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Search for heavy resonances decaying to a top quark and a bottom quark in the lepton+jets final state in proton–proton collisions at 13 TeV

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A search is presented for narrow heavy resonances decaying to a top quark and a bottom quark using data collected by the CMS experiment at $\sqrt{s} = 13\,\text{TeV}$ in 2016. The data set analyzed corresponds to an integrated luminosity of $35.9\,\text{fb}^{-1}$. Final states that include a single lepton (e, μ), multiple jets, and missing transverse momentum are analyzed. No evidence is found for the production of a W′ boson, and the production of right-handed W′ bosons is excluded at 95% confidence level for masses up to 3.6 TeV depending on the scenario considered. Exclusion limits for W′ bosons are also presented as a function of their coupling strength to left- and right-handed fermions. These limits on a W′ boson decaying via a top and a bottom quark are the most stringent published to date.

1. Introduction

Despite the broad success of the standard model (SM), the absence of answers to the hierarchy problem, among other shortcomings, has led to the development of many theories for new physics that lies beyond the SM. A common prediction of many of these theories is the existence of new heavy gauge bosons [1–5]. These particles typically arise from additional symmetries in the theories, and it is common to generically refer to charged instances of these resonances as W′ bosons. In scenarios where the W′ boson is sufficiently heavy, the decay $\mathrm{W}' \to \mathrm{tb}$ has several features that make it an appealing search channel. Searches in this channel directly probe the W′ boson coupling to third generation quarks, which, in some models [6,7], can be enhanced with respect to the coupling to lighter quarks. Additionally, the large continuum multijet background has less impact on searches for $\mathrm{W}' \to \mathrm{tb}$ decay than on searches for the decay to light quarks ($\mathrm{W}' \to \mathrm{qq}'$). The $\mathrm{W}' \to \mathrm{tb}$ search is complementary to searches for $\mathrm{W}' \to \ell\nu$ and $\mathrm{W}' \to \mathrm{WZ}$, where ℓ denotes a charged lepton and ν denotes a neutrino. Unlike searches for $\mathrm{W}' \to \ell\nu$, the search for $\mathrm{W}' \to \mathrm{tb} \to \mathrm{bb}\ell\nu$ decay allows the W′ boson mass to be fully reconstructed, up to a quadratic ambiguity.

Searches for W′ bosons in the top and bottom quark (tb) decay channel have been performed at the Fermilab Tevatron [8–10] and at the CERN LHC by both CMS [11–13] and ATLAS [14,15] Collaborations. The most stringent limits to date on the production of W′ bosons come from the CMS search performed at $\sqrt{s} = 13\,\text{TeV}$ [13], using $2.2\,\text{fb}^{-1}$ of data collected in 2015.

This Letter presents a search for W′ bosons decaying via the tb channel using proton–proton collision data at $\sqrt{s} = 13\,\text{TeV}$, collected by the CMS experiment in 2016. The analyzed data correspond to an integrated luminosity of $35.9\,\text{fb}^{-1}$. Events with exactly one electron or muon, significant missing transverse momentum, and multiple jets in the final state are selected. This search focuses on W′ bosons with widths that are narrow compared to their masses. In addition to searching for W′ bosons with purely right- or left-handed couplings, we also search for W′ bosons with varying combinations of these couplings. This analysis is sensitive to W′ bosons with masses between 1 and 4 TeV.

2. The CMS detector

The central feature of the CMS apparatus [16] is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL),

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each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

The particle-flow (PF) algorithm [17] reconstructs and identifies individual particle candidates with an optimized combination of information from relevant elements of the CMS detector. The energy of photons is measured using the ECAL and corrected for zero-suppression effects. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The primary interaction vertex is defined as the vertex with the largest sum of p_T^2 of associated tracks. The energies of muons are obtained from the curvature of the corresponding tracks. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits. This measurement is then corrected for zero-suppression effects and for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energy.

In the barrel section of the ECAL, an energy resolution of about 1% is achieved for unconverted or late-converting photons in the tens of GeV energy range. The resolution for photons not belonging to this category is about 1.3% up to $|\eta| = 1$, rising to about 2.5% at $|\eta| = 1.4$. In the endcaps, the resolution of unconverted or late-converting photons is about 2.5%, while the remaining photons have a resolution between 3 and 4% [18]. The momentum resolution for electrons with transverse momentum $p_T \approx 45\,\text{GeV}$ from $Z \to ee$ decays ranges from 1.7% for nonshowering electrons in the barrel region to 4.5% for showering electrons in the endcaps [19]. When combining information from the entire detector, the jet energy resolution amounts typically to 15% at 10 GeV, 8% at 100 GeV, and 4% at 1 TeV, to be compared to about 40, 12, and 5% obtained when the ECAL and HCAL calorimeters alone are used [20].

Muons are measured in the range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers. Matching muons to tracks measured in the silicon tracker results in a relative transverse momentum resolution for muons with $20 < p_T < 100\,\text{GeV}$ of 1.3–2.0% in the barrel, and better than 6% in the endcaps. The p_T resolution in the barrel is better than 10% for muons with p_T up to 1 TeV [21].

The missing transverse momentum vector $\vec{p}_T^{\,\text{miss}}$ is defined as the projection on the plane perpendicular to the beams of the negative vector sum of the momenta of all reconstructed particles in an event.

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [16].

3. Signal and background modeling

3.1. Signal modeling

Simulated signal samples are generated at leading order and their cross sections are scaled to next-to-leading order with a K-factor of 1.25 [22,23] appropriate for our signal mass range of interest. All signal samples are generated using the CompHEP [24] 4.5.2 package according to the following lowest-order effective Lagrangian [22]:

$$\mathcal{L} = \frac{V_{f_i f_j}}{2\sqrt{2}} g_W \bar{f}_i \gamma_\mu \left[a_R (1+\gamma^5) + a_L (1-\gamma^5) \right] W'^{\mu} f_j + \text{h.c.}, \qquad (1)$$

where $V_{f_i f_j}$ is the Cabibbo–Kobayashi–Maskawa matrix if f is a quark and $V_{f_i f_j} = \delta_{ij}$ if f is a lepton, g_W is the SM weak coupling constant, and a_R and a_L are the coupling strengths of the W′ to right- and left-handed fermions, respectively. We consider values of a_L and a_R that range from 0 to 1, and any signal with $a_L > 0$ takes into account interference with the SM W boson. The signal simulation includes decays involving a τ lepton, and no distinction is made in the analysis selection or strategy between an electron or muon produced directly from the W boson decay, and an electron or muon from a subsequent τ lepton decay. We use W′ boson width values computed in CompHEP for each mass point, and use a narrow-width approximation for the generation of W′ bosons that have both left- and right-handed couplings. The typical width is approximately 3% of the signal resonance mass. The widths of all generated samples are significantly smaller than the detector and reconstruction resolutions, and therefore the precise values of the width do not affect our results.

