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Search For s Channel Single Top Quark Production In pp Collisions At √s = 7 And 8 TeV

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Search for s channel single top quark production in pp collisions at $\sqrt{s} = 7$ and 8 TeV

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Abstract: A search is presented for single top quark production in the s channel in proton-proton collisions with the CMS detector at the CERN LHC in decay modes of the top quark containing a muon or an electron in the final state. The signal is extracted through a maximum-likelihood fit to the distribution of a multivariate discriminant defined using boosted decision trees to separate the expected signal contribution from background processes. The analysis uses data collected at centre-of-mass energies of 7 and 8 TeV and corresponding to integrated luminosities of 5.1 and 19.7 fb^{-1}, respectively. The measured cross sections of 7.1 ± 8.1 pb (at 7 TeV) and 13.4 ± 7.3 pb (at 8 TeV) result in a best fit value of 2.0 ± 0.9 for the combined ratio of the measured and expected values. The signal significance is 2.5 standard deviations, and the upper limit on the rate relative to the standard model expectation is 4.7 at 95% confidence level.

Keywords: Hadron-Hadron scattering (experiments), Top physics

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Contents

1 Introduction

Top quarks at the CERN LHC are produced mainly in pairs through the strong interaction, but can also be produced individually via a charged-current electroweak interaction. The study of single top quark production thereby provides probes of the electroweak sector of the standard model (SM), which predicts three production channels: the s channel, the t channel, and the W-associated or tW production channel (figure 1).

The first observations of single top quark production were announced by the D0 and CDF collaborations at the Fermilab Tevatron in 2009 [1, 2]. Evidence for s channel production was announced by the D0 collaboration in 2013 [3], while the process was definitively observed when combining the searches from both the D0 and the CDF collaborations [4]. Evidence for s channel production was confirmed by the ATLAS Collaboration at the LHC [5], where the search is challenging because the process is suppressed in proton-proton (pp) collisions.

For pp collisions at $\sqrt{s} = 7$ and $8\,\text{TeV}$, the SM predicted s channel cross sections are

$$\sigma_s(7\,\text{TeV}) = 4.56 \pm 0.07\,(\text{scale}) \pm 0.17\,(\text{PDF})\,\text{pb}, \quad \text{and}$$
$$\sigma_s(8\,\text{TeV}) = 5.55 \pm 0.08\,(\text{scale}) \pm 0.21\,(\text{PDF})\,\text{pb},$$

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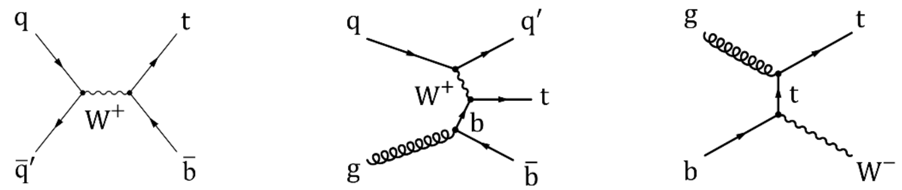

Figure 1. Leading-order Feynman diagram for single top quark production in (left) the s channel, whose production rate is studied in this paper, (middle) the dominant next-to-leading-order diagram in the t channel, and (right) the tW production channel.

as calculated in quantum chromodynamics (QCD) at approximate next-to-next-to-leading order (NNLO), including resummation of soft-gluon emission within next-to-next-to-leading logarithms (NNLL) [6]. The first uncertainty corresponds to a doubling and halving of the renormalization and factorization scales. The second uncertainty is from the choice of parton distribution functions (PDFs) at the 90% confidence level (CL).

All three single top quark production channels, shown in figure 1, are directly related to the Cabibbo-Kobayashi-Maskawa matrix element V_{tb}, providing a direct measurement of this SM parameter. The s channel production process is of special interest since a possible deviation from the SM prediction of its cross section may indicate the presence of mechanisms beyond the standard model (BSM), as predicted by models that involve the exchange of a non-SM mediator, such as a W′ boson or a charged Higgs boson [7]. A review of deviations from SM predictions for s and t channel modes in BSM scenarios can be found in ref. [8].

This paper presents a search performed at the CMS experiment for single top quark production in the s channel considering the leptonic decay channels of the W boson produced in top quark decay. Only the decays of the W boson into a muon or an electron ($\ell = \mu$, e) and a corresponding neutrino are considered. Decays of the W boson into a tau lepton and a neutrino, where the tau lepton subsequently decays into a muon or an electron, are regarded as part of the signal. Events are selected considering the kinematic properties of physical objects reconstructed in the final state. Three statistically independent analysis categories are therefore defined, according to the number and flavour of the reconstructed jets. Dedicated strategies are used in data to estimate and reject multijet backgrounds. The procedure for signal extraction consists of a simultaneous fit to the distributions of multivariate discriminants trained separately in each analysis category on a set of kinematic variables that show separation between signal and background.

This measurement is performed using LHC pp collision data collected by the CMS detector corresponding to the integrated luminosities of 5.1 and 19.7 fb^{-1} at centre-of-mass energies of 7 and 8 TeV, respectively. While at 7 TeV only the muon channel is considered, at 8 TeV both the muon and electron channels are included.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter providing an axial magnetic field of 3.8 T. The inner region accommodates the

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silicon pixel and strip tracker which records charged particle trajectories with high granularity and precision up to pseudorapidity $|\eta| = 2.5$. An electromagnetic calorimeter (ECAL) made of lead tungstate crystals and a brass and scintillator sampling hadron calorimeter, both arranged in a barrel assembly and two endcaps, surround the tracking volume and extend up to the region $|\eta| < 3.0$. Coverage up to $|\eta| = 5.0$ is provided by a quartz-fibre and steel absorber Cherenkov calorimeter. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system and the relevant kinematic variables, can be found in ref. [9].

3 Simulated samples

The nominal s channel single top quark events in this study are generated using the next-to-leading order (NLO) POWHEG 1.0 [10] event generator. The CTEQ6.6M program [11] is used to model the proton PDF. The top quark mass is set to 172.5 GeV, and tau lepton decays are modelled with TAUOLA [12]. For the 7 TeV analysis, a large sample of signal events generated using the leading-order (LO) matrix-element CompHEP 4.4 [13] generator is employed for the training of the multivariate discriminant. The generators are interfaced to LO PYTHIA 6.4 (Z2 tune) [14] for showering and hadronization. Monte Carlo (MC) simulated events with a single top quark are normalized to the approximate NNLO+NNLL cross section of 3.14 pb at 7 TeV and 3.79 pb at 8 TeV [6]. MC simulated events with a top antiquark are normalized to the approximate NNLO+NNLL cross section of 1.42 pb at 7 TeV and 1.76 pb at 8 TeV. The other single top quark processes, t channel, and tW production, are considered as backgrounds for this measurement and are simulated using the POWHEG 1.0 generator.

