Search for vector-like T quarks decaying to top quarks and Higgs bosons in the all-hadronic channel using jet substructure (Postprint)

Authors: Khachatryan, Vardan and others

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Full Text

Preamble

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The CMS Collaboration∗

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∗See Appendix A for the list of collaboration members

1 Introduction

The discovery of a Higgs boson with a mass of 125 GeV/c^2 [1, 2] motivates the search for exotic states involving the newly discovered particle. The mechanism that stabilizes the mass of the Higgs particle is not entirely clear and could be explained by little Higgs models [3, 4], models with extra dimensions [5, 6], and composite Higgs models [5–7]. These theories predict the existence of heavy vector-like quarks that may decay into top quarks and Higgs bosons. This article presents a search for exotic resonances decaying into Higgs bosons and top quarks. A model of vector-like T quarks with charge 2/3 e, which are produced in pairs by the strong interaction, is used as a benchmark for this analysis.

The left-handed and right-handed components of vector-like quarks transform in the same way under the standard model (SM) symmetry group SU(3) × SU(2) × U(1) . This allows direct mass terms in the Lagrangian of the form m that do not violate gauge invariance. As a consequence, vector-like quarks do not acquire their mass via Yukawa couplings, in contrast to the other quark families. A fourth generation of chiral fermions, replicating one of the three generations of the SM with identical quantum numbers, is disfavoured by electroweak fits within the framework of the SM [8]. This is because of the large modifications to the Higgs production cross sections and branching fractions, if a single SM-like Higgs doublet is assumed. Vector-like heavy quarks are not similarly constrained by the measurements of the Higgs boson properties [9].

Vector-like T quarks can decay into three different final states: tH, tZ, and bW [9]. The assumption of decays with 100% branching fraction (B) has been used in various searches by the ATLAS and CMS collaborations [10–13]. Other searches that do not make specific assumptions on the branching fractions have also been performed [14]. In the present analysis the event selection is optimized to be sensitive to exclusive T quark decays to tH. In addition, the results are quoted as a function of the branching fractions to the three decay modes: tH, tZ, and bW.

While searches for T quarks have been performed in leptonic final states [10–

14], this article presents the first analysis that exploits the all-hadronic final state in the search for vector-like quarks. In the SM the Higgs boson decays predominantly into b quark pairs with a branching fraction of 58% for a mass of 125 GeV/c^2, while the top quark decays almost exclusively into a bottom quark and a W boson, which in turn decays hadronically 67.6% of the time. The main final state is therefore the all-hadronic final state T → tH → (bjj)(bb), where j denotes the light-flavour jets of the W boson decay and b denotes the b-flavour jets from the top quark or Higgs boson decays. For sufficiently large T quark mass values, the decay products can be highly Lorentz-boosted, leading to final states with overlapping and merged jets. In the extreme case, all top quark decay products are merged into a single jet. A similar topology may arise for the Higgs boson decaying into b quarks. A related analysis concept has been proposed in Ref. [15]. In recent years, the methodology of jet substructure analysis has proved to be very powerful in resolving such boosted topologies [16–19]. For example, the analysis of high-mass Z' resonances decaying into top quark pairs became feasible in the all-hadronic final state as a result of the application of jet substructure methods [20–22]. A similar strategy is followed in this analysis by applying algorithms for the identification of boosted top quarks (t tagging) and boosted Higgs bosons (H tagging) in combination with algorithms for the identification of b quark jets (b tagging). In particular, the application of b tagging in subjets has enhanced the identification of boosted bb final states, for instance H → bb decays. This is the first analysis to apply an algorithm for tagging boosted Higgs bosons that is based on a combination of jet substructure information and b tagging.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter. Within the superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors.

The energy resolution for photons with E   60 GeV varies between 1.1 and 2.6% over the solid angle of the ECAL barrel, and from 2.2 to 5% in the endcaps. The HCAL, when combined with the ECAL, measures jets with a resolution ΔE/E   100%/√E[GeV]   5% [23]. In the region | | < 1.74, the HCAL cells have widths of 0.087 in   and 0.087 in azimuth ( ). In the - plane, and for | | < 1.48, the HCAL cells map onto 5 × 5 ECAL crystal arrays to form calorimeter towers projecting radially outwards from close to the nominal interaction point. At larger values of | |, the size of the towers increases and the matching ECAL arrays contain fewer crystals. Within each tower, the energy deposits in ECAL and HCAL cells are summed to define the calorimeter tower energies, subsequently used to provide the energies and directions of hadronic jets.

