >99% from Z decays [29]. In addition, the muon track is required to be consistent with originating from the principal primary interaction vertex, which is defined by the one associated with tracks yielding the largest value for the sum of their p_T^2.

Reconstruction of electron candidates starts from clusters of energy deposits in the ECAL, which are then matched to hits in the silicon tracker. Electron candidates are required to have $p_T > 20$ GeV/c. Candidates are required to be reconstructed in the fiducial volume of the barrel ($|\eta| < 1.44$) or in the end-caps ($1.57 < |\eta| < 2.4$). The electron candidate track is required to be consistent with originating from the principal primary interaction vertex. Electrons are identified using variables which include the ratio between the energies deposited in the HCAL and the ECAL, the shower width in η, and the distance between the calorimeter shower and the particle trajectory in the tracker, measured in both η and azimuthal angle (ϕ). The selection criteria are optimized [30] to reject the background from hadronic jets while maintaining an efficiency of 80% for the electrons from W or Z decays.

Jets are reconstructed by an anti-k_T jet-clustering algorithm with a distance parameter $R = 0.5$ [31]. Particle energies are calibrated [32] separately for each particle type, and resulting jet energies therefore require only small corrections that account for thresholds and residual inefficiencies. All jet candidates must have $p_T > 25\,\text{GeV}/c$ and be within $|\eta| < 2.4$. Neutrinos from W boson decays escape the detector, and thereby give rise to a significant imbalance in the net transverse momentum measured for each event. This missing transverse momentum, expressed as the quantity $\not\!\!E_T$, is defined as the absolute value of the vector sum of the transverse momenta of all reconstructed particles [33].

In contrast to the earlier analysis of Ref. [17], b-tagging is now used to reject events from backgrounds that do not include a top-quark decay. The b-tagging algorithm applied in this analysis generates a list of tracks associated with each jet, and calculates the significance of each track's impact-parameter (IP), as determined by the ratio of the IP to its uncertainty. For the jet to be tagged as a b-jet, the IP significance of at least three of its listed tracks must exceed a threshold value, chosen to give an identification efficiency of 50% for b-jets and a misidentification rate of 1% for other particle jets [34].

Electrons and muons from $W \to \ell\nu$ ($\ell = e, \mu$) decays are expected to be isolated from other particles in the detector. A cone of $\Delta R < 0.3$, where $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, is constructed around each lepton-candidate's direction, and if the scalar sum of the transverse momenta of

Table 1: Summary of expected $b'\overline{b}'$ cross sections [40], selection efficiencies, and yields for the two signal channels as a function of the b′ mass.

$M_{b'}$	Cross section	Same-charge dilepton		Trilepton	
[GeV/c^2]	[pb]	efficiency [%]	yield	efficiency [%]	yield
450	0.662	1.52 ± 0.13	49	0.47 ± 0.05	15
500	0.330	1.64 ± 0.14	26	0.51 ± 0.05	8.2
550	0.171	1.71 ± 0.14	14	0.56 ± 0.05	4.7
600	0.0923	1.69 ± 0.14	7.6	0.60 ± 0.06	2.7
650	0.0511	1.71 ± 0.15	4.3	0.63 ± 0.06	1.6

the particles inside the cone, excluding contributions from the lepton candidate, exceeds 15% of the candidate p_T, then the lepton candidate is rejected. Electron candidates are required to be separated from any selected muon candidates by $\Delta R > 0.1$ to remove misidentified electrons due to muon bremsstrahlung. Electron candidates identified as originating from photon conversions are also rejected.

Events are required to have at least one well-reconstructed interaction vertex [35]. Events with two leptons of the same electric charge, or with three leptons (two of which must be oppositely charged), are selected. For the same-charge dilepton (trilepton) channel, events with fewer than four (two) jets are rejected. At least one jet must be identified as a b-jet. In addition, events that have any two muons or electrons whose invariant mass $M_{\ell\ell}$ is within 10 GeV/c^2 of the Z-mass ($|M_{\ell\ell} - M_Z| < 10\,\mathrm{GeV}/c^2$) are rejected, in order to suppress the background from $Z \to \ell^+\ell^-$ decays. For each event, the scalar quantity $S_T = \sum|\vec{p}_T(\text{jets})| + \sum|\vec{p}_T(\text{leptons})| + \not{E}_T$ is required to satisfy the condition $S_T > 500$ GeV. The selection criteria described above are not fully optimized in terms of discovery reach, but in fact they are more robust because they have a single background component in the background estimation with data.