The main background in this analysis is top quark pair production ($\mathrm{t\bar{t}}$) in final states with one or two charged leptons. Single vector bosons in association with jets, W+jets, and Z+jets, are also included in the background. Both $\mathrm{t\bar{t}}$ and single vector boson events are generated using LO matrix element MadGraph 5.1 [15] interfaced to PYTHIA 6.4. The background from diboson (WW, ZZ, and WZ) events is small and is generated with PYTHIA 6.4. Multijet background events from QCD processes are extracted directly from data or from a simulated sample generated with PYTHIA 6.4 (see section 6). The cross sections for the background processes in the analysis are summarized in table 1.

The cross sections are reported at approximate NNLO+NNLL accuracy for single top quark [6] and $\mathrm{t\bar{t}}$ production [16], at NNLO accuracy for Z/γ^*+jets and W+n jets (with $n = 1, 2, 3,$ and 4) events [17], and at the LO level for the remaining contributions. When stated, the cross section includes the branching ratio of the leptonic decay, including electrons, muons, and tau leptons. The multijet sample is defined by the presence of at least one generator-level muon with $p_T > 15$ GeV, and requiring the transverse momentum generated in the hard scattering parton process to be greater than 20 GeV.

For all generated processes, the detector response is simulated using a detailed description of the CMS detector, based on Geant4 [18]. A reweighting procedure is applied to

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Process	σ [pb] at 7 TeV	σ [pb] at 8 TeV
Single top quark (t channel)	43.0	56.4
Single antitop quark (t channel)	22.9	30.7
Single top or antitop quark (tW)	7.8	11.1
$t\bar{t}$	172.0	245.8
$W(\to \ell\nu)$+1 jet	4500	5400
$W(\to \ell\nu)$+2 jets	1400	1800
$W(\to \ell\nu)$+3 jets	300	520
$W(\to \ell\nu)$+4 jets	170	210
$Z/\gamma^*(\to \ell^+\ell^-)$+jets	3000	3500
WW	43	57
WZ	18	32
ZZ	5.9	8.3
μ-enriched multijet events	85 000	—

Table 1. Monte Carlo cross sections calculated for background processes.

simulated events to reproduce the distribution of the number of multiple pp interactions per bunch crossing (pileup events) observed in data.

4 Selection and reconstruction

The final-state topology in the s channel is characterized by the presence of one isolated muon or electron, a neutrino that results in an imbalance in the transverse momentum of the event, and two b quarks, one originating from the top quark decay and one recoiling against the top quark.

Events with at least one muon were selected by the online trigger [9], requiring $p_T > 17$ GeV at 7 TeV, $p_T > 24$ GeV at 8 TeV, $|\eta| < 2.1$, and lepton isolation criteria. Similarly, for electrons at 8 TeV, the corresponding values are $p_T > 27$ GeV and $|\eta| < 2.5$.

Because of the increase in instantaneous luminosity during the second part of the 7 TeV run, the single muon trigger had to be prescaled and was replaced by a hadronic trigger that required at least one muon as defined above and at least one jet in the central region of the detector with $p_T > 30$ GeV, satisfying an online b tagging criterion. Simulated leptonic trigger efficiencies are corrected to match those measured in data. Hadronic trigger efficiencies are not simulated but are measured in data and parametrized as a function of the jet p_T in order to reweight the simulated events.

At least one primary vertex is required to be reconstructed from at least four tracks and to satisfy $|z_{PV}| < 24$ cm and $\rho_{PV} < 2$ cm, where $|z_{PV}|$ and ρ_{PV} are the respective longitudinal and transverse distances of the primary vertex relative to the center of the detector. When more than one interaction vertex is found, the one with largest sum in p_T^2 of associated tracks is defined as the primary vertex.

The particle candidates are required to originate from the primary vertex, and are reconstructed using the CMS particle-flow (PF) algorithm [19]. Reconstructed muons with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ at 7 TeV and $p_{\mathrm{T}} > 26\,\mathrm{GeV}$ at 8 TeV within the trigger acceptance ($|\eta| < 2.1$) are selected for analysis. At 8 TeV, reconstructed electrons [20] with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ within $|\eta| < 2.5$ are selected, excluding the transition region between ECAL barrel and endcaps ($1.44 < |\eta| < 1.57$) where the reconstruction of electrons is not optimal.

Lepton isolation is applied using the I_{rel} variable, defined as the ratio between the sum of the transverse energies (E_{T}) of stable charged hadrons, photons, and neutral hadrons in a cone of size $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ around the lepton direction (where ϕ is the azimuth in radians), and the p_{T} of the lepton. At 7 TeV, the muon isolation requirement is $I_{\mathrm{rel}} < 0.15$ with $\Delta R = 0.3$. At 8 TeV, I_{rel} is corrected by subtracting the average contribution from neutral particles in pileup events. It is required $I_{\mathrm{rel}} < 0.12$ with $\Delta R = 0.4$ for muon isolation, and $I_{\mathrm{rel}} < 0.1$ with $\Delta R = 0.3$ for electron isolation.

The presence of a single muon or electron satisfying the criteria described above is required to reduce the contribution from dilepton events, which can arise from $\mathrm{t\bar{t}}$ or from $\mathrm{q\bar{q}} \to \ell^+\ell^-$+jets Drell-Yan (DY) processes. Events containing additional muons or electrons, with looser requirements for muons of $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ within the full acceptance of $|\eta| < 2.5$, and $I_{\mathrm{rel}} < 0.2$, and for electrons with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$, $|\eta| < 2.5$, and $I_{\mathrm{rel}} < 0.15$ are rejected.

Jets are reconstructed using the anti-k_{T} algorithm [21] with a distance parameter of 0.5, using as input the particles identified through the PF algorithm. To reduce contamination from pileup events, charged particle candidates not associated with the primary vertex are excluded from the jet reconstruction. The energies of jets are corrected by the estimated amount of energy deposited in the jet area [22] from pileup hadrons. Scale factors depending on the E_{T} and η of the jets [23] are further applied and reflect the detector response. The analysis considers jets within $|\eta| < 4.5$ and $p_{\mathrm{T}} > 40\,\mathrm{GeV}$. We identify jets stemming from b quarks through b tagging algorithms [24]. The threshold on the discriminant value is set to provide a misidentification probability (mistag) for light-parton jets of about 0.1%. The corresponding b tagging efficiency ranges from 40 to 60%, depending on jet p_{T} and η and on the specific algorithm. Simulated b tagging efficiencies are corrected to match those measured in data [24, 25].