The silicon tracker measures charged particles within the pseudorapidity range $| \ | < 2.5$. It consists of 1440 silicon pixel and 15,148 silicon strip detector modules and is located in the 3.8 T field of the superconducting solenoid. For nonisolated particles of $1 < p \ < 10$ GeV/c and $| \ | < 1.4$, the track resolutions are typically 1.5% in p and 25–90 (45–150) m in the transverse (longitudinal) impact parameter [24].

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. [25].

3 Event samples

The data used for this analysis were collected by the CMS experiment using pp collisions provided by the CERN LHC with a centre-of-mass energy of 8 TeV, and correspond to an integrated luminosity of 19.7 fb^{1}. Events are selected online by a trigger algorithm that requires H , the scalar sum of the transverse momenta of reconstructed jets in the detector, to be greater than 750 GeV/c. The online H is calculated from calorimeter jets with $p \ > 40$ GeV/c. Calorimeter jets are reconstructed from the energy deposits in the calorimeter towers, clustered by the anti-k algorithm [26, 27] with a size parameter of 0.5.

Simulated samples are used to determine signal selection efficiencies as well as the background contribution from tt plus jets, ttH, and hadronically decaying W/Z plus b jet production. The background from QCD multijet production is derived from data.

Events from T quark decays are generated for mass hypotheses between 500 and 1000 GeV/c^2 in steps of 100 GeV/c^2. The inclusive cross sections for the signal samples and tt samples are calculated at next-to-next-to-leading order (NNLO) for the reaction $gg \rightarrow tt + X$. The fixed order calculations are supplemented with soft-gluon resummation with next-to-next-to-leading logarithmic accuracy [28]. The tt cross sections are computed based on the TOP++ v2.0 implementation using the MSTW2008nnlo68cl parton distribution functions (PDF) and the 5.9.0 version of LHAPDF [28, 29]. The evaluated tt cross section is 252.9 pb, assuming a top quark mass of 172.5 GeV/c^2. The theoretical pair-production cross sections for the signal samples are listed in Table 1 .

The mass of the Higgs boson in the signal samples is set to 120 GeV/c^2, as the samples were produced before the discovery of the Higgs boson. The branching fractions of the Higgs boson decays are corrected to the expected values for a Higgs boson with a mass of 125 GeV/c^2 using the recommendations from Ref. [30]. The difference between the actual mass of the Higgs boson (125 GeV/c^2) and the simulated mass (120 GeV/c^2) has no impact on the analysis results.

The tt background sample is generated with POWHEG v1.0 [31–33] interfaced to PYTHIA 6.426 [34] to simulate the parton shower and hadronisation. All other background samples and the signal samples are simulated with MADGRAPH 5.1 [35], interfaced with PYTHIA 6.426. The CTEQ6L1 [36] PDF set is used with MADGRAPH, while the POWHEG samples have been produced with CTEQ6M. For PYTHIA, the Z2* tune is used to simulate the underlying event [37].

Simulated QCD multijet samples are used to validate the estimation of this background from data. These samples are simulated with MADGRAPH in the same way as the other background samples described above.

4 Event reconstruction

Tracks are reconstructed using an iterative tracking procedure [24]. The primary vertices are reconstructed with a deterministic annealing method [38] from all tracks in the event that are compatible with the location of the proton-proton interaction region. The vertex with the highest $(p)^2$ is defined as the primary interaction vertex, whose position is determined from an adaptive vertex fit [39].

The particle-flow event algorithm [40, 41] reconstructs and identifies each individual particle with an optimized combination of information from the various elements of the CMS detector. The energy of photons is directly obtained from the ECAL measurement, 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 energy of muons is obtained from the curvature of the corresponding track. 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, 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.