Signal selection efficiencies are estimated using simulated event samples. Fourth generation quarks production is implemented as a straightforward extension to the standard model configuration of the MADGRAPH/MADEVENT generator version 5.131 [36]. Parton showering and hadronization are provided by PYTHIA 6.424 [37] using the matching prescription described in Ref. [38]. Finally, these generated signal events are passed through the CMS detector simulation based on GEANT4 [39].

Table 1 shows the expected efficiencies for a b′ signal, for $450 \leq M_{b'} \leq 650\,\mathrm{GeV}/c^2$. The efficiencies vary between 1.5% and 1.7% for the same-charge dilepton channel, and between 0.47% and 0.63% for the trilepton events, in the chosen range of $M_{b'}$. These efficiencies include the branching fractions for W-decay and the b-tagging performance [34]. Jet multiplicities for the same-charge dilepton and the trilepton channels are shown in Fig. 1, and the S_T distributions are presented in Fig. 2. The expected distributions for a b′ signal having $M_{b'} = 500\,\mathrm{GeV}/c^2$ are normalized to the production cross sections from Ref. [40] that include approximate next-to-next-to-leading-order perturbative QCD corrections, and standard QCD couplings are assumed.

4 Background estimation

Because of the b-tagging requirement, 98% of the expected background events in the same-charge dilepton channel have at least one top quark from $t\bar{t}$, $t\bar{t} + W/Z$, or single-top processes.

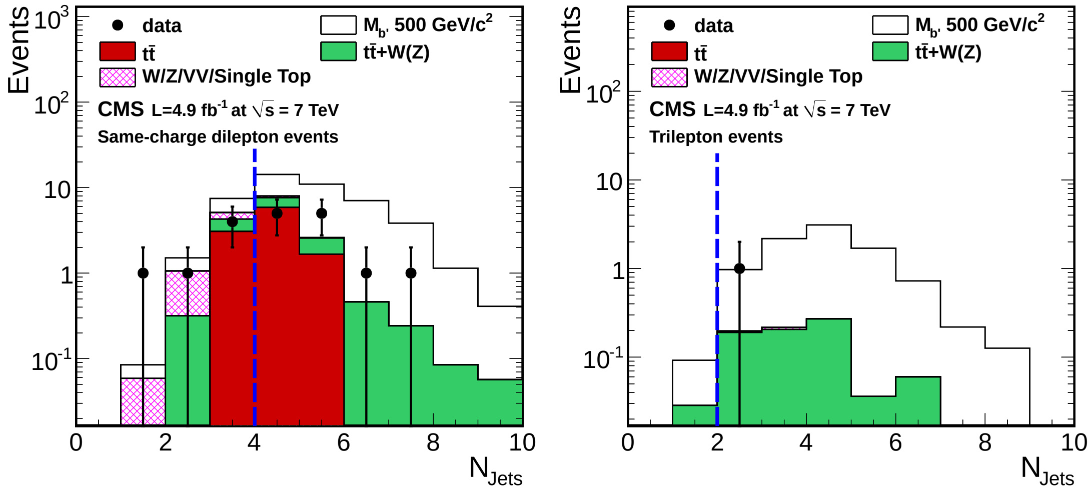

Figure 1: Jet multiplicity distributions for the same-charge dilepton channel (left), and the trilepton channel (right). The open histogram shows the contribution expected from a b′ having $M_{b'} = 500\,\text{GeV}/c^2$. The contributions from standard model processes are normalized to the total estimated background. All selection criteria are applied except the one corresponding to the plotted variable. The vertical dotted lines indicate the minimum number of jets required in events selected for each of the channels.