The imbalance in transverse momentum (vector $\vec{p}\!\!\!/_{\mathrm{T}}$) is defined as the projection on the plane perpendicular to the beams of the negative of the vector sum of the momenta of all reconstructed particles in an event. Its magnitude is referred to as $E\!\!\!/_{\mathrm{T}}$. It is assumed that the x and y components of the missing momentum, $(\vec{p}\!\!\!/_{\mathrm{T}})_x$ and $(\vec{p}\!\!\!/_{\mathrm{T}})_y$, are entirely due to the escaping neutrino. The longitudinal component $p_{z,\nu}$ of the neutrino momentum is estimated from a quadratic equation obtained by imposing that the invariant mass of the lepton-neutrino system must be equal to the invariant mass of the W boson. In case of two real solutions, the smallest $p_{z,\nu}$ is chosen, while when two complex solutions are found the imaginary part is eliminated by recalculating $(\vec{p}\!\!\!/_{\mathrm{T}})_x$ and $(\vec{p}\!\!\!/_{\mathrm{T}})_y$ independently, to provide a W boson with a transverse mass of 80.4 GeV. The W boson transverse mass is defined as

$$m_{\mathrm{T}} = \sqrt{(p_{\mathrm{T},\ell} + p_{\mathrm{T},\nu})^2 - (p_{x,\ell} + p_{x,\nu})^2 - (p_{y,\ell} + p_{y,\nu})^2},$$

where $p_{\mathrm{T},\ell}$ and $p_{\mathrm{T},\nu}$ are the lepton and neutrino transverse momenta and $p_{x,\ell}$, $p_{y,\ell}$, $p_{x,\nu}$ and $p_{y,\nu}$ are the components of the lepton and neutrino transverse momenta along the x and y axes. Finally, four-momenta of top quark candidates are reconstructed from the lepton and the jet originating from the b quark produced in top quark decay, using also the quantities $\not{p}_{\mathrm{T}}$ and $p_{z,\nu}$. In events with more than 1 b jet, the one which results in a reconstructed top mass closer to the nominal one is chosen.

The selected events are classified into statistically independent "N-jets M-tags" analysis categories, where N refers to the number of reconstructed jets above 40 GeV and M to the number of selected jets passing the b tagging requirement. Three event categories are used for this analysis: the 2-jets 2-tags category is s channel enriched, and employed in signal extraction, the 2-jets 1-tag category is useful to constrain the t channel and W+jets backgrounds, while the 3-jets 2-tags category is useful to constrain the dominant $\mathrm{t\bar{t}}$ background. In each event category, further requirements are applied to reject the multijet background, which in the 8 TeV analysis is separated from the other components by means of a QCD BDT discriminator. The strategies to reject the multijet background and to estimate its contribution will be described in section 6.

An additional selection is applied in the 8 TeV signal 2-jets 2-tags category that exploits the property of s channel events to have a lower number of additional jets with $20 < p_{\mathrm{T}} < 40$ GeV (loose jets) than $\mathrm{t\bar{t}}$ events. Only events with no more than 1 loose jet are selected. The requirement selects 60% of $\mathrm{t\bar{t}}$ events and 90% of s channel events.

Because of the presence of two b-tagged jets in the final state, the 2-jets 2-tags and the 3-jets 2-tags categories are reconstructed with a top quark candidate for each of the two b jets. The candidate with invariant mass closest to the nominal top quark mass of 172.5 GeV is then selected for further study in the analysis. Using this method, the efficiency of association of the correct b jet to the top quark is measured to be 74% in s channel events and 70% in $\mathrm{t\bar{t}}$ events. The dependence of the correct b jet association on top quark mass is evaluated in s channel events by changing the top quark mass by the conservative estimation of its uncertainty of ± 1.5 GeV, which yields changes in efficiency of less than 1%.

5 Implementation of the multivariate analysis

Since the SM prediction for the signal yield is much smaller than the background processes, it is important to enhance the separation between signal and background events to measure the s channel with highest possible significance. A multivariate analysis was therefore developed, in which boosted decision tree (BDT) discriminants [26] are defined for each event category, based on a set of input discriminants. In this section the BDTs for signal extraction are described, while in the next section the BDTs for the multijet background rejection will be presented.

The BDT training and the choice of the input discriminants is performed separately for the muon channels at 7 and 8 TeV and for the electron channel at 8 TeV, taking into account the different selections and the different level of background, in particular for the multijet background. The samples employed for training and evaluation of performance are taken from simulation, with the exception of the multijet background, which is taken from a data control sample, as described in section 6.

Several discriminants are investigated for possible input to the BDTs, in particular kinematic and angular variables exploiting the properties of s channel events [27]. For each channel, the set of input variables are defined according to the following criteria. A variable must be well modelled in simulation, and must significantly increase the discrimination power of a BDT (after comparing performance of the BDTs trained without it).

The most important variables chosen as input to the BDTs in the 2-jets 2-tags category are: m_{T}, the angular separation between the two jets (ΔR_{bb}), the invariant mass of the system composed of the lepton and subleading jet ($m_{\ell \mathrm{b}2}$), the transverse momentum of the two-jet system ($p_{\mathrm{T}}^{\mathrm{bb}}$), and the difference in azimuthal angle between the top quark and the leading jet ($\Delta\phi_{\mathrm{t,b1}}$). The leading and subleading jets refer to the two jets with largest p_{T}.

The other variables used as input to the BDTs are the invariant mass of the top quark candidate in the event ($m_{\ell\nu\mathrm{b}}$), the scalar sum of the p_{T} of all jets (H_{T}), the cosine of the angle between lepton and the beam axis in the top quark rest frame ($\cos\theta_\ell$), $E\!\!\!/_{\mathrm{T}}$, the lepton p_{T}, and the difference in azimuthal angle between the top quark and the next-to-leading b jet ($\Delta\phi_{\mathrm{t,b2}}$).

Figure 2 shows the comparison between data and MC events for the highest ranked variables, where the simulation is normalized to the number of events selected in data.

The most important variables chosen as input to the BDTs in the 2-jets 1-tags category are: the angular separation between the two jets (ΔR_{bq}), the cosine of the angle between the lepton and the jet recoiling against the top quark in the top quark rest frame ($\cos\theta^*$), $m_{\ell\nu\mathrm{b}}$, the invariant mass of the two-jet system (m_{bq}), and H_{T}. The other variables are the invariant mass of the system composed of the lepton and subleading jet ($m_{\ell,\mathrm{j}2}$), the lepton pseudorapidity (η_ℓ), and the difference in azimuthal angle between the $\not{p}_{\mathrm{T}}$ and the lepton ($\Delta\phi_{\not{p}_{\mathrm{T}},\ell}$).

The most important variables chosen as input to the BDTs in the 3-jets 2-tags category are: $p_{\mathrm{T}}^{\mathrm{bb}}$, $m_{\ell\mathrm{b}2}$, the cosine of the angle between the lepton and the non b-tagged jet in the top quark rest frame ($\cos\theta^*_{\mathrm{q}}$), and m_{T}. The other variables are $m_{\ell\nu\mathrm{b}}$, H_{T}, the transverse momentum of the next-to-leading b jet ($p_{\mathrm{T}}^{\mathrm{b}2}$), and the transverse momentum of the non b-tagged jet ($p_{\mathrm{T}}^{\mathrm{q}}$).

6 Multijet background

In the 7 TeV analysis, the W boson m_{T} distribution is employed to discriminate against the multijet background. Multijet events populate the lower part of the m_{T} spectrum and the requirement $m_{\mathrm{T}} > 50\,\mathrm{GeV}$ is applied to suppress their contribution to a negligible level in the 2-jets 1-tag event category. The number of multijet events that pass the selection is estimated from simulation. In the other categories, the level of multijet production is already small compared to other backgrounds, and its contribution is estimated through a maximum-likelihood fit to the m_{T} distribution.