For each event, hadronic jets are clustered from these reconstructed particles with the infrared and collinear-safe anti-k algorithm or with the Cambridge-Aachen algorithm (CA jets) [42]. The jet momentum is defined to be the vector sum of all particle momenta in this jet, and is found in the simulation to be within 5% to 10% of the true momentum over the whole p spectrum and detector acceptance. Jet energy corrections are derived from the simulation, and are confirmed with in situ measurements using the energy balance of dijet and photon+jet events [43]. 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 calorimeters are used alone for jet clustering.

The jets contain neutral particles from additional collisions within the same beam crossing (pileup). The contribution from these additional particles is subtracted based on the average expectation of the energy deposited from pileup in the jet area, using the methods described in Ref. [44].

5 Analysis strategy

Event selection criteria that make use of novel jet substructure methods are applied to reduce the large background contributions from QCD multijet and tt events in the analysis. The jet substructure methods are described in detail in Section 6 and the event selection criteria are summarized in Section 7.

Two variables are used to distinguish signal from background events after the event selection: H and the invariant mass m_bb of two b-tagged subjets in Higgs boson candidate jets. High H values characterize events with large hadronic activity as in the case of signal events. The shape and normalization of the H and m_bb distributions of QCD multijet events in this analysis are derived using data in signal-depleted sideband regions. The sideband regions are defined by inverting the jet substructure criteria. Closure tests are performed with simulated QCD events to verify that the method predicts the rates and shapes of H and m_bb accurately. The background determination is discussed in detail in Section 8.

The H and m_bb variables are combined into a single discriminator that enhances the sensitivity of the analysis. This combination is performed using a likelihood ratio method, which is described in Section 10. Two event categories are used in the statistical interpretation of the results: a category with a single Higgs boson candidate and a category with at least two Higgs boson candidates. These are denoted as single and multiple H tag categories. They are chosen as such to be statistically independent and are combined in setting the final limit. For the multiple H tag category, the Higgs boson candidate with the highest transverse momentum is used in the likelihood definition. The procedure of the limit setting is discussed in detail in Section 10.

6 Jet substructure methods

For the identification of b jets, the combined secondary vertex (CSV) algorithm is used and the medium operating point (CSVM) is applied [45]. With this operating point the b tagging efficiency is 70% and the light flavour jet misidentification rate is 1% in tt events. This algorithm uses information from reconstructed tracks and secondary vertices that are displaced from the primary interaction vertex. The information is combined into a single discriminating variable. The same b tagging algorithm is used in boosted topologies and the corresponding efficiencies and misidentification rates are tested in the relevant samples. More details on b tagging in boosted topologies are given in Section 6.

Because of the large mass of the T quarks, the top quarks and Higgs bosons from T quark decays would have significant Lorentz boosts. Daughter particles of these top quarks are therefore not well separated. In many cases all of the top quark decay products are clustered into a single, large jet by the event reconstruction algorithms. The approximate spread of a hadronic top quark decay can be determined on simulated events from the ΔR distances between the quarks produced during its decay. The four-momenta of the two quarks with the smallest ΔR distance, ΔR(q , q), are vectorially summed and the ΔR distance between the vector sum and the third quark, ΔR(q , q), is evaluated. The maximum distance between ΔR(q , q) and ΔR(q , q) indicates the approximate size ΔR_bij needed to cluster the entire top quark decay within one single CA jet. For the boosted decays of a Higgs boson in H → bb events, the corresponding quantity can be defined as the angular distance ΔR_bb = √(Δ $)^2$ + (Δ $)^2$ between the two generated b quarks.

Figure 1 [Figure 1: see original paper] shows the distributions of these quantities plotted as a function of the transverse momentum of the top quark and of the Higgs boson, generated from the decay of a T quark with a mass of 1000 GeV/c^2. This shows that, for large transverse momenta, and hence for large T quark mass values, the decay products from Higgs bosons and top quarks are generally collimated and are difficult to separate using standard jet reconstruction algorithms.