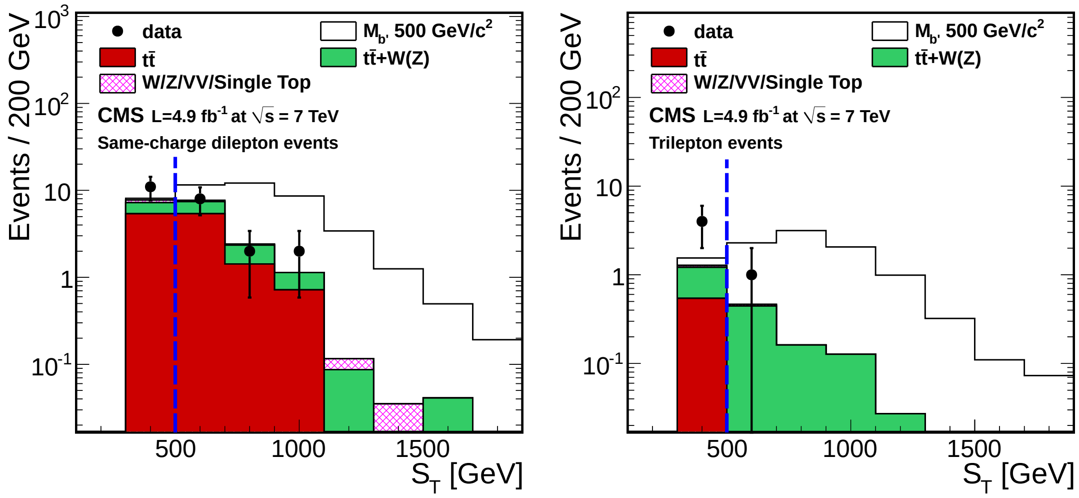

Figure 2: Distributions in S_{T}, the scalar sum of the transverse momenta of objects, in the same-charge dilepton channel (left), and the trilepton channel (right). The open histogram is the contribution expected from a b′ having $M_{b'} = 500\,\text{GeV}/c^2$. The histograms for standard model processes are normalized to the total expected background. All selection criteria are applied except the one corresponding to the plotted variable. The vertical dotted line indicates the lower bound on S_{T} used in the analysis.

These backgrounds are categorized into three sources: (i) true $\ell^+\ell^-$ events with a electron of misidentified charge, (ii) single-lepton events with an extra misidentified or non-isolated lepton candidate, and (iii) events with two prompt leptons of the same charge. The contribution due to the charge misidentification of electrons is determined using a control sample that, while keeping the remaining signal selection criteria, has oppositely-charged electron pairs or electrons and muons. The charge misidentification rate (0.03% and 0.31% for barrel and endcap candidates, respectively) is determined by counting the events containing two same-charge electron candidates, whose invariant mass is consistent with that of a Z-boson, relative to the yield of $Z \to e^+e^-$ events. Background from source (ii) is estimated as follows. Leptons passing the selection criteria described in Section 3 for signal are denoted as "tight", while muon candidates passing relaxed isolation thresholds and track-fit quality requirements, or electron candidates passing relaxed identification and isolation requirements, are referred to as "loose". Tight lepton candidates are excluded from the selection of loose lepton candidates. The background from events containing a false or non-isolated lepton candidate is estimated using another data control sample containing one tight lepton candidate and one loose lepton candidate, with the remaining selection criteria kept identical to those used for the signal sample. By definition, this control sample excludes events in the signal sample. The contributions of the backgrounds in the selected events are calculated using the yields observed in the control sample multiplied by the ratio of the number of lepton candidates passing tight selection criteria to those passing the loose criteria. This ratio, also determined in data, is calculated as the number of events containing one loose and one tight lepton candidate divided by the number of those containing two loose lepton candidates. Applying the above methods to data, a background yield of 7.8 ± 2.8 events is estimated to originate from sources (i) and (ii).

The estimated yield to the same-charge dilepton channel from processes that produce prompt same-charge dileptons, including $t\bar{t} + Z$, $t\bar{t} + W$, and diboson channels (WZ, ZZ, and same-charge $W^{\pm}W^{\pm}$+jets), is determined using simulations of these processes. The contribution in the signal region is estimated to be 3.6 ± 0.6 events.

For the trilepton channel, the background is an order of magnitude smaller than for the same-charge dilepton channel, and is dominated by processes that produce three prompt leptons, such as $t\bar{t} + W/Z$. The yield in the signal region, which is only 0.78 ± 0.21 events, is estimated using simulated samples. Contributions from $pp \to t\bar{t}$ and W/Z processes are normalized to the cross sections measured by CMS [41, 42]. The single-top contributions are normalized to the next-to-next-to-leading-logarithm cross sections [43, 44]. Production rates for dibosons are estimated from the next-to-leading-order cross sections given by MCFM [45]. The $t\bar{t} + W/Z$ and same-charge $W^{\pm}W^{\pm}$+jets processes are normalized to the next-to-leading-order cross sections given in Ref. [46].

The multijet background contribution is estimated using a control sample of events containing two (three) loose lepton candidates for the same-charge dilepton (trilepton) channel, maintaining other selection criteria. The yield of multijet events in the signal region is calculated by multiplying the yield observed in the control sample by the ratio squared (cubed) of the number of lepton candidates passing tight selection to the number passing loose selection. The contribution of multijet events to the signal region is estimated to be smaller than 0.12 (0.001) events for the same-charge dilepton (trilepton) channel, and thus is negligible compared to contributions from the other background processes.