In the 8 TeV analysis, BDT discriminants, referred to as QCD BDTs, are used to reject multijet events following the same procedure as in section 5. For each event category a

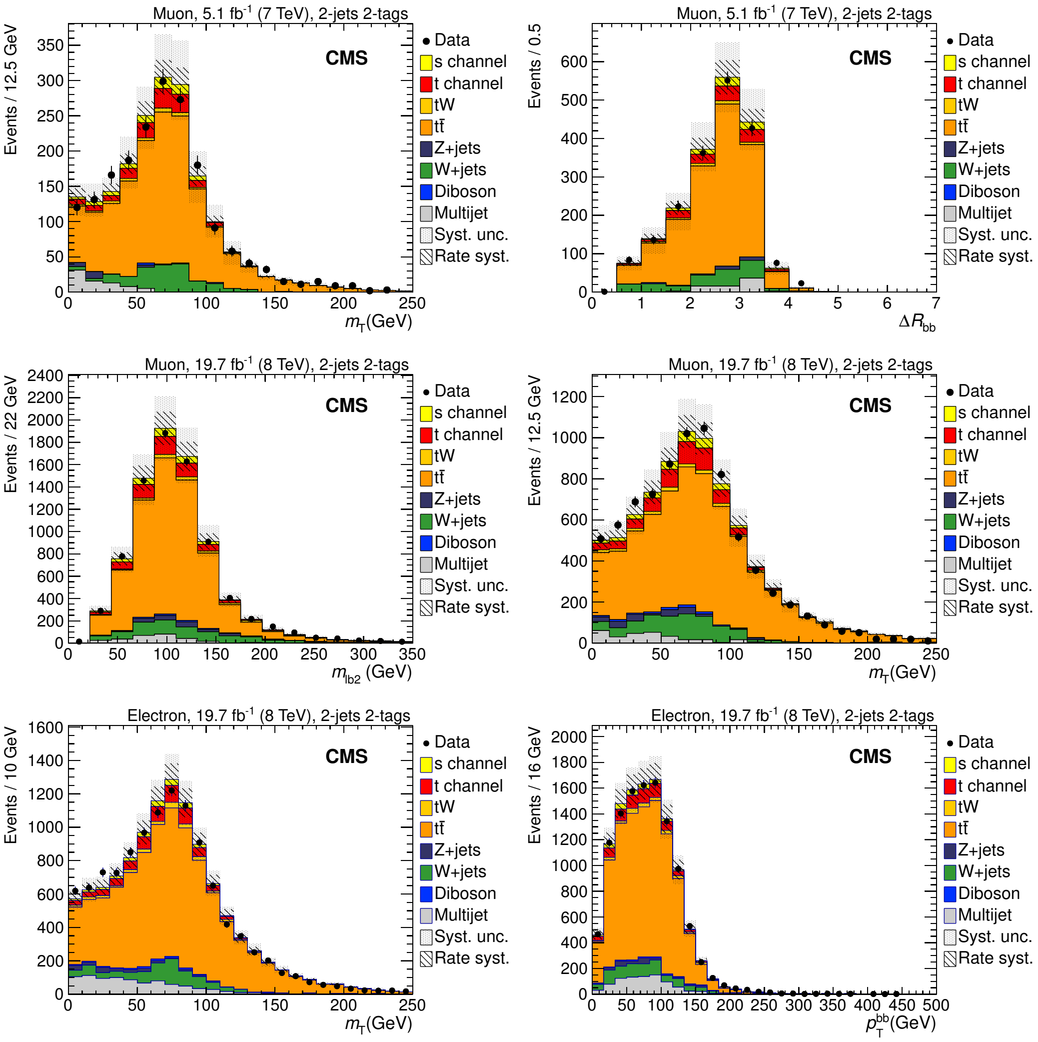

Figure 2. Comparison between data and simulation in distributions of highest-ranked variables in the 2-jets 2-tags category: (upper left) m_{T} and (upper right) ΔR_{bb} for the muon channel at 7 TeV, (middle left) $m_{\ell\mathrm{b}2}$ and (middle right) m_{T} for the muon channel at 8 TeV, and (bottom left) m_{T} and (bottom right) $p_{\mathrm{T}}^{\mathrm{bb}}$ for the electron channel at 8 TeV. The simulation is normalized to the data and the multijet background is normalized through the maximum-likelihood fit discussed in section 6, prior to rejecting the multijet background. The smaller error bands represent only the systematic uncertainties on the background normalizations, while the larger ones include the total systematic uncertainty obtained from the sum in quadrature of the individual contributions listed in section 7.

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Lepton	Event category	Acceptance (%)	
		Multijet	s channel
μ	2-jets 1-tag	38	75
	2-jets 2-tags	50	92
	3-jets 2-tags	30	74
e	2-jets 1-tag	29	58
	2-jets 2-tags	60	92
	3-jets 2-tags	40	68

Table 2. QCD BDT selection acceptance for multijet and s channel events at 8 TeV.

QCD BDT is trained using multijet events as signal against non-multijet processes, and the distribution of the QCD BDT discriminant in data is employed to define a multijet-enriched interval. Events with the discriminant value in this interval are rejected from the analysis. The number of rejected multijet events is estimated through a maximum-likelihood fit to the QCD BDT distribution in the multijet-enriched interval in data. This number, multiplied by a scale factor obtained from the selection acceptance, provides the yield of remaining multijet events for each category.

The most important variables chosen as input to the QCD BDTs in the 2-jets 2-tags category are: lepton p_{T}, lepton η, $m_{\ell\nu\mathrm{b}}$, m_{T}, $\cos\theta^{*}$, and the transverse momentum of the leading b jet ($p_{\mathrm{T}}^{\mathrm{b}}$). The distributions for the multijet background are extracted from a data sample enriched with such events. In the muon channel, the sample is defined by an anti-isolation requirement on the muon ($0.2 < I_{\mathrm{rel}} < 0.5$ at 7 TeV and $I_{\mathrm{rel}} > 0.2$ at 8 TeV). In the electron channel, it is defined by requiring the failure either of the isolation criteria or the tight identification criteria on the electron. Since the number of events in the multijet-enriched data sample at 7 TeV is lower than at 8 TeV due to smaller integrated luminosity, no QCD BDT is defined in the 7 TeV analysis.

Table 2 presents the s channel and multijet event acceptances of the QCD BDT selection. Different acceptances are observed in the different event categories since the QCD BDT selection is optimized to minimize the loss of signal events.

Figure 3 shows a comparison of the distributions in QCD BDT discriminants in data and simulation in the 2-jets 2-tags category for muon and electron channels at 8 TeV, where the simulation is normalized to events in data.

Both in 7 and 8 TeV analyses (except for 2-jets 1-tag category at 7 TeV) a maximum-likelihood fit is performed to determine the yield in multijet events. We define the parametrized function $F(x) = a\,V(x) + b\,M(x)$, where x represents the discriminant variable and $V(x)$ and $M(x)$ are the respective distributions (templates) in the sum of all processes including a W or Z boson in the final state, or multijet events. The $V(x)$ distribution is taken from simulation, while $M(x)$ is the template based on the multijet-enriched data sample.