The approach adopted by this analysis is to apply the CA algorithm using a large size parameter R = 1.5, in order to cluster the decay products from top quarks and Higgs bosons into single large CA jets, using an implementation based on FASTJET 3.0 [27]. To identify these so called "top jets" and "Higgs jets" , the analysis uses dedicated jet substructure tools, in particular a t tagging algorithm and a H tagging algorithm that relies on b tagging of individual subjets. A more detailed description of these algorithms is provided in the following sections.

6.1 Subjet b tagging and H tagging

It is not possible to identify b jets in boosted top quark decays using the standard CMS b tagging algorithms, since these are based on separated, non-overlapping jets. For dense environments where standard jet reconstruction algorithms are not suitable, two dedicated b tagging concepts have been investigated: (i) tagging of CA jets, reconstructed using a distance parameter of 0.8 (CA8 jets) or 1.5 (CA15 jets). The 0.8 and the 1.5 jet size parameters are used because they have been found to provide optimal performance for large and for intermediate boost ranges, respectively, as discussed in the following sections. (ii) tagging of subjets that are reconstructed within CA jets.

The subjets of CA15 jets are reconstructed using the "filtering algorithm" [16], splitting jets into subjets based on an angular distance of R = 0.3. Only the three highest p subjets are retained. This filtering algorithm has been found to provide the best mass resolution for CA15 jets compared to the jet pruning [46] and trimming [47] algorithms. The pruning, trimming, and filtering algorithms are often referred to as jet grooming algorithms and their main purpose is to remove soft and wide-angle radiation as well as pileup contributions. Subjets of

CA8 jets are reconstructed using the pruning algorithm, which is found to give the best performance for the reduced jet size.

For the application of b tagging to CA jets, tracks in a wide region around the jet axis are considered. The association region corresponds to the size of the CA jet. For the application of b tagging to subjets, tracks in a region of $\Delta R < 0.3$ around the subjet axis are used by the b tagging algorithm. This is the cone size employed by the standard CMS b tagging algorithms, and has also been found to give good performance for subjet b tagging. The advantage of subjet b tagging is that it allows two subjets within a single CA jet to be identified as b jets. This is the main component of the H tagging algorithm that distinguishes between boosted Higgs bosons decaying to bb and boosted top quarks.

6.1.1 Algorithm performance Figure 2 [Figure 2: see original paper] shows the performance of the CSV b tagging algorithm in simulated events with CA15 jets and with subjets within the same CA15 jet. The misidentification probability for inclusive QCD jets is shown versus the b tagging efficiency for boosted top quarks originating from T quark decays, for CA15 jet transverse momentum ranges of (left) $200 < p \; < 400$ GeV/c and (right) $800 < p \; < 1000$ GeV/c. It can be seen that subjet b tagging outperforms the CA15 jet b tagging.

For the identification of boosted Higgs bosons, two subjets must be b tagged and their invariant mass must be greater than 60 GeV/c^2. Both CA8 jets and CA15 jets are considered. The performance of the H tagging algorithm is shown in Fig. 3 [Figure 3: see original paper] for two different regions of transverse jet momentum. The tagging efficiency is shown versus the misidentification probability for inclusive QCD jets. Figure 4 [Figure 4: see original paper] shows the performance obtained when evaluating the misidentification probability from tt events. The performance of the standard b tagging algorithm based on AK5 jets is also shown. A CA15 jet is considered as satisfying the H tagging requirement if two AK5 jets satisfy the b tagging requirement and have a ΔR distance < 1.1 from the CA15 jet. Overall, subjet b tagging is found to provide better performance than b tagging based on AK5 jets. The choice of the optimal CA jet size parameter R depends on the p region considered. A size of $R = 1.5$ is found to be optimal for most signal mass hypotheses and is chosen for the analysis.

6.1.2 Scale factors The subjet b tagging efficiency has been measured in data using a sample of semileptonic tt events. Scale factors have been derived to correct the efficiency predicted by simulation to that measured in data. The “flavor-tag consistency” (FTC) method [45] has been used to measure these scale factors. The FTC method requires consistency between the number of b-tagged jets in data and simulation for boosted top quark events. A maximum likelihood fit is performed in which the b tagging efficiency scale factor SF_b and the tt cross section are free parameters. Usually the light flavour misidentification scale factor SF_light is fixed to a value obtained independently, but in this case the simultaneous fit of SF_light, SF_b, and the tt cross section has been performed for the first time. This method relies on simulation for the flavour of the subjets. A systematic uncertainty of 2% in the subjet flavour composition is taken into account.