For W'_R bosons we consider two scenarios for the mass of the hypothetical right-handed neutrinos. If the right-handed neutrinos are lighter than the W'_R boson ($M_{\nu_R} < M_{W'_R}$), then both $W'_R \to \ell\nu_R$ and $W'_R \to qq'$ decays are allowed. However, if the right-handed neutrinos are heavier than the W'_R boson ($M_{\nu_R} > M_{W'_R}$), then the $W'_R \to \ell\nu_R$ decay is forbidden, resulting in an enhancement of the branching fraction for $W' \to tb$. This branching fraction varies slightly with mass and ranges from 0.32 to 0.33 if $M_{\nu_R} > M_{W'_R}$ and from 0.24 to 0.25 if $M_{\nu_R} < M_{W'_R}$ for W'_R boson masses between 1 and 4 TeV. For the purposes of signal generation all neutrinos are assumed to be massless. When calculating the number of expected signal events (in Table 1), showing expected signal distributions (in Figs. 1 and 2), or presenting results for arbitrary left- and right-handed couplings (in Fig. 5), it is always assumed that the masses of hypothetical right-handed neutrinos are much lighter than that of the W'_R boson. Both scenarios are considered when presenting results for W'_R (in Figs. 3 and 4).

3.2. Background modeling

The most significant contributions to the background come from W+jets and $t\bar{t}$ production. Smaller contributions, from s- and t-channel single top quark production, associated production of a top quark and a W boson, Z/γ^*+jets, and diboson production (VV), are also included in the total background estimate. Predictions for all background processes are taken from simulation with corrections applied in cases where initial modeling is found to be inaccurate. Further details on the background modeling can be found in Section 5. The contribution to the total background from the multijet background is found to be negligible after the full selection and is therefore not included.

Simulated samples for Z/γ^*+jets, s- and t-channel single-top quark, and W+jets events are produced using MadGraph5_aMC@NLO [25–27] v2.2.2, $t\bar{t}$ and associated production of a top quark and a W boson are produced using POWHEG v2 [28–32], and all other background processes are produced using PYTHIA 8.212 [33]. The $t\bar{t}$ process contribution is then assigned a correction based on the top quark p_T, which is known to be improperly modeled [34]. A correction for the relative fraction of W+light quark/gluon jets and W+charm/bottom jets in W+jets events is derived and then checked in a control region. More details on the background estimation methods can be found in Section 5.

All simulated signal and background samples are processed through PYTHIA for parton fragmentation and hadronization. The simulation of the CMS detector is performed by GEANT 4 [35,36]. The NNPDF 3.0 parton distribution function (PDF) set is used for sample generation [37]. All simulated samples include additional proton–proton interactions (pileup) and are weighted such that the distribution of the number of interactions in each event agrees with that in the data.

4. Event selection

All leptons, jets, and $\vec{p}_{\mathrm{T}}^{\text{miss}}$ used in this search are reconstructed using the particle-flow algorithm. Jets are clustered using the anti-k_{T} algorithm [38,39] with a size parameter of 0.4 (AK4), and dedicated jet energy corrections [20,40] are then applied. Any charged hadrons that are not associated with the leading vertex are removed from the event, using the charged hadron subtraction method [41]. The leading vertex is defined as the primary vertex with the largest squared sum of the transverse momenta of its associated tracks. The neutral-hadron contribution to jets from pileup is also subtracted, using the jet area method [42]. Charged hadron subtraction is applied before any jet clustering, while area-based subtractions are applied after clustering but before the final level of jet energy corrections.

Jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be within 5 to 10% of the true momentum over the whole p_{T} spectrum and detector acceptance [16]. An offset correction is applied to jet energies to take into account the contribution from pileup. Jet energy corrections are derived from simulation, and are confirmed with in situ measurements of the energy balance in dijet, multijet, photon+jet, and leptonically decaying Z+jets events. Additional selection criteria are applied to each event to remove spurious jet-like features originating from isolated noise patterns in certain HCAL regions.

The combined secondary vertex version 2 algorithm [43,44] is used to identify jets that have originated from a b quark. The algorithm combines secondary vertex and track based lifetime information to discriminate b jets from light quark and gluon jets. The operating point used has a b jet identification (b tagging) efficiency of 80% and a light-flavor jet misidentification (mistag) probability of 10%. Our signal selection requires at least one of the two leading p_{T} jets to be b-tagged. This requirement is critical in reducing the contributions from some SM background processes like W+jets. Scale factors to account for observed differences between data and simulation are applied as a function of p_{T}.

The event selection, which is optimized separately for the electron and muon channels, results in different requirements for the two channels. Most notably, the multijet background, through misidentification of showers, is significantly larger in the electron channel than in the muon channel. For electron events we therefore require higher $|\vec{p}_{\mathrm{T}}^{\text{miss}}|$ and correspondingly lower leading jet p_{T} than for muon events, in order to keep acceptance high for signal events.

Events are required to have at least two jets with $p_{\mathrm{T}} > 30\,\text{GeV}$ and $|\eta| < 2.4$, and the leading p_{T} jet must have $p_{\mathrm{T}} > 350\,(450)\,\text{GeV}$ in the electron (muon) channel.

One lepton in each event is required to have fired a single-lepton trigger that has no isolation requirement, be within the detector acceptance ($|\eta| < 2.5$ for electrons, excluding the barrel endcap transition region, $1.444 < |\eta| < 1.566$, and $|\eta| < 2.4$ for muons) and be associated with a reconstructed primary vertex. For heavy W′ resonance masses, the top quark from the W′ decay is highly boosted, causing the b-jet and lepton to be close to each other. For this reason, leptons are not required to be isolated. Electrons and muons are required to have $p_{\mathrm{T}} > 180\,\text{GeV}$ and to fulfill several identification criteria. Electron candidates are selected using a boosted decision tree based on the shower shape information, the quality of the track, the match between the track and electromagnetic cluster, the fraction of total cluster energy in the hadronic calorimeter, the amount of activity in the surrounding regions of the tracker and calorimeters, and the probability of the electron originating from a converted photon. The track associated with a muon candidate is required to have hits in the pixel and muon detectors, a good-quality fit, and be consistent with originating from the primary vertex. To reduce the multijet background, the candidate lepton is required to satisfy either ΔR (lepton, nearest jet) > 0.4 or $p_{\mathrm{T}}^{\text{rel}}$ (lepton, nearest jet) $> 60\,(50)\,\text{GeV}$ for electrons (muons), where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ and $p_{\mathrm{T}}^{\text{rel}}$ is defined as the magnitude of the lepton momentum orthogonal to the jet axis. Events with additional charged leptons with $p_{\mathrm{T}} > 35\,\text{GeV}$ and $|\eta| < 2.5$ for electrons and $|\eta| < 2.4$ for muons are vetoed.

The four-vectors of identified lepton candidate particles are subtracted from those of jets containing them. This procedure helps to ensure the reconstructed jets are not contaminated by nearby high-energy leptons as is common in the characteristic boosted signal topology. Scale factors resulting from small differences between lepton identification and trigger efficiencies in data and simulation are derived in a $\mathrm{Z} \to \ell\ell$ sample as a function of $|\eta|$ and p_{T} and applied as a correction to simulated events.

Events are required to have at least $|\vec{p}_{\mathrm{T}}^{\text{miss}}| > 120\,(50)\,\text{GeV}$ in the electron (muon) channel. Additionally, events in the electron channel must have $|\Delta\phi(\mathrm{e}, \vec{p}_{\mathrm{T}}^{\text{miss}})| < 2$ radians. These requirements are responsible for differences between the two channels in yields from some background processes. This selection, along with the other requirements, also helps reject nearly all multijet background events.