The total uncertainty on the multijet background is obtained by considering the statistical uncertainty from the fit and possible systematic contributions, which are evaluated by repeating the fit after changing the sum of non-multijet components by 20% and employing

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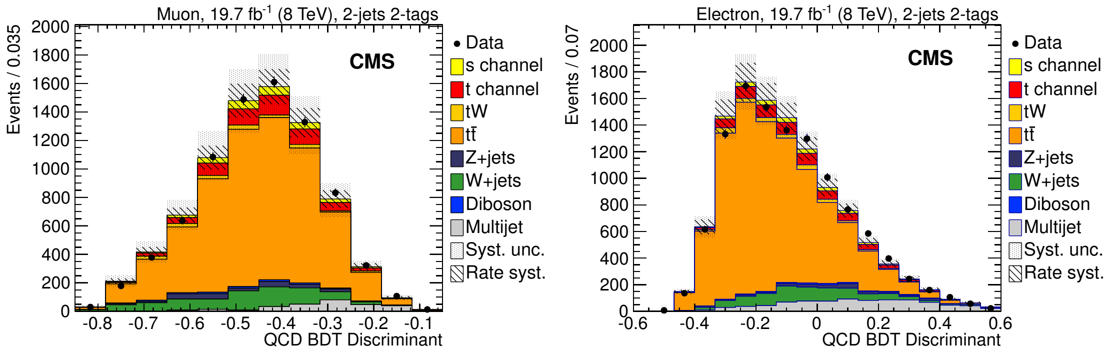

Figure 3. Comparison of data with simulation for distributions in the QCD BDT discriminant in the 2-jets 2-tags event category, in (left) the muon and (right) electron channel at 8 TeV. The simulation is normalized to the data. While the smaller error bands include the systematic uncertainties on the background normalizations only, the larger ones include the total systematic uncertainty obtained summing in quadrature the individual contributions discussed in section 7.

a multijet template model taken from an independent sample in data, where neither of the two jets pass the b tagging requirement.

7 Systematic uncertainties

Several sources of systematic uncertainties have been investigated and determined as follows. Uncertainties on the normalization are summarized in table 3. Uncertainties on $\mathrm{t\bar{t}}$ and W+jets are based on the CMS measurements [28] and [29], respectively. We refer to a 7 TeV measurement of relative uncertainty in W+jets, since it represents the most recent result within CMS of the W boson production cross section in association with two b jets. Uncertainties on Z+jets and dibosons come from refs. [30] and [31], respectively, while the uncertainties on single top quark tW production and t channel are taken from refs. [6, 32, 33]. Uncertainties on the multijet background normalization reported in the table come from the extraction procedure described in section 6.

The uncertainties on jet energy scale (JES) and jet energy resolution (JER) are taken into account in line with ref. [34]. The "unclustered energy" in the event, which is computed by subtracting from the $\not{p}_{\mathrm{T}}$ the negative vector sum of the uncorrected transverse momenta of jets and leptons not clustered in jets, is changed by 10%. For each of these changes the $\not{E}_{\mathrm{T}}$ is recalculated accordingly. The uncertainties in lepton-reconstruction and trigger-efficiency scale factors are measured using DY events. The parametrizations describing the hadronic trigger efficiencies are varied and new weights are applied to simulated events in order to estimate the hadronic trigger uncertainty. The scale factors used to correct simulation to reproduce the b tagging efficiency and the mistag fraction measured in data are changed by their measured uncertainties [25].

The uncertainty in the total number of interactions per bunch crossing (5%) is propagated to the modelling of pileup in the simulated samples. The integrated luminosity is known to an uncertainty of 2.2% for the 7 TeV data [35] and 2.6% for the 8 TeV data [36].

Process	Uncertainty (%)
$t\bar{t}$	10
W+jets	20
Z+jets	20
Diboson	30
tW	15
t channel	10
Multijet, μ, 7 TeV	30, 100, 100
Multijet, μ, 8 TeV	30, 10, 30
Multijet, e, 8 TeV	20, 5, 25

Table 3. Summary of normalization uncertainties on the background processes. The uncertainties on the multijet background refer to the 2-jets 2-tags, 2-jets 1-tag, and 3-jets 2-tags categories, respectively.

The uncertainty from the choice of factorization and renormalization scales μ_F and μ_R in the QCD calculation is based on dedicated simulated samples of $t\bar{t}$, single top quark production in s channel and t channel, and W+jets events, with μ_F and μ_R varied from half to twice their nominal values. The uncertainty from matching matrix element and parton shower thresholds is determined from simulated samples of $t\bar{t}$ and W+jets with parton matching threshold doubled and halved relative to their nominal values. The uncertainty on the chosen set of PDF is estimated by reweighting the simulated events with each of the 52 eigenvectors of the CT10 PDF parametrization [37].

Differential measurements have shown that the p_T spectrum of the top quarks in $t\bar{t}$ events is significantly softer than the one generated using MC simulation programs [38]. Scale factors for event reweighting are derived from these measurements. The s channel cross section is remeasured based on samples without any reweighting and samples that have been reweighted with doubled weights, as an indication of the corresponding uncertainty. The effect of the limited number of events in the simulated samples has been taken into account using the "Barlow-Beeston light" method [39].

8 Cross section extraction

A binned maximum-likelihood fit is performed to the BDT data distributions in the 2-jets 2-tags, 2-jets 1-tag, and 3-jets 2-tags categories simultaneously. In particular, the inclusion in the fit of the 2-jets 1-tag and 3-jets 2-tags regions largely constrains the W+jets and the $t\bar{t}$ backgrounds respectively while taking into account all possible correlations in the systematic uncertainties for the three samples. The expected total yield λ_i in each bin i of the BDT distribution is given by the sum of all the background contributions $B_{p,i}$ and the signal yields S_i scaled by the signal-strength modifier β_{signal}, which is defined as the ratio between the measured signal cross section and the SM prediction, as

$$\lambda_i(\beta_{\text{signal}}, \theta_u) = \beta_{\text{signal}}\, S_i + \sum_p c_p(\theta_u) B_{p,i}.$$

The modelling of BDT distributions for the s channel and for each background process p, S, and B_p, are scaled to the integrated luminosity of the data according to the SM cross sections. The uncertainty in each background normalization, except for multijet events, is included in the likelihood model through a "nuisance" parameter with a log-normal prior ($c_p(\theta_u)$). The multijet component is instead fixed to the value estimated with the method described in section 6.

The measured s channel cross section is given by the value of β_{signal} at which the logarithm of the likelihood function reaches its maximum. The 68% CL interval for the cross section is evaluated by profiling the logarithm of the likelihood as a function of β_{signal}, and taking the parameter values for which the profile likelihood is 0.5 units below its maximum.

The impact from the systematic uncertainty in the background normalizations on the s channel cross section is evaluated by removing one nuisance at a time from the likelihood model and measuring the corresponding change in the total uncertainty. The impact of the uncertainties that are not included in the fit are evaluated using the following procedure. For each systematic effect two pseudo-experiments are generated by changing the corresponding quantity by $+1$ and -1 standard deviation. Maximum-likelihood fits are then performed for each of the pseudo-experiments, and the differences between the fitted β_{signal} and the nominal one are taken as the corresponding uncertainties.