The FTC method is applied to three different p regions of the CA15 jet: 150 p < 350 GeV/c, p 350 GeV/c, and p 450 GeV/c. No significant deviation of the scale factors for the three different samples is observed. Both the scale factors SF_b and SF_light are found to be in agreement with the scale factors measured for standard b tagging of AK5 jets in the non-boosted regime.

The efficiency of the invariant mass selection requirement for the two b-tagged subjets of the Higgs boson candidate is validated with a sample of semileptonic tt events. Since no sample of Higgs bosons decaying into b quark pairs can be obtained in data, the validation procedure is based on the selection of a pure sample of W bosons. The selection of semileptonic tt events requires a muon and a b-tagged AK5 jet. In addition, one CA15 jet is required to be selected by the t tagging algorithm (see Section 6.2). The t-tagged jet must have exactly one b-tagged subjet. The two subjets that are not b-tagged are used to calculate the invariant mass of a W boson candidate. The distribution of the W boson candidate mass is shown in Fig. 5 [Figure 5: see original paper]. The shape of the W boson candidate mass distribution is the same in data and simulation and no additional scale factors or systematic uncertainties are assigned.

6.2 t tagging

The HEPTOPTAGGER algorithm, described in Ref. [19], is applied based on the implementation in FASTJET 3.0 [27]. The algorithm uses CA15 jets as input. This choice of jet size is suitable for the region of phase space with intermediate boosts (with a jet p slightly above 200 GeV/c). When the T quark mass is below 1 TeV/c^2, a considerable fraction of the decay products populate the intermediate boost range. Such resolved events could in principle be reconstructed with standard methods using AK5 jets. The HEPTOPTAGGER provides a seamless transition between the non-boosted and boosted domains.

For each jet, the HEPTOPTAGGER analyses the substructure by stepping backward through the clustering history of the jet in an iterative procedure until the conditions for splitting are no longer fulfilled and the subjets are not split any further. The filtering algorithm is applied to each combination of three subjets that are found. The filtering algorithm reclusters the constituents with a variable distance parameter R_filt = min(0.3, ΔR_ij/2), where i and j are the closest subjets in ΔR in the subjet triplet. The five reclustered subjets with the largest p are retained and the sum yields the invariant mass of the top quark candidate. The configuration that has an invariant mass closest to the top quark mass is chosen. The constituents of the five leading reclustered subjets are further reclustered using the exclusive CA algorithm, which forces the jet to have exactly three final subjets. The HEPTOPTAGGER uses these three final subjets and selects top quark jets based on the pairwise and three-way subjet masses. Selections are applied in the two-dimensional plane defined by the ratio m /m and the arctangent of m /m . Here m is the pairwise mass of the second and third leading subjets. The variables m , m , and m are defined in a similar fashion. The distribution of events in this plane is shown for simulated tt events in Fig. 6 [Figure 6: see original paper] (left) and for a mixture of background (boson+jets, diboson, single top quark, tt all-hadronic, and tt leptonic) events in Fig. 6 (right). A region with a well enhanced structure is only present for tt events. The region is highlighted by the thick black lines in Fig. 6. This structure can be used to suppress backgrounds that do not contain boosted top quarks by rejecting events that lie outside of this region. Additionally, a selection on the top candidate mass, $140 < m < 250$ GeV/c^2, is applied. Another populated region shows up below and to the left of the selected region because of unmerged top decays. This contribution disappears for boosted top quarks above $p > 300$ GeV/c.

6.2.1 Algorithm performance Figure 7 [Figure 7: see original paper] shows the mistag rate versus t tagging efficiency for the HEPTOPTAGGER and the combination of the HEPTOPTAGGER with subjet b tagging, for CA15 jets matched to generated partons with $p > 200$ GeV/c. The mistag rate is obtained from simulated QCD multijet events, while the efficiency is determined using simulated tt events. The selection criteria used in the algorithm are varied iteratively and the efficiency and mistag rate are calculated for each iteration. The minimum mistag rate for a given signal efficiency is shown in the figure. The HEPTOPTAGGER curve is determined by fixing the m selection ($140 < m < 250$ GeV/c^2) and varying the width of the region selected by the algorithm. The other curve is obtained by applying simultaneously the HEPTOPTAGGER and the subjet b tagging criteria and varying their requirements. Details of these selection criteria are given in Ref. [48].