4.1. Mass reconstruction

The tb invariant mass is reconstructed from the momenta of the charged lepton and two jets in the event, together with the $\vec{p}_{\mathrm{T}}^{\text{miss}}$. The transverse components of the neutrino momentum are set to the $\vec{p}_{\mathrm{T}}^{\text{miss}}$ and the longitudinal component p_z^{ν} is calculated by constraining the invariant mass of the lepton and neutrino to the W boson mass. This method leads to a quadratic equation in p_z^{ν}. In the case that the two solutions are real numbers, both solutions are used to reconstruct W boson candidates. If both solutions contain imaginary parts, then p_z^{ν} is set to the real part of the solutions, and then recompute p_{T}^{ν}, which yields another quadratic ambiguity. In this case, we use only the solution with the mass closest to 80.4 GeV. Once all the components of the neutrino momentum have been assigned, the viable solutions for the neutrino are combined with the charged lepton to define W boson candidate(s). The top quark candidate is then reconstructed by combining the four-momenta of each W boson candidate with each jet with $p_{\mathrm{T}} > 25\,\text{GeV}$ and $|\eta| < 2.4$. The jet that yields a top quark mass closest to the nominal top quark mass is used to reconstruct the top quark candidate. In the case of two W candidates, only the candidate that yields the best top quark mass is used. Finally, the top quark candidate is combined with the highest p_{T} jet remaining in the event, yielding the reconstructed W′ candidate. The mass of the W′ candidate is referred to as M_{tb}.

Additional requirements that improve the rejection of background events are placed on the combinations of objects involved in the mass reconstruction. The top quark candidate is required to have $p_{\mathrm{T}}^{\mathrm{t}} > 250\,\text{GeV}$ and $100 < m_{\mathrm{t}} < 250\,\text{GeV}$, and $p_{\mathrm{T}}^{\mathrm{j_1+j_2}} > 350\,\text{GeV}$, where $p_{\mathrm{T}}^{\mathrm{j_1+j_2}}$ is the p_{T} of the four-vector sum of the two leading p_{T} jets.

Two event categories based on $p_{\mathrm{T}}^{\mathrm{t}}$ and $p_{\mathrm{T}}^{\mathrm{j_1+j_2}}$ are used when setting cross section limits. All events satisfying the above criteria are classified as Type A except for those with $p_{\mathrm{T}}^{\mathrm{t}} > 650\,\text{GeV}$ and $p_{\mathrm{T}}^{\mathrm{j_1+j_2}} > 700\,\text{GeV}$, which are labeled Type B events. This cate-

Table 1
Observed and expected event yields from all the background processes and W'_R bosons with three different masses. HF and LF indicate heavy flavor and light flavor events, respectively. Yields are separated into eight event categories by the lepton type (e or μ), number of b tags (1 or 2), and p_T^t and $p_T^{j_1+j_2}$ (Type A or B). The uncertainty in the total expected background includes both the systematic and statistical sources.

Process	Electron channel				Muon channel			
	Type A		Type B		Type A		Type B	
	1 b tag	2 b tags	1 b tag	2 b tags	1 b tag	2 b tags	1 b tag	2 b tags
Background								
$t\bar{t}$	760	249	69	22	731	263	75	30
tqb	14	6	1	0	14	6	1	0
tW	117	50	15	5	116	44	22	5
tb	2	2	0	0	3	1	0	0
$W(\rightarrow \ell\nu)$+jets (LF)	189	17	16	2	177	16	15	1
$W(\rightarrow \ell\nu)$+jets (HF)	581	98	52	7	631	107	51	8
$Z(\rightarrow \ell\ell)$+jets	19	11	0	0	64	1	20	0
VV	35	9	2	0	33	1	5	4
Total background	1717±62	442±34	155±23	36±7	1769±70	439±30	189±22	48±9
Data	1750	437	133	40	1754	482	164	44
Signal								
$M_{W'_R} = 2000\,\text{GeV}$	53	43	41	25	79	75	57	35
$M_{W'_R} = 2600\,\text{GeV}$	8	6	16	10	14	12	24	15
$M_{W'_R} = 3200\,\text{GeV}$	2	1	4	3	3	2	8	5

gorization improves the sensitivity to high signal masses without sacrificing the performance for lower masses.

Finally, events are also separated into two categories based on whether both (2 b tags) or only one (1 b tag) of the two leading p_T jets is b-tagged.

Event yields in all these categories after the event selection are shown in Table 1.

5. Backgrounds

5.1. The W+jets background

For the W+jets background, the relative fractions of the heavy and light flavor components in simulation are known to differ from those in data [45]. The validity of the modeling of the flavor content is tested and two scale factors are derived for W+jets heavy and light flavor events using two samples that differ from the signal selection only in b tagging. The *pre tag* sample does not have any b tagging requirements, while the events in the *0 tag* sample must not have any b-tagged jets. In these two regions the relative fractions of the W+jets heavy and light flavor events are distinctly different. The yields from data and simulation in these two regions are used to solve a system of equations for the relative fractions of W+jets heavy and light flavor components, while requiring that the overall W+jets yield remains unchanged. Uncertainties are determined from repeating the calculation after varying the b tagging efficiencies and mistag rates within their uncertainties. The scale factors are found to be $2.10\pm^{0.21}_{0.18}$ and $0.49\pm^{0.08}_{0.10}$ for W+jets heavy and light flavor events, respectively. The corresponding scale factor is then applied to all simulated W+jets events.

5.2. The top quark pair production background

For the $t\bar{t}$ background, we verify normalization as well as the modeling of the top quark p_T. This check is performed in two signal-depleted $t\bar{t}$-enriched regions: one that requires $450 < M_{tb} < 750\,\text{GeV}$ and at least two b tags, and another that removes the second-lepton veto and instead requires an additional electron or muon with a p_T of at least 35 GeV. These comparisons motivate a reweighting of the $t\bar{t}$ background using a correction factor obtained from measurements of the differential top quark p_T distribution. This correction factor is applied to the $t\bar{t}$ simulation, as a function of the generator-level top quark p_T. The $t\bar{t}$ simulation without the correction factor applied is used as an estimate of the systematic uncertainty in the reweighting procedure.

Table 2
List of systematic uncertainties taken into account in the analysis. For sources that affect the shape of the M_{tb} distribution the given rate uncertainty is approximate. The pileup, top quark p_T reweighting, and W+jets heavy/light flavor systematic uncertainties are described in more detail in the text. A check mark in the "Signal" column indicates that the uncertainty is also applied to the signal samples. For the PDF uncertainty, only its shape component is included for signal samples.

Source	Rate uncertainty	Signal
Normalization		
Integrated luminosity	2.5%	✓
$t\bar{t}$ cross section	8%	–
W+jets cross section	10%	–
Trigger eff. (e/μ)	2%/2%	✓
Lepton id. eff. (e/μ)	2%/2%	✓
Shape and normalization		
Jet energy scale	3%	✓
Jet energy resolution	1%	✓
b/c tagging	2%	✓
Light quark mistagging	2%	✓
Pileup	1%	✓
PDF	6%	✓
Top quark p_T reweighting	15%	–
W+jets heavy/light flavor	1%	–
μ_R and μ_F scales	15%	–

6. Systematic uncertainties

The systematic uncertainties in this analysis can be grouped into two categories: uncertainties in the overall normalization and in the shape of the M_{tb} distribution.