The uncertainties arising from different systematic sources are combined according to ref. [40]. A breakdown of contributions to the overall uncertainty in the measurement is reported in table 4.

Figures 4, 5, and 6 show the comparison of the BDT discriminant distributions for all the event categories in the muon channel at 7 TeV and muon and electron channels at 8 TeV, after the fit to the combined channels. Tables 5, 6 and 7 summarize the number of events selected according to the requirements described in section 4, including the requirement $m_{\text{T}} > 50\,\text{GeV}$ at 7 TeV in the 2-jets 1-tag category, and after the fit to the combined channels. The SM expectation for the s channel in the 2-jets 2-tags category is 64 events selected in the muon channel at 7 TeV, 223 in the muon channel at 8 TeV, and 171 in the electron channel at 8 TeV.

The sensitivity to the s channel single top quark signal is estimated using the derivative of the likelihood test statistic, defined as

$$q_0 = \left.\frac{\partial \log L}{\partial \beta_{\text{signal}}}\right|_{\beta_{\text{signal}}=0},$$

and evaluated at the maximum-likelihood estimate in the background-only hypothesis. Pseudo-data are generated to construct the distribution of the test statistic for the background-only and the signal + background hypotheses. All the nuisance parameters are allowed to vary according to their prior distributions in the pseudo-experiments, while in the evaluation of q_0, the likelihood is maximized only with respect to the background normalizations nuisance parameters.

Source	Uncertainty (%)				
	μ, 7 TeV	μ, 8 TeV	e, 8 TeV	$\mu + $e, 8 TeV	7+8 TeV
Statistical	34	15	14	10	11
$\mathrm{t\bar{t}}$, single top quark normalization	29	15	14	12	14
W/Z+jets, diboson normalization	23	11	13	12	12
Multijet normalization	9	3	5	2	2
Lepton efficiency	14	1	2	1	3
Hadronic trigger	5	—	—	—	1
Luminosity	10	5	6	4	6
JER & JES	66	39	29	34	18
b tagging & mistag	34	15	14	14	16
Pileup	6	11	7	9	7
Unclustered $\not\!\!E_{\mathrm{T}}$	5	8	2	6	5
$\mu_{\mathrm{R}}, \mu_{\mathrm{F}}$ scales	54	34	31	30	28
Matching thresholds	43	11	12	7	17
PDF	12	8	7	7	9
Top quark p_{T} reweighting	3	5	7	6	6
Total uncertainty	115	64	54	55	47

Table 4. Summary of the relative impact of the statistical and systematic uncertainties on the cross section measurement. Different prior uncertainties have been assigned to $\mathrm{t\bar{t}}$, single top quark t channel and tW production, W+jets, Z+jets and diboson normalizations, see section 7.

Process	μ, 7 TeV	μ, 8 TeV	e, 8 TeV
$\mathrm{t\bar{t}}$	1380 ± 80	4960 ± 340	4290 ± 300
W+jets	150 ± 30	580 ± 110	620 ± 110
Z+jets	22 ± 7	160 ± 40	90 ± 30
Diboson	3 ± 3	59 ± 16	46 ± 13
Multijet	70 ± 20	130 ± 40	290 ± 60
tW	37 ± 6	149 ± 19	130 ± 16
t channel	135 ± 16	570 ± 50	420 ± 40
s channel	129 ± 5	452 ± 16	347 ± 12
Total MC	1920 ± 110	7060 ± 370	6240 ± 320
Data	1883	7023	6301

Table 5. Event yields for the main processes in the 2-jets 2-tags region, at 7 and 8 TeV. The yields of the simulated samples are quoted after the likelihood-maximization procedure for the combined 7+8 TeV fit. The uncertainties include the statistical uncertainty on the simulation, the background normalizations uncertainties and the b tagging uncertainty.

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Process	μ, 7 TeV	μ, 8 TeV	e, 8 TeV
$t\bar{t}$	6390 ± 310	38900 ± 1800	33200 ± 910
W+jets	4850 ± 310	32900 ± 1500	20090 ± 940
Z+jets	240 ± 50	2640 ± 580	1820 ± 390
Diboson	26 ± 10	650 ± 140	330 ± 70
Multijet	78 ± 78	4640 ± 460	6080 ± 300
tW	750 ± 60	5380 ± 460	3820 ± 330
t channel	2260 ± 140	12730 ± 760	7680 ± 460
s channel	281 ± 5	1412 ± 9	870 ± 5
Total MC	14870 ± 480	99240 ± 2600	73900 ± 1500
Data	14851	99240	73895

Table 6. Event yields for the main processes in the 2-jets 1-tag region, at 7 and 8 TeV. The yields of the simulated samples are quoted after the likelihood-maximization procedure for the combined 7+8 TeV fit. The uncertainties include the statistical uncertainty on the simulation, the background normalizations uncertainties and the b tagging uncertainty.

Process	μ, 7 TeV	μ, 8 TeV	e, 8 TeV
$t\bar{t}$	3260 ± 220	15200 ± 900	12520 ± 720
W+jets	94 ± 20	280 ± 60	230 ± 50
Z+jets	13 ± 5	90 ± 30	34 ± 14
Diboson	0 ± 0	24 ± 6	17 ± 4
Multijet	40 ± 40	80 ± 20	310 ± 90
tW	78 ± 13	370 ± 60	320 ± 50
t channel	210 ± 30	790 ± 90	580 ± 70
s channel	38 ± 2	126 ± 5	94 ± 4
Total MC	3730 ± 230	16940 ± 910	14120 ± 730
Data	3848	16934	13512

Table 7. Event yields for the main processes in the 3-jets 2-tags region, at 7 and 8 TeV. The yields of the simulated samples are quoted after the likelihood-maximization procedure for the combined 7+8 TeV fit. The uncertainties include the statistical uncertainty on the simulation, the background normalizations uncertainties and the b tagging uncertainty.

9 Results

The single top quark production cross section in the s channel has been measured to be:

$$\begin{aligned} \sigma_s &= 7.1 \pm 8.1\,(\text{stat} + \text{syst})\,\text{pb}, && \text{muon channel, 7 TeV;} \\ \sigma_s &= 11.7 \pm 7.5\,(\text{stat} + \text{syst})\,\text{pb}, && \text{muon channel, 8 TeV;} \\ \sigma_s &= 16.8 \pm 9.1\,(\text{stat} + \text{syst})\,\text{pb}, && \text{electron channel, 8 TeV;} \\ \sigma_s &= 13.4 \pm 7.3\,(\text{stat} + \text{syst})\,\text{pb}, && \text{combined, 8 TeV.} \end{aligned}$$