Three working points are defined as indicated by markers in the figure. The working point used in this analysis is WP2, which is defined by the standard HEPTOPTAGGER criteria in addition to a b-tagged subjet identified with the CSVM b tagging algorithm. The other working points (WP1 and WP0) use relaxed HEPTOPTAGGER criteria and relaxed b tagging, and are used to validate the scale factor measurements which are described in the following section.

6.2.2 Scale factors A semileptonic tt sample is used to study boosted hadronic top quark decays in data. This sample is then used to measure data to simulation scale factors for the t tagging efficiency using WP2. This procedure was introduced in Ref. [20]. The tt sample is defined by requiring one muon and at least one b-tagged AK5 jet. Additionally, a top quark candidate CA15 jet is required, with high transverse momentum $p > 200$ GeV/c and with at least one b-tagged subjet. This semileptonic selection is very pure and background contributions are negligible. The efficiency of the

HEPTOPTAGGER is determined as the fraction of top quark candidate CA15 jets that pass all of the tagging requirements. These measurements yield scale factors ranging from 0.85 to 1.15 depending on the p and the of the jet.

7 Event selection

The H variable used in the analysis is calculated from the transverse momenta of all subjets within the reconstructed CA15 jets with p > 150 GeV/c. This definition is more accurate than that used in the trigger because particle-flow reconstruction is exploited. A threshold of H > 720 GeV/c is applied in the offline analysis as the trigger is almost fully efficient above this value. The simulation is corrected to match the data by weighting events based on the ratio between the trigger efficiency calculated in data and in simulation. The systematic uncertainty introduced by this procedure is discussed in Section 9.

The full event selection requires the following criteria to be fulfilled: (i) At least one CA15 jet must be t-tagged by the HEPTOPTAGGER algorithm and must contain at least one b-tagged subjet (identified by the CSV b tagging algorithm at the medium operating point). The t-tagged jets must have p $>$ 200 GeV/c. (ii) At least one CA15 jet must have p > 150 GeV/c and must be H-tagged (at least two subjets identified by the CSVM b tagging algorithm). The invariant mass of the two b-tagged subjets has to be larger than 60 GeV/c^2. This jet must not be identical to the top-quark candidate jet.

As mentioned in Section 5, the event selection is split further into two categories: single and multiple H tags. The number of reconstructed CA15 jets predicted by simulation with p > 150 GeV/c is shown in the left plot of Fig. 8 [Figure 8: see original paper], while the right plot shows the number of jets passing the t tagging criteria. In the following figures the hatched regions indicate the statistical uncertainty in the simulated background. The signal hypotheses are represented by the solid and dashed lines.

The impact of subjet b tagging is visible in Fig. 9 [Figure 9: see original paper]. The left plot shows the number of t-tagged CA15 jets with a subjet b tag, while the right plot shows the number of H-tagged jets for events that have at least one t-tagged CA15 jet with a subjet b tag. These figures demonstrate the strong reduction of QCD multijet background by the jet substructure criteria. The number of selected events for each signal sample of the benchmark model and the selection efficiencies, derived from simulated events, are given in Table 1.

8 Background estimation

The tt background is evaluated from simulated events, corrected for differences between data and simulation in b tagging and trigger efficiencies described above. The uncertainties in the normalization and shape of tt events are discussed in Section 9. Background contributions from ttH and hadronically decaying W/Z plus heavy flavour processes are found to be below 1% and are neglected.