The normalization uncertainties include the uncertainty in the integrated luminosity (2.5%) [46], the $t\bar{t}$ and W+jets cross sections (8 and 10%, respectively), the lepton identification (2%), and the trigger efficiencies (2%).

The uncertainty due to variations in the renormalization and factorization scales (μ_R and μ_F, respectively) is evaluated at the matrix element level using event weights from varying the scales by 0.5 and 2 while restricting to $0.5 \leq \mu_R/\mu_F \leq 2$ [47,48].

Uncertainties resulting from ±1 standard deviation (s.d.) variations in the b tagging efficiency and mistagging rate scale factors, jet energy scale, and jet energy resolution are also included.

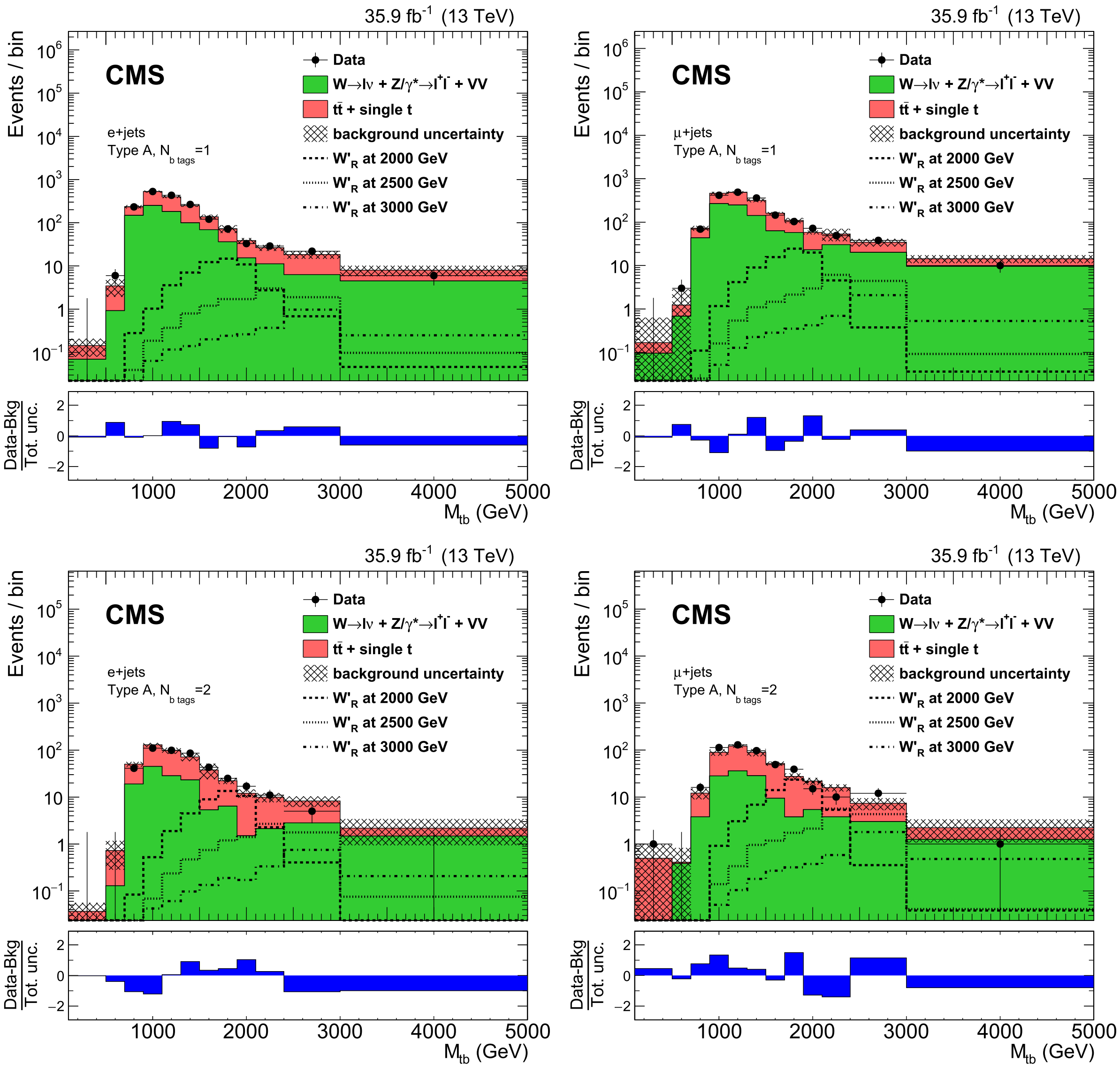

Fig. 1. The reconstructed M_{tb} distributions in the 1 b tag (upper) and 2 b tags (lower) categories, for the electron (left) and muon (right) channels, for Type A events. Distributions for W'_{R} bosons with masses of 2, 2.5, and 3 TeV are shown. The distribution is shown after the application of all selections. The background uncertainty includes both statistical and systematic components, while "Tot. unc." in the lower panels corresponds to the combined uncertainty of the background prediction and data. (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

A correction is applied to all simulated samples to better match the distribution of pileup interactions observed in data. This procedure uses a total inelastic cross section of 69.2 mb, and an uncertainty is calculated by varying the cross section by ±5% [49].

To estimate the uncertainty arising from the choice of PDF, we evaluate the root-mean-square of the distribution of 100 NNPDF 3.0 replicas as the ±1 s.d. uncertainties according to the guidelines in Ref. [50]. When considering signal samples only the shape component of the uncertainty due to PDFs is included.

The uncertainty in the W+jets heavy and light flavor scale factors is included as a variation in the W+jets background. The $\mathrm{t\bar{t}}$ background with an uncorrected top quark p_{T} spectrum is included as a one-sided +1 s.d. variation.

All uncertainties are listed in Table 2. The uncertainties with the largest effect on the overall background normalization are those associated with the top quark p_{T} reweighting, μ_{R} and μ_{F} scales, and PDFs, which have effects of approximately 15, 15, and 6%, respectively.

7. Results

Distributions of M_{tb} are shown in Figs. 1 and 2. The binning is chosen to reduce uncertainties due to the size of the simulated event samples and is one bin from 0 to 500 GeV, eight bins of 200 GeV width from 500 to 2100 GeV, one bin from 2100 to 2400 GeV, one bin from 2400 to 3000 GeV, and one bin above 3000 GeV. Having observed that data agree with the predicted SM background processes, we set 95% confidence level (CL) upper limits on the W′ boson production cross section for masses between 1 and 4 TeV.