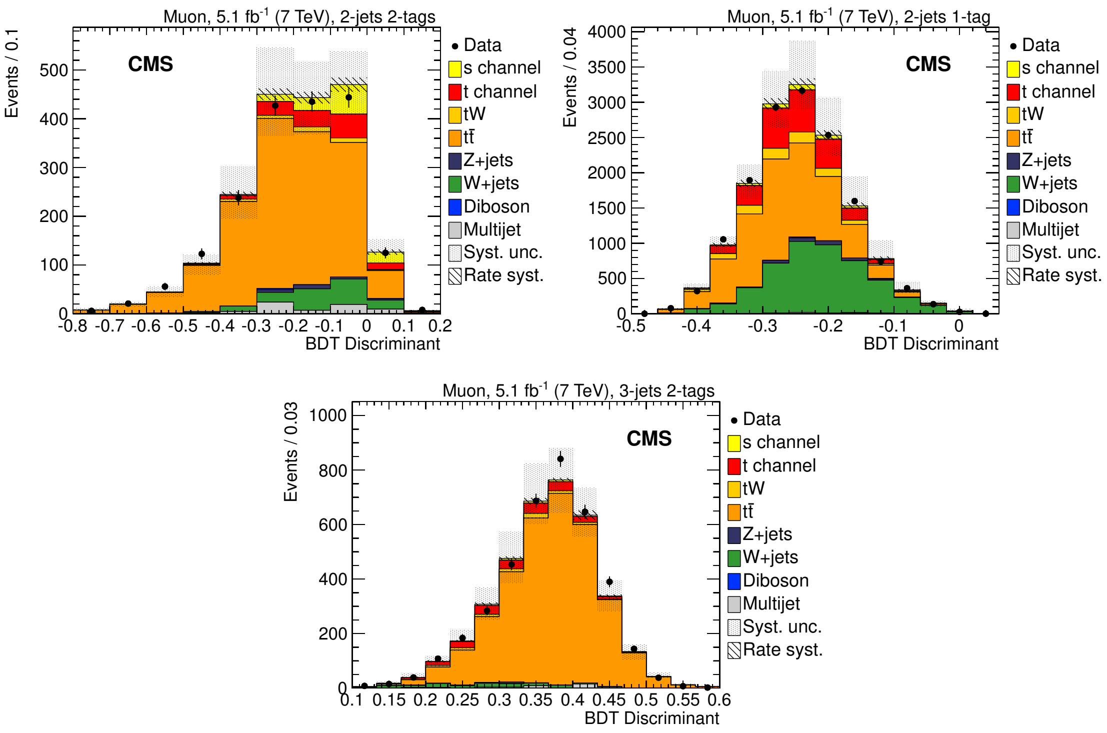

Figure 4. Comparison of data with simulation for distributions of the BDT discriminants in the (upper left) 2-jets 2-tags, (upper right) 2-jets 1-tag, and (bottom) 3-jets 2-tags event category, for the muon channel at 7 TeV. The simulation is normalized to the combined (7+8 TeV) fit results. The inner uncertainty bands include the post-fit background normalizations uncertainties only, the outer ones include the total systematic uncertainty obtained summing in quadrature the individual contributions.

The observed (expected) significance of the measurement is 0.9 (0.5) standard deviations at 7 TeV and 2.3 (0.8) for the combined muon and electron fit at 8 TeV. The 68% CL interval for the expected significance is 0.0–1.5 at 7 TeV and 0.0–1.8 at 8 TeV.

The combined fit to the 7 and 8 TeV data determines the signal cross section relative to the SM predictions with a best fit value of $\beta_{\text{signal}} = 2.0 \pm 0.9$. The observed significance of the measurement is 2.5 standard deviations with 1.1 standard deviations expected.

The observed upper limit on the s channel cross section at 95% CL is 31.4 pb at 7 TeV and 28.8 pb for the combined muon and electron channel at 8 TeV. Combining the 7 and 8 TeV data, the observed upper limit on the signal strength is 4.7. In table 8, we report a summary of the observed and expected upper limits at 7 and 8 TeV and for the combination of the channels.

10 Summary

A search is presented for single top quark production in the s channel in pp collisions at centre-of-mass energies of 7 and 8 TeV with the CMS detector at the LHC. A multivariate approach based on boosted decision trees is adopted to discriminate the signal from

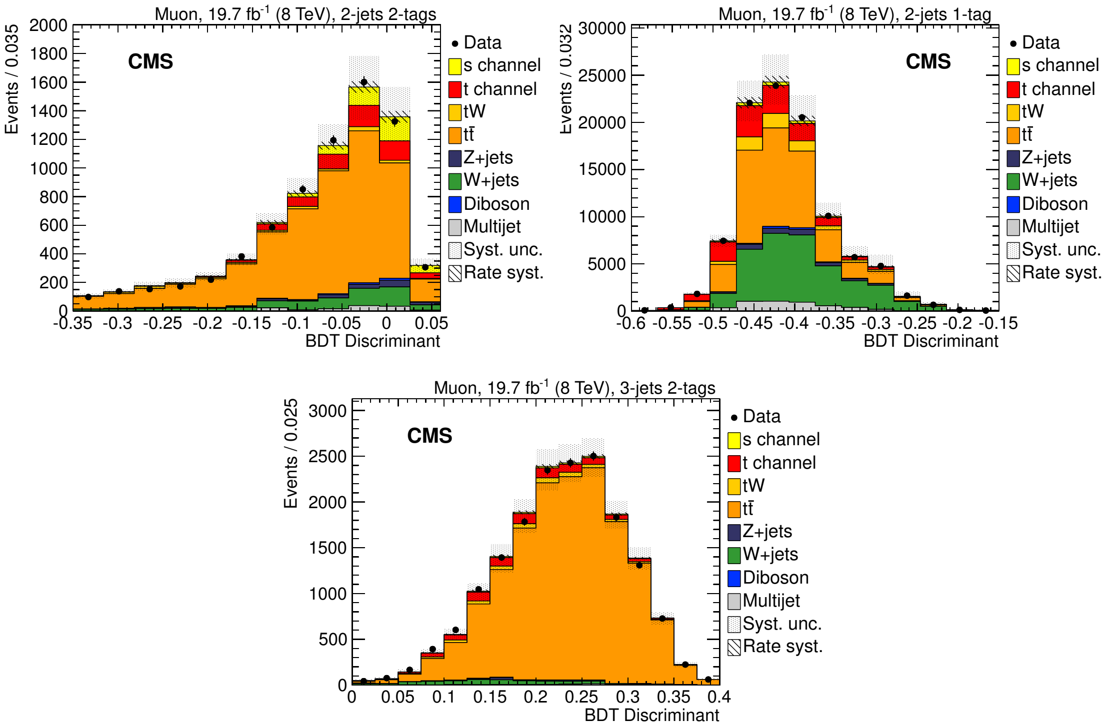

Figure 5. Comparison of data with simulation for the distributions of the BDT discriminants in the (upper left) 2-jets 2-tags, (upper right) 2-jets 1-tag, and (bottom) 3-jets 2-tags event category, for the muon channel at 8 TeV. The simulation is normalized to the combined (7+8 TeV) fit results. The inner uncertainty bands include the post-fit background normalizations uncertainties only, the outer ones include the total systematic uncertainty, obtained summing in quadrature the individual contributions.