The QCD multijet background is estimated in data using a two-dimensional sideband extrapolation. In this method, two uncorrelated criteria in the event selection are inverted to obtain sideband regions that are enriched in QCD multijet events and depleted in signal events. Inverting each criterion individually, as well as both at the same time, results in three exclusive sideband regions, denoted A, B and C: (i) Sideband region B is obtained by inverting the selection criteria of the HEPTOPTAGGER algorithm. The top quark mass window as well as all requirements on the pairwise subjet mass in the HEPTOPTAGGER are inverted. Events outside of the selected region shown in Fig. 6 (Section 6) are used to define the inverted HEPTOPTAGGER control region, while the events that are inside define the signal region. Details of these selection criteria of the HEPTOPTAGGER are given in Section 6 and [48]. (ii) Sideband region C is obtained by inverting the H tagging algorithm. Only events with zero H tags are selected and the requirement on the pairwise subjet mass is removed. (iii) Sideband region A is obtained by inverting both the H tagging and the t tagging algorithms as described above. (iv) Events in the signal region D have all tagging requirements applied.

The tt contamination in the sideband regions amounts to a maximum of 8% in region C. This is accounted for by subtracting the tt contribution predicted by the simulation in each of the sideband regions. Backgrounds due to ttH and hadronically decaying W/Z plus heavy flavour processes are found to have a negligible contribution in the sideband regions. A signal injection test has been performed to evaluate the impact of a hypothetical signal on the background model. It has been found that the signal contamination in the sideband regions leads to a small effect of less than 1.4% for m_T = 700 GeV/c² on the measured QCD multijet event rate, and therefore the possible signal contamination in the sideband regions is neglected in the analysis.

The QCD multijet yield in the signal region is calculated as R_D = R_B × (R_C/R_A), where R_A denotes the rate of events in sideband A. The tt contamination in the sideband regions is subtracted. The event rates in the three sideband regions and the signal region are provided in Table 2 . The resulting predictions of the QCD multijet backgrounds are given in Table 3 for the two event categories.

The closure of this method is verified with simulated QCD multijet events. As the method assumes the selection criteria defining the sideband regions to be uncorrelated, the following condition must be fulfilled: R_A/R_B = R_C/R_D. According to simulation, the ratios are R_A/R_B = 185 ± 5 (1417 ± 97) and R_C/R_D = 185 ± 17 (1203 ± 250) for the single (multi) H tag event category. The quoted uncertainties are statistical. It can be seen that the ratios agree within the statistical uncertainties. The largest uncertainties occur in the R_C/R_D ratio and are about 10 (20)% for the single (multi) H tag category.

In addition to the event yields, the shapes of the H and m_bb distributions for the QCD multijet processes are also derived from the sideband regions. For both the H and m_bb variables the sideband region B (inverted t tagger) is used. The expected contribution from tt events is subtracted from the sideband. Closure is also verified for the shape of H and m__bb distributions in the signal and sideband regions. Figure 10 [Figure 10: see original paper] shows a comparison of the H and m__bb shapes in the sideband and signal regions for the single and the multiple H tag event categories. The distributions agree within statistical uncertainties.

The method has also been validated in data. The shapes of the simulated H and m__bb distributions in the signal region agree well with the predicted distributions in data. The absolute rate of events shows a disagreement between simulation and the data-derived rate of a factor of two. This disagreement is taken into account when assigning systematic uncertainties in the background, as explained in Section 9.

9 Systematic uncertainties

As the analysis relies on simulation for the tt background prediction, a careful evaluation of uncertainties affecting both the normalization and shape of the tt background events is needed. This is also required for the simulated signal events. The QCD multijet background is obtained from data. The rate and shape of the tt background have an effect on the measurement of the QCD multijet background because the tt contamination in the sideband region is subtracted from data.

The detailed list of systematic uncertainties is given below. Most of these uncertainties have an impact on both the shapes and normalization of the sensitive variables H and m__bb, while the uncertainty in the integrated luminosity only affects the normalization. The uncertainties are summarized in Table 4 .