The analysis separates events into eight independent categories in order to improve the signal sensitivity. Categories are created according to lepton type (electron or muon), the number of b-tagged jets among the first two leading p_{T} jets (1 or 2), and $p_{\mathrm{T}}^{\mathrm{t}}$ and $p_{\mathrm{T}}^{\mathrm{j_1+j_2}}$ (Type A or B). Categorization according to the number of b tags allows the analysis to maintain acceptance for signal events where one of the jets is not correctly b tagged, and categorization accord-

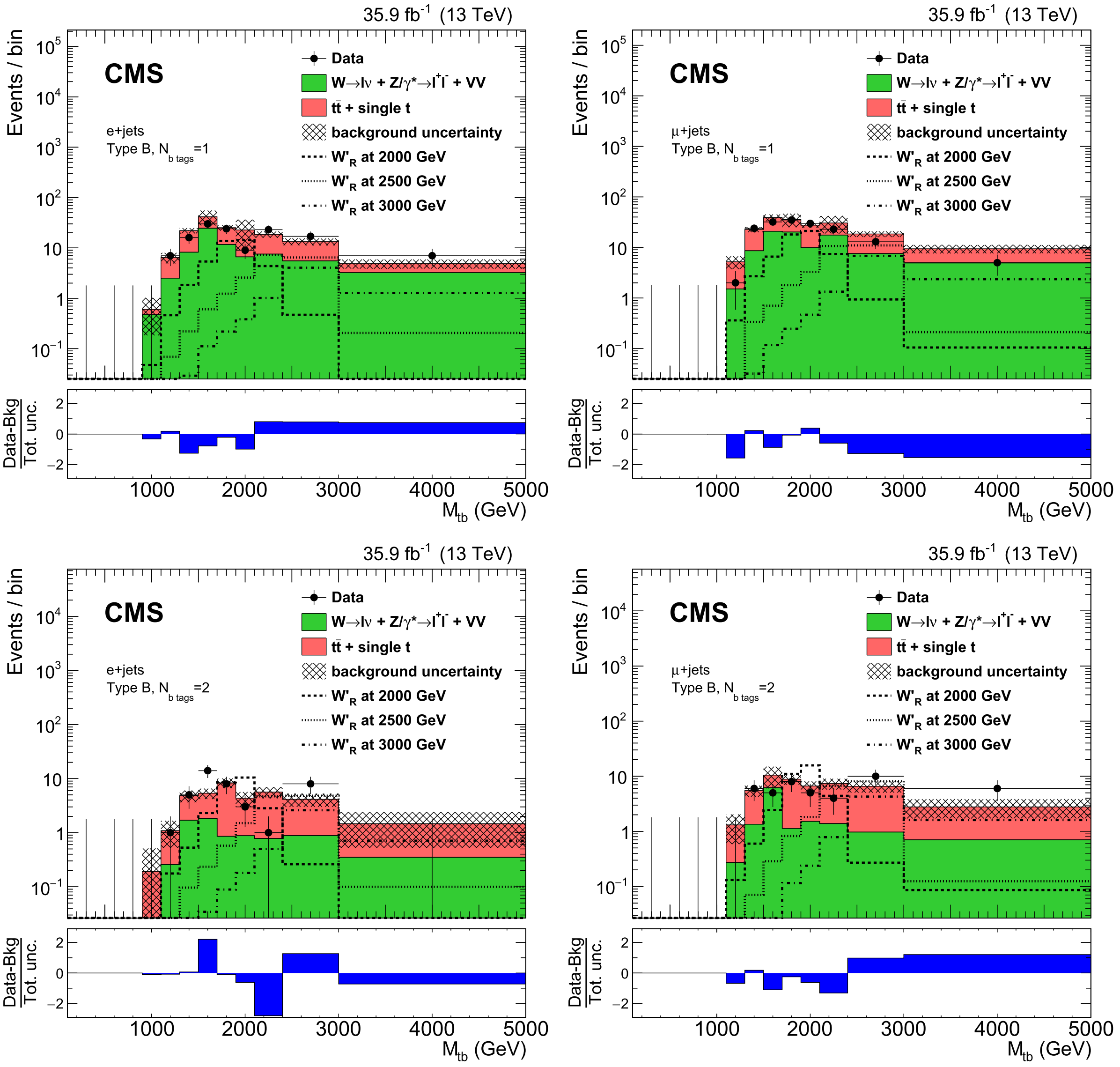

Fig. 2. The reconstructed M_{tb} distributions in the 1 b tag (upper) and 2 b tags (lower) categories, for the electron (left) and muon (right) channels, for Type B events. Distributions for W'_{R} bosons with masses of 2, 2.5, and 3 TeV are shown. The distribution is shown after the application of all selections. The background uncertainty includes both statistical and systematic components, while "Tot. unc." in the lower panels corresponds to the combined uncertainty of the background prediction and data. (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

ing to the $p_{\mathrm{T}}^{\mathrm{t}}$ and $p_{\mathrm{T}}^{\mathrm{j_1+j_2}}$ allows the analysis to perform well over a large range of possible signal masses.

Limits on the cross section of W′ bosons are calculated using a Bayesian method with a prior uniform in the signal cross section, as implemented with the THETA package [51]. The Bayesian approach uses a binned likelihood in order to calculate the 95% CL upper limits on the product of the signal production and the branching fraction $\sigma(\mathrm{pp} \to \mathrm{W}')\mathcal{B}(\mathrm{W}' \to \mathrm{tb})$. Statistical uncertainties related to the background prediction are treated using the "Barlow–Beeston lite" method [52]. All uncertainties given in Section 6 are included as nuisance parameters. Uncertainties in the shape of the M_{tb} distribution are treated using template interpolation and all rate uncertainties are included with log-normal priors.

Results for right-handed W′ bosons are shown in Figs. 3 and 4. W'_{R} bosons with masses below 3.4 TeV are excluded at 95% CL.

Although models with a W′ boson that couples exclusively to right-handed fermions are simpler because of the lack of interference, the effective Lagrangian in Eq. (1) allows us to analyze models with arbitrary combinations of left- and right-handed couplings. In order to accomplish this the interference between the SM s-channel tb production and the tb production via an intermediate left-handed W′ boson must be accounted for since these processes initial and final states are identical.

The cross section for single top quark production given a W′ boson can be written for any set of a_{L} and a_{R} coupling values in terms of the cross sections of four simulated signal samples. It is assumed that the couplings to fermions are independent of generation, such that each signal can be described by a single value of a_{L} and a single value of a_{R}. The four simulated signals are then σ_{L} for purely left-handed couplings $(a_{\mathrm{L}}, a_{\mathrm{R}}) = (1, 0)$, σ_{R} for purely right-handed couplings $(a_{\mathrm{L}}, a_{\mathrm{R}}) = (0, 1)$, σ_{LR} for mixed couplings $(a_{\mathrm{L}}, a_{\mathrm{R}}) = (1/\sqrt{2}, 1/\sqrt{2})$, and σ_{SM} for SM couplings $(a_{\mathrm{L}}, a_{\mathrm{R}}) = (0, 0)$, and the cross section for single top quark production is

$$\sigma = (1 - a_{\mathrm{L}}^2)\sigma_{\mathrm{SM}} + \frac{1}{a_{\mathrm{L}}^2 + a_{\mathrm{R}}^2}\Big[a_{\mathrm{L}}^2(a_{\mathrm{L}}^2 - a_{\mathrm{R}}^2)\sigma_{\mathrm{L}} + a_{\mathrm{R}}^2(a_{\mathrm{R}}^2 - a_{\mathrm{L}}^2)\sigma_{\mathrm{R}} + 4a_{\mathrm{L}}^2 a_{\mathrm{R}}^2\sigma_{\mathrm{LR}} - 2a_{\mathrm{L}}^2 a_{\mathrm{R}}^2\sigma_{\mathrm{SM}}\Big]. \quad (2)$$