5 Systematic uncertainties

To validate the procedure for estimating background, and to assign a proper systematic uncertainty, the study in the same-charge dilepton channel is repeated using a mixture of simulated samples representing the potential background sources. The full estimation procedure is then applied to the simulated samples, and results are compared to the input values. The observed difference (2.7 ± 0.9 events) is included as a systematic uncertainty. The statistical uncertainties in the control samples are also included in the systematic uncertainties.

The following uncertainties are included in both dilepton and trilepton channels. The b-tagging efficiency as measured in data has a precision of 10% per b-jet [34], resulting in a 6.7% uncertainty in the efficiency of signal samples. The effect of this uncertainty on the background contributions determined using simulated samples is estimated to be 0.35 (0.08) events for the dilepton (trilepton) channel. Lepton selection efficiencies are measured using inclusive $Z \to \ell^+\ell^-$ data, and the difference between efficiencies measured in data and simulation is taken as a systematic uncertainty. An additional systematic uncertainty of 50% of the difference in efficiency between simulated Z and b′ samples is included, to cover the effects of different event topologies. This estimation yields uncertainties of 1.7% and 2.7% for electrons and muons, respectively. The uncertainty in signal efficiency, calculated using appropriate weighting of the electron and muon contributions, is 3.3% (5.0%) for the dilepton (trilepton) channel.

The uncertainties in the background normalization are estimated to be 0.74 and 0.12 events for dilepton and trilepton channels, respectively, and the uncertainties for each of the individual processes are included as follows: $\pm$11% for $t\bar{t}$ [41], $\pm$3% ($\pm$4%) for W (Z) [42], $\pm$30% for single top processes, $\pm$26% for WW, $\pm$30% for WZ, $\pm$21% for ZZ, $\pm$30% for ttW, $\pm$30% for ttZ, $\pm$49% for $W^{\pm}W^{\pm}$+jets, and $\pm$100% for multijet. The uncertainties in the normalization of diboson, ttW, ttZ, and $W^{\pm}W^{\pm}$+jets processes are taken from a comparison of next-to-leading-order and leading-order predictions. The uncertainty related to the presence of additional interactions (pile-up) in the same beam crossing interval as an event is examined by varying the number of such interactions included in the simulations. The systematic effects of the uncertainties in jet-energy-scale, jet resolution, $E\!\!\!/_T$ resolution, pile-up events, and trigger efficiency are found to be small [32, 33]. Uncertainty sets given by CTEQ6 [47] are used to determine the uncertainties from the choice of parton distribution functions. The relative uncertainty in the integrated luminosity measurement is estimated to be 2.2% [48], and is included in the calculation of limits. The details of uncertainties in the signal selection efficiency and in the background estimation are presented in Table 2.

6 Results

There are 12 (1) events found in the signal region for the dilepton (trilepton) channel, to be compared with an estimated background of 11.4 ± 2.9 (0.78 ± 0.21) (Table 3).

Most of the background sources contain at least one top quark in the final state, with a b-quark produced in the top quark decay. Therefore, modifying the required number of b-tagged jets, in a separate study, provides a good check of the analysis. The observed yields when requiring ≥ 0, ≥ 1, or ≥ 2 b-tagged jets are consistent with the estimated background, and in agreement with the expected dominance of background from top quarks.

For each b′ mass hypothesis, cross sections, selection efficiencies, and associated uncertainties are estimated (Tables 1 and 2). From these values, the estimated background yield, and the number of observed events, upper limits on $b'\overline{b}'$ pair production cross sections at 95% CL are

Table 2: Summary of relative systematic uncertainties in signal selection efficiencies ($\Delta\epsilon/\epsilon$) and the absolute systematic uncertainties in the number of expected background events (ΔB). The ranges given below represent the dependence on $M_{b'}$, varying from 450 GeV/c^2 to 650 GeV/c^2.