Channel	Observed UL	Expected UL—SM signal	Expected UL—no signal
μ, 7 TeV	31.4 pb	25.4 [19.0, 36.6] pb	20.2 pb
$\mu + \mathrm{e}$, 8 TeV	28.8 pb	20.5 [13.4, 26.7] pb	15.6 pb
7+8 TeV	4.7	3.1 [2.1, 4.0]	2.2

Table 8. Observed and expected upper limits (UL) at 7 and 8 TeV and for the combination of the data. Both the expected limits assuming the presence of a SM signal or in the absence of a signal are reported. In the hypothesis of a SM signal, the 68% CL interval for the expected limit is also reported within square brackets. In the last row the upper limits are given in terms of the rate relative to the SM expectation.

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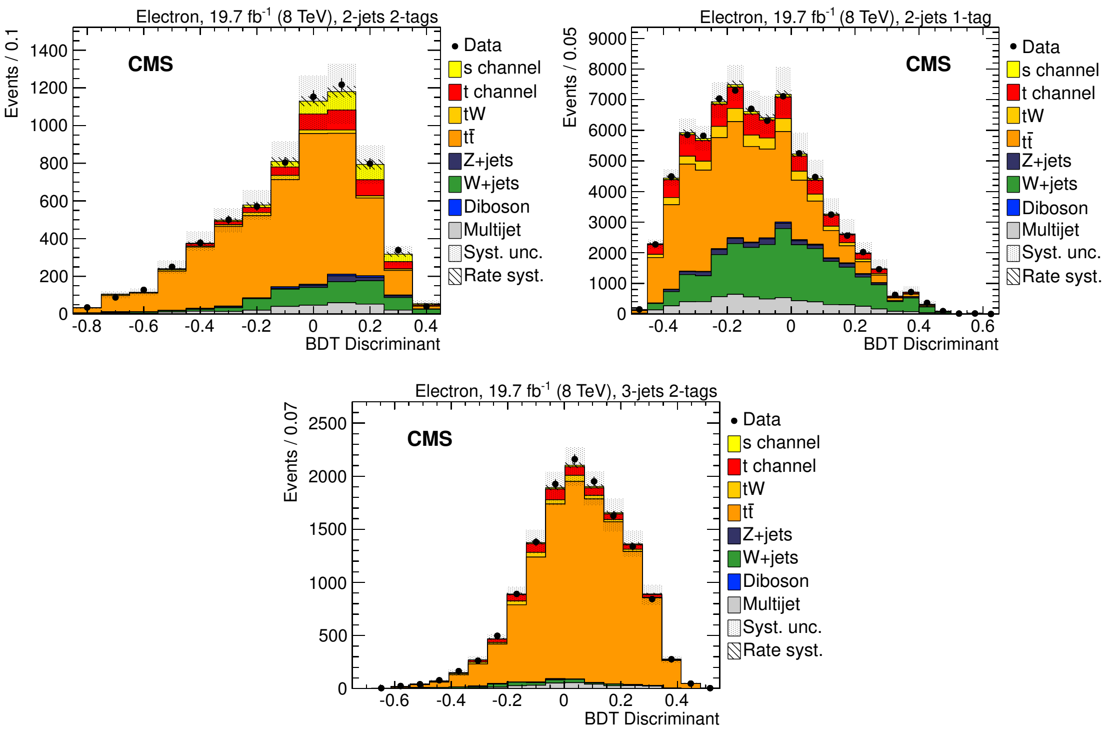

Figure 6. Comparison of data with simulation for the distributions of the BDT discriminants in the (upper left) 2-jets 2-tags, (upper right) 2-jets 1-tag, and (bottom) 3-jets 2-tags event category, for the electron channel at 8 TeV. The simulation is normalized to the combined (7+8 TeV) fit results. The inner uncertainty bands include the post-fit background normalizations uncertainties only, the outer ones include the total systematic uncertainty, obtained summing in quadrature the individual contributions.

background contributions. The cross section is measured to be 7.1 ± 8.1 (stat + syst) pb at 7 TeV and 13.4 ± 7.3 (stat + syst) pb at 8 TeV, corresponding to a combined signal rate relative to SM expectations of 2.0 ± 0.9 (stat + syst). The observed significance of the combined measurement is 2.5 standard deviations with 1.1 standard deviations expected. The observed and expected upper limits on the combined signal strength are found to be 4.7 and 3.1 at 95% CL, respectively. The measurements are in agreement with the prediction of the standard model.

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4: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
5: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
6: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
7: Also at Universidade Estadual de Campinas, Campinas, Brazil
8: Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France
9: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
10: Also at Joint Institute for Nuclear Research, Dubna, Russia
11: Also at Ain Shams University, Cairo, Egypt
12: Also at Zewail City of Science and Technology, Zewail, Egypt
13: Also at British University in Egypt, Cairo, Egypt
14: Also at Université de Haute Alsace, Mulhouse, France
15: Also at Tbilisi State University, Tbilisi, Georgia
16: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
17: Also at University of Hamburg, Hamburg, Germany
18: Also at Brandenburg University of Technology, Cottbus, Germany
19: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
20: Also at Eötvös Loránd University, Budapest, Hungary
21: Also at University of Debrecen, Debrecen, Hungary

22: Also at Wigner Research Centre for Physics, Budapest, Hungary
23: Also at Indian Institute of Science Education and Research, Bhopal, India
24: Also at University of Visva-Bharati, Santiniketan, India
25: Now at King Abdulaziz University, Jeddah, Saudi Arabia
26: Also at University of Ruhuna, Matara, Sri Lanka
27: Also at Isfahan University of Technology, Isfahan, Iran
28: Also at University of Tehran, Department of Engineering Science, Tehran, Iran
29: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
30: Also at Università degli Studi di Siena, Siena, Italy
31: Also at Purdue University, West Lafayette, USA
32: Now at Hanyang University, Seoul, Korea
33: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
34: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
35: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
36: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
37: Also at Institute for Nuclear Research, Moscow, Russia
38: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
39: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
40: Also at California Institute of Technology, Pasadena, USA
41: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
42: Also at INFN Sezione di Roma; Università di Roma, Roma, Italy
43: Also at National Technical University of Athens, Athens, Greece
44: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
45: Also at National and Kapodistrian University of Athens, Athens, Greece
46: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
47: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
48: Also at Gaziosmanpasa University, Tokat, Turkey
49: Also at Mersin University, Mersin, Turkey
50: Also at Cag University, Mersin, Turkey
51: Also at Piri Reis University, Istanbul, Turkey
52: Also at Adiyaman University, Adiyaman, Turkey
53: Also at Ozyegin University, Istanbul, Turkey
54: Also at Izmir Institute of Technology, Izmir, Turkey
55: Also at Marmara University, Istanbul, Turkey
56: Also at Kafkas University, Kars, Turkey
57: Also at Istanbul Bilgi University, Istanbul, Turkey
58: Also at Yildiz Technical University, Istanbul, Turkey
59: Also at Hacettepe University, Ankara, Turkey
60: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
61: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
62: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
63: Also at Utah Valley University, Orem, USA
64: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
65: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy

66: Also at Argonne National Laboratory, Argonne, USA
67: Also at Erzincan University, Erzincan, Turkey
68: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
69: Also at Texas A&M University at Qatar, Doha, Qatar
70: Also at Kyungpook National University, Daegu, Korea