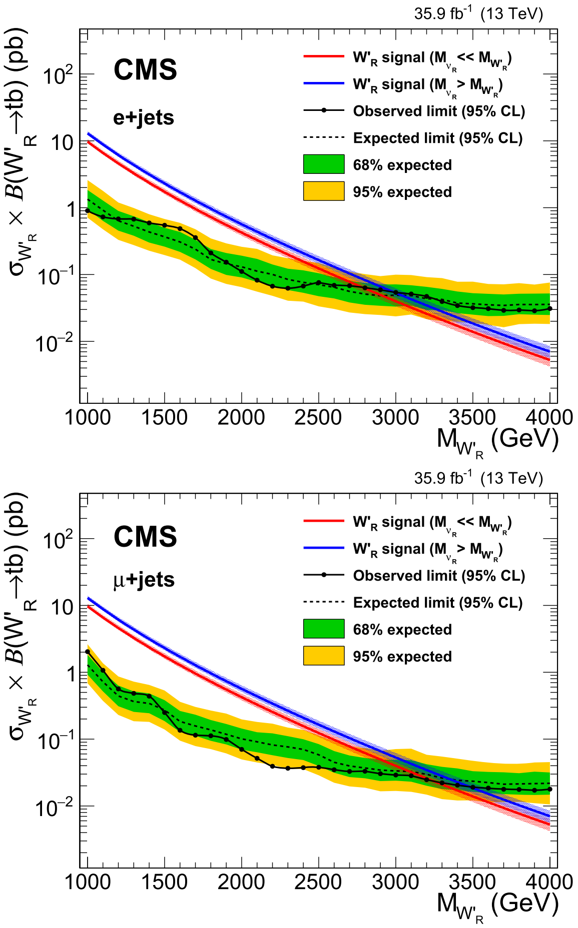

Fig. 3. Upper limit at 95% CL on the W'_R boson production cross section separately in the electron (top) and muon (bottom) channels. Signal masses for which the theoretical cross section (in red and blue for $M_{\nu_R} \ll M_{W'_R}$ and $M_{\nu_R} > M_{W'_R}$, respectively) exceeds the observed upper limit (in solid black) are excluded at 95% CL. The green and yellow bands represent the ±1 and 2 s.d. uncertainties in the expected limit, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

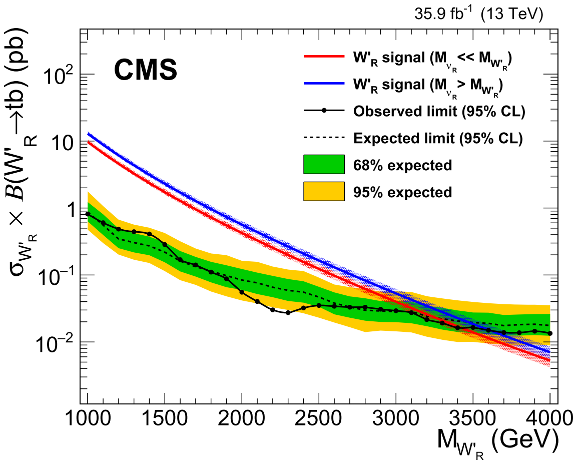

Fig. 4. Upper limit at 95% CL on the W'_R boson production cross section for the combined electron and muon channels. Signal masses for which the theoretical cross section (in red and blue for $M_{\nu_R} \ll M_{W'_R}$ and $M_{\nu_R} > M_{W'_R}$, respectively) exceeds the observed upper limit (in solid black) are excluded at 95% CL. The green and yellow bands represent the ±1 and 2 s.d. uncertainties in the expected limit, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

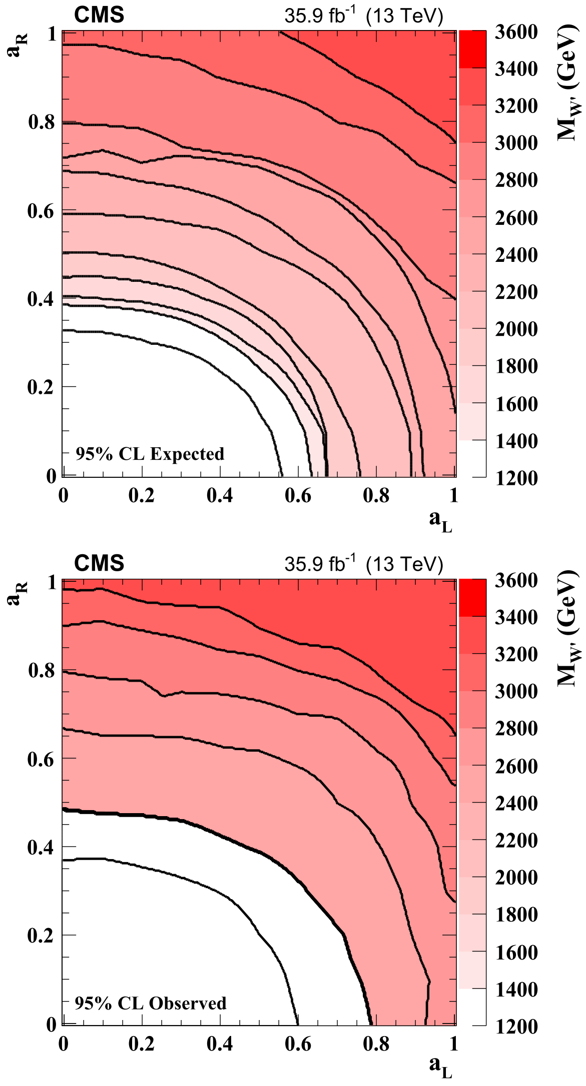

Fig. 5. Expected (top) and observed (bottom) limits on the W′ boson mass as function of the left-handed (a_L) and right-handed (a_R) couplings. Black lines represent contours of equal W′ boson mass separated by 200 GeV. (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

By combining four signal samples according to this equation we are able to produce invariant mass distributions for a W′ boson with arbitrary a_L and a_R couplings. A notable adjustment for this paper with respect to previous CMS publications is in the definition of the mixed coupling sample, which was previously defined as $(a_L, a_R) = (1, 1)$. This change results in slightly different expressions for the total cross section, and is chosen to ensure that the widths of all three simulated signal samples are identical.

It should be noted that in the case that the W′ boson couples exclusively to right-handed fermions, this equation reduces to the sum of SM *s*-channel tb production and W'_R production, as expected. For pure W'_L or W'_{LR} boson production, the equation reduces to the cross section of the respective sample, which is generated already including SM *s*-channel tb production and interference with W′ production.

A scan is performed over the a_L and a_R plane in 0.1 steps from 0 to 1 to produce cross section limits for arbitrary combinations of a_L and a_R. For each point in the scan the expected and observed 95% CL upper limits on the cross section are calculated using the same method described above. Fig. 5 shows the excluded W′ boson mass for each (a_L, a_R) point, in addition to an interpolation between points to create smooth contours of equivalent signal mass limits.