	Same-charge dilepton		Trilepton	
	$\Delta\epsilon/\epsilon$ [%]	ΔB	$\Delta\epsilon/\epsilon$ [%]	ΔB
Accuracy of control-sample method	-	2.63	-	-
Control sample statistics	-	0.76	-	-
b-tagging	6.7	0.35	6.7	0.08
Lepton selection	3.3	0.03	4.9 – 5.1	0.04
Background normalization	-	0.74	-	0.12
Pile-up events	0.5	0.13	0.6	0.03
Jet energy scale	1.1 – 2.0	0.31	0.3 – 1.0	0.02
Jet energy resolution	0.3 – 1.4	0.22	0.3 – 0.9	0.02
Missing energy resolution	0.1 – 0.7	0.38	0.1 – 2.2	0.07
Trigger	1.4	0.11	0.7	0.01
PDF	0.4 – 1.9	0.26	0.4 – 1.3	0.03
Simulated sample statistics	2.7 – 3.4	0.26	4.5 – 6.5	0.12
Integrated luminosity	2.2	0.24	2.2	0.05
Total	8.6 – 9.0	2.9	10 – 11	0.21

Table 3: Summary of the estimated background contributions to the same-charge dilepton channel and the trilepton channel, and the observed event yield in data. The given uncertainties are systematic.

Sources	Same-charge dilepton	Trilepton
Same-charge dilepton with a charge-misidentified electron, or a misidentified or non-isolated lepton (from data)	7.8 ± 2.8	
Prompt same-charge dilepton, or trilepton (simulated)	3.6 ± 0.6	0.78 ± 0.21
Background sum	11.4 ± 2.9	0.78 ± 0.21
Observed yield in data	12	1

derived, using a modified frequentist approach (CL_s) [49]. These limits are plotted as the solid line in Fig. 3, while the dotted line represents the limits expected with the available integrated luminosity, assuming the presence of standard model processes alone. By comparing to the theoretical production cross section for $pp \to b'\overline{b}'$, a lower limit of 611 GeV/c^2 is extracted for the mass of the b' quark, at 95% CL, while a limit of 619 GeV/c^2 is expected for a background-only hypothesis.

7 Summary

Results have been presented from a search for heavy bottom-like quarks pair-produced in proton-proton collisions at $\sqrt{s} = 7$ TeV. The process of $pp \to b'\overline{b}' \to t\overline{t}W^+W^-$ has been studied in data corresponding to an integrated luminosity of 4.9 fb^{-1}, collected with the CMS detector. Estimated background contributions have been found to be small, since final states containing the signatures of trileptons or same-charge dileptons are produced rarely in standard model

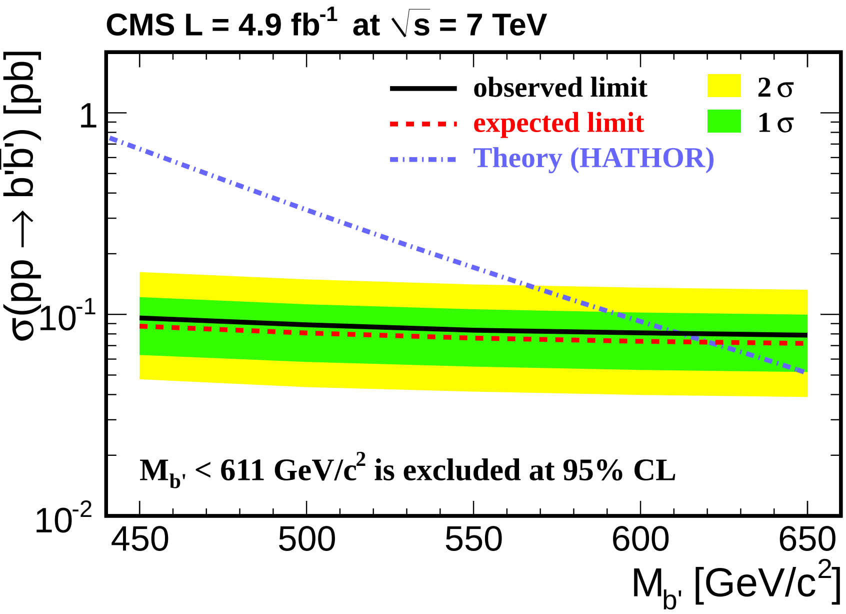

Figure 3: Exclusion limits at 95% CL on the $pp \to b'\bar{b}'$ production cross section (σ). The solid line represents the observed limits, while the dotted line represents the limits expected for the available integrated luminosity, assuming the presence of standard model processes alone. A comparison with the production cross-sections excludes b' masses $M_{b'} < 611\,\mathrm{GeV}/c^2$ at 95% CL for a 100% $b' \to tW$ decay branching fraction.

processes. Assuming a branching fraction of 100% for the decay $b' \to tW$, b' quarks with masses below $611\,\mathrm{GeV}/c^2$ are excluded at 95% CL. This is the most stringent limit to date.

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