8. Summary

A search for a narrow heavy W$'$ boson resonance decaying to a top quark and a bottom quark has been performed in lepton+jets final states using data collected at $\sqrt{s} = 13$ TeV by the CMS detector in 2016, corresponding to an integrated luminosity of 35.9 fb^{-1}. No evidence is observed for the production of a W$'$ boson, and 95% CL upper limits on the product of the right-handed W$'$ (W$'_\mathrm{R}$) boson production cross section and its branching fraction to a top and a bottom quark are calculated as a function of the W$'_\mathrm{R}$ boson mass. The observed (expected) 95% CL upper limit is 3.4 (3.3) TeV if $M_{\mathrm{W}'_\mathrm{R}} \gg M_{\nu_\mathrm{R}}$ and 3.6 (3.5) TeV if $M_{\mathrm{W}'_\mathrm{R}} < M_{\nu_\mathrm{R}}$, where M_{ν_R} is the mass of the right-handed neutrino. Exclusion limits are also presented for W$'$ bosons with varied left- and right-handed couplings to fermions, for the first time at $\sqrt{s} = 13$ TeV. These results are the most stringent limits to date on the production of W$'$ bosons that decay to a top and a bottom quark.

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References

[1] M. Schmaltz, D. Tucker-Smith, Little Higgs review, Annu. Rev. Nucl. Part. Sci. 55 (2005) 229, https://doi.org/10.1146/annurev.nucl.55.090704.151502, arXiv:hep-ph/0502182.

[2] T. Appelquist, H.-C. Cheng, B.A. Dobrescu, Bounds on universal extra dimensions, Phys. Rev. D 64 (2001) 035002, https://doi.org/10.1103/PhysRevD.64.035002, arXiv:hep-ph/0012100.

[3] H.-C. Cheng, C.T. Hill, S. Pokorski, J. Wang, Standard model in the latticized bulk, Phys. Rev. D 64 (2001) 065007, https://doi.org/10.1103/PhysRevD.64.065007, arXiv:hep-th/0104179.

[4] R.S. Chivukula, E.H. Simmons, J. Terning, Limits on noncommuting extended technicolor, Phys. Rev. D 53 (1996) 5258, https://doi.org/10.1103/PhysRevD.53.5258, arXiv:hep-ph/9506427.

[5] R.N. Mohapatra, J.C. Pati, Left–right gauge symmetry and an 'isoconjugate' model of CP violation, Phys. Rev. D 11 (1975) 566, https://doi.org/10.1103/PhysRevD.11.566.

[6] D.J. Muller, S. Nandi, Topflavor: a separate SU(2) for the third family, Phys. Lett. B 383 (1996) 345, https://doi.org/10.1016/0370-2693(96)00745-9, arXiv:hep-ph/9607328.

[7] E. Malkawi, T. Tait, C.-P. Yuan, A model of strong flavor dynamics for the top quark, Phys. Lett. B 385 (1996) 304, https://doi.org/10.1016/0370-2693(96)00859-3, arXiv:hep-ph/9603349.

[8] V.M. Abazov, D0, Search for W' boson resonances decaying to a top quark and a bottom quark, Phys. Rev. Lett. 100 (2008) 211803, https://doi.org/10.1103/PhysRevLett.100.211803, arXiv:0803.3256.

[9] V.M. Abazov, D0, Search for W$'$ → tb resonances with left- and right-handed couplings to fermions, Phys. Lett. B 699 (2011) 145, https://doi.org/10.1016/j.physletb.2011.03.066, arXiv:1101.0806.

[10] T.A. Aaltonen, CDF, Search for resonances decaying to top and bottom quarks with the CDF experiment, Phys. Rev. Lett. 115 (2015) 061801, https://doi.org/10.1103/PhysRevLett.115.061801, arXiv:1504.01536.

[11] CMS Collaboration, Search for W$'$ → tb decays in the lepton+jets final state in pp collisions at $\sqrt{s} = 8$ TeV, J. High Energy Phys. 05 (2014) 108, https://doi.org/10.1007/JHEP05(2014)108, arXiv:1402.2176.

[12] CMS Collaboration, Search for W$'$ → tb decays in proton–proton collisions at $\sqrt{s} = 8$ TeV, J. High Energy Phys. 02 (2016) 122, https://doi.org/10.1007/JHEP02(2016)122, arXiv:1509.06051.

[13] CMS Collaboration, Searches for W$'$ bosons decaying to a top quark and a bottom quark in proton–proton collisions at 13 TeV, J. High Energy Phys. 08 (2017) 029, https://doi.org/10.1007/JHEP08(2017)029, arXiv:1706.04260.

[14] ATLAS Collaboration, Search for W$'$ → tb → qqbb decays in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, Eur. Phys. J. C 75 (2015) 165, https://doi.org/10.1140/epjc/s10052-015-3372-2, arXiv:1408.0886.

[15] ATLAS Collaboration, Search for W$'$ → t$\bar{\mathrm{b}}$ in the lepton plus jets final state in proton–proton collisions at a centre-of-mass energy of $\sqrt{s} = 8$ TeV with the ATLAS detector, Phys. Lett. B 743 (2015) 235, https://doi.org/10.1016/j.physletb.2015.02.051, arXiv:1410.4103.

[16] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. 3 (2008) S08004, https://doi.org/10.1088/1748-0221/3/08/S08004.

[17] CMS Collaboration, Particle-flow reconstruction and global event description with the CMS detector, https://doi.org/10.1088/1748-0221/12/10/P10003, arXiv:1706.04965, 2017.

[18] CMS Collaboration, Performance of photon reconstruction and identification with the CMS detector in proton–proton collisions at $\sqrt{s} = 8$ TeV, J. Instrum. 10 (2015) P08010, https://doi.org/10.1088/1748-0221/10/08/P08010, arXiv:1502.02702.

[19] CMS Collaboration, Performance of electron reconstruction and selection with the CMS detector in proton–proton collisions at $\sqrt{s} = 8$ TeV, J. Instrum. 10 (2015) P06005, https://doi.org/10.1088/1748-0221/10/06/P06005, arXiv:1502.02701.

[20] CMS Collaboration, Determination of jet energy calibration and transverse momentum resolution in CMS, J. Instrum. 6 (2011) P11002, https://doi.org/10.1088/1748-0221/6/11/P11002, arXiv:1107.4277.

[21] CMS Collaboration, Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV, J. Instrum. 7 (2012) P10002, https://doi.org/10.1088/1748-0221/7/10/P10002, arXiv:1206.4071.

[22] Z. Sullivan, Fully differential W' production and decay at next-to-leading order in QCD, Phys. Rev. D 66 (2002) 075011, https://doi.org/10.1103/PhysRevD.66.075011, arXiv:hep-ph/0207290.

[23] D. Duffty, Z. Sullivan, Model independent reach for W-prime bosons at the LHC, Phys. Rev. D 86 (2012) 075018, https://doi.org/10.1103/PhysRevD.86.075018, arXiv:1208.4858.

[24] E. Boos, V. Bunichev, M. Dubinin, L. Dudko, V. Ilyin, A. Kryukov, V. Edneral, V. Savrin, A. Semenov, A. Sherstnev, CompHEP, CompHEP 4.4: automatic computations from Lagrangians to events, Nucl. Instrum. Methods A 534 (2004) 250, https://doi.org/10.1016/j.nima.2004.07.096, arXiv:hep-ph/0403113.

[25] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.S. Shao, T. Stelzer, P. Torrielli, M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, J. High Energy Phys. 07 (2014) 079, https://doi.org/10.1007/JHEP07(2014)079, arXiv:1405.0301.

[26] R. Frederix, S. Frixione, Merging meets matching in MC@NLO, J. High Energy Phys. 12 (2012) 061, https://doi.org/10.1007/JHEP12(2012)061, arXiv:1209.6215.

[27] J. Alwall, S. Höche, F. Krauss, N. Lavesson, L. Lönnblad, F. Maltoni, M.L. Mangano, M. Moretti, C.G. Papadopoulos, F. Piccinini, S. Schumann, M. Treccani, J. Winter, M. Worek, Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions, Eur. Phys. J. C 53 (2008) 473, https://doi.org/10.1140/epjc/s10052-007-0490-5, arXiv:0706.2569.

[28] P. Nason, A new method for combining NLO QCD with shower Monte Carlo algorithms, J. High Energy Phys. 11 (2004) 040, https://doi.org/10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.

[29] S. Frixione, P. Nason, C. Oleari, Matching NLO QCD computations with parton shower simulations: the POWHEG method, J. High Energy Phys. 11 (2007) 070, https://doi.org/10.1088/1126-6708/2007/11/070.

[30] S. Alioli, P. Nason, C. Oleari, E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX, J. High Energy Phys. 06 (2010) 043, https://doi.org/10.1007/JHEP06(2010)043, arXiv:1002.2581.

[31] S. Frixione, P. Nason, G. Ridolfi, A positive-weight next-to-leading-order Monte Carlo for heavy flavour hadroproduction, J. High Energy Phys. 09 (2007) 126, https://doi.org/10.1088/1126-6708/2007/09/126, arXiv:0707.3088.

[32] E. Re, Single-top Wt-channel production matched with parton showers using the POWHEG method, Eur. Phys. J. C 71 (2011) 1547, https://doi.org/10.1140/epjc/s10052-011-1547-z, arXiv:1009.2450.

[33] T. Sjöstrand, S. Ask, J.R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C.O. Rasmussen, P.Z. Skands, An introduction to PYTHIA 8.2, Comput. Phys. Commun. 191 (2015) 159, https://doi.org/10.1016/j.cpc.2015.01.024, arXiv:1410.3012.

[34] CMS Collaboration, Measurement of differential cross sections for top quark pair production using the lepton+jets final state in proton–proton collisions at 13 TeV, Phys. Rev. D 95 (2017) 092001, https://doi.org/10.1103/PhysRevD.95.092001, arXiv:1610.04191.

[35] S. Agostinelli, et al., GEANT4, GEANT4: a simulation toolkit, Nucl. Instrum. Methods A 506 (2003) 250, https://doi.org/10.1016/S0168-9002(03)01368-8.

[36] J. Allison, et al., GEANT4 developments and applications, IEEE Trans. Nucl. Sci. 53 (2006) 270, https://doi.org/10.1109/TNS.2006.869826.

[37] R.D. Ball, et al., NNPDF, Parton distributions for the LHC run II, J. High Energy Phys. 04 (2015) 040, https://doi.org/10.1007/JHEP04(2015)040, arXiv:1410.8849.

[38] M. Cacciari, G.P. Salam, G. Soyez, The anti-k_t jet clustering algorithm, J. High Energy Phys. 04 (2008) 063, https://doi.org/10.1088/1126-6708/2008/04/063, arXiv:0802.1189.

[39] M. Cacciari, G.P. Salam, G. Soyez, FastJet user manual, Eur. Phys. J. C 72 (2012) 1896, https://doi.org/10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.

[40] CMS Collaboration, Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV, J. Instrum. 12 (2017) P02014, https://doi.org/10.1088/1748-0221/12/02/P02014, arXiv:1607.03663.

[41] D. Krohn, M.D. Schwartz, M. Low, L.-T. Wang, Jet cleansing: pileup removal at high luminosity, Phys. Rev. D 90 (2014) 065020, https://doi.org/10.1103/PhysRevD.90.065020, arXiv:1309.4777.

[42] M. Cacciari, G.P. Salam, Pileup subtraction using jet areas, Phys. Lett. B 659 (2008) 119, https://doi.org/10.1016/j.physletb.2007.09.077, arXiv:0707.1378.

[43] CMS Collaboration, Identification of b-quark jets with the CMS experiment, J. Instrum. 8 (2013) P04013, https://doi.org/10.1088/1748-0221/8/04/P04013, arXiv:1211.4462.

[44] CMS Collaboration, Identification of b Quark Jets at the CMS Experiment in the LHC Run 2, CMS Physics Analysis Summary CMS-PAS-BTV-15-001, 2016, http://cdsweb.cern.ch/record/2138504.

[45] CMS Collaboration, Measurement of the $\mathrm{t\bar{t}}$ production cross section in pp collisions at 7 TeV in lepton+jets events using b-quark jet identification, Phys. Rev. D 84 (2011) 092004, https://doi.org/10.1103/PhysRevD.84.092004, arXiv:1108.3773.

[46] CMS Collaboration, CMS Luminosity Measurements for the 2016 Data Taking Period, CMS Physics Analysis Summary CMS-PAS-LUM-17-001, 2017, http://cds.cern.ch/record/2257069.

[47] M. Cacciari, S. Frixione, M.L. Mangano, P. Nason, G. Ridolfi, The $t\bar{t}$ cross-section at 1.8 TeV and 1.96 TeV: a study of the systematics due to parton densities and scale dependence, J. High Energy Phys. 04 (2004) 068, https://doi.org/10.1088/1126-6708/2004/04/068, arXiv:hep-ph/0303085.

[48] S. Catani, D. de Florian, M. Grazzini, P. Nason, Soft gluon resummation for Higgs boson production at hadron colliders, J. High Energy Phys. 07 (2003) 028, https://doi.org/10.1088/1126-6708/2003/07/028, arXiv:hep-ph/0306211.

[49] ATLAS Collaboration, Measurement of the inelastic proton–proton cross section at $\sqrt{s} = 13$ TeV with the ATLAS detector at the LHC, Phys. Rev. Lett. 117 (2016) 182002, https://doi.org/10.1103/PhysRevLett.117.182002, arXiv:1606.02625.

[50] J. Butterworth, et al., PDF4LHC recommendations for LHC run II, J. Phys. G 43 (2016) 023001, https://doi.org/10.1088/0954-3899/43/2/023001, arXiv:1510.03865.

[51] T. Müller, J. Ott, J. Wagner-Kuhr, theta — a framework for template-based modeling and inference, http://www-ekp.physik.uni-karlsruhe.de/~ott/theta/testing/html/theta__auto__intro.html, 2010.

[52] R. Barlow, C. Beeston, Fitting using finite Monte Carlo samples, Comput. Phys. Commun. 77 (1993) 219, https://doi.org/10.1016/0010-4655(93)90005-W.

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