- **b tagging scale factor uncertainties**: Based on the measurements described in Section 6.1 and Ref. [49], scale factors with their corresponding uncertainties are applied to simulated samples. The scale factor uncertainties for the b tagging efficiency depend on p and . The typical size of these uncertainties is between 1 and 2% while the mistag rate uncertainty is around 15%. The b tagging scale factor uncertainties affect both the normalization and shape of the tt background and signal events. Depending on the sample and signal mass point, the impact of the b tagging scale factor uncertainty on the expected number of selected signal and tt events is 5 to 8% while the impact of the mistag scale factor uncertainty is 0.3 to 4%.
- **HEPTOPTAGGER scale factor uncertainty**: The efficiency of the HEPTOPTAGGER has been measured and compared to simulation to derive scale factors as described in Section 6.2. The uncertainties in these scale factor measurements are between 3 and 6%, and are parameterized as a function of p . These uncertainties affect both the normalization and shape of the tt background and signal events. The impact on the expected number of signal and tt events is 0.4 to 2.3%.

- **Jet energy corrections**: Dedicated energy corrections for CA15 jets are not available. Therefore, the energy corrections for jets reconstructed with the anti-k algorithm with size parameter R = 0.7 (AK7) [26] have been used [43]. It has been verified that these corrections are valid by comparing the reconstructed jets in simulation to the corresponding generator level jets where exactly the same clustering and grooming algorithms have been applied. The ratio between reconstructed and generated momentum for these jets is found to be consistent with unity, with variations that are less than 4%. The impact of the uncertainty on the jet energy scale of filtered CA15 jets is evaluated by varying the jet four-momentum up and down by the jet energy scale uncertainties of AK7 jets, with an additional 4% systematic uncertainty. The uncertainty in the subjet energy scale is assumed to be similar to the energy scale uncertainty of AK5 jets. The impact on the expected number of selected tt and signal events is less than 0.5% for CA15 jets and less than 5% for subjets.
- **PDF uncertainties**: Simulated tt events are weighted according to the uncertainties parameterized by the CTEQ6 eigenvectors [36]. The shifts produced by the individual eigenvectors are added in quadrature in each bin of the H and m__bb distributions. The resulting uncertainty in the number of expected tt events ranges from 2.4 to 8%.
- **Scale uncertainties**: The impact of the renormalization and factorization scale uncertainties on the tt simulation has been studied using tt event samples generated with two different values of these scales (moving them simultaneously up or down by a factor of two relative to the nominal value). It has been verified that this uncertainty has no impact on the shapes of H and m__bb distributions within the statistical uncertainties of the simulated samples. The resulting impact on the selected number of tt events is 34%.
- **QCD multijet background normalization**: The normalization and shape of QCD multijet events do not show any discrepancy between the predicted and observed shapes in the signal region based on the closure test with simulated events, as discussed in Section 8. The comparison of the simulated sidebands with data shows a very good agreement of the shapes as well, but the normalization is not in agreement. Therefore a systematic uncertainty in the normalization of QCD multijet events is taken into account. This uncertainty is derived from the statistical precision of the closure test, which is limited by the finite size of simulated event samples. The uncertainty in the single H tag category is 10% while the uncertainty is 20% in the multi H tag category. The only systematic uncertainty in the shape of the QCD multijet background arises from the subtraction of tt events. The effect of the tt scale uncertainty on the estimation of the QCD multijet background is less than 1%. Uncertainties in the tt simulation and the corresponding propagated uncertainties in the QCD multijet prediction are treated as correlated, but they have opposite

effects.

- **Trigger reweighting**: A scale factor SF_trig is applied to correct for the different behaviour between data and simulation in the region in which the trigger is not fully efficient. A systematic uncertainty in the scale factor is obtained by varying SF_trig by $\pm 0.5(1 - \text{SF\_trig})$. This uncertainty does not affect the plateau region of the trigger, where SF_trig = 1. This uncertainty is taken into account both as a shape and as a rate uncertainty. It only affects the low-H range. The trigger efficiency is measured in a tt-enriched data sample. For $720 < \text{H}$ 780 GeV/c the efficiency is 75%, with a SF_trig of 80%. For $780 < \text{H}$ 840 GeV/c the trigger efficiency is 93%, with a SF_trig of 94%. For $\text{H} > 840$ GeV/c the trigger has an efficiency always greater than 99% and a SF_trig consistent with one. The overall impact of this uncertainty on the event yield is 3.5%.
- **Luminosity**: An uncertainty in the integrated luminosity of 2.6% is taken into account [50].
- **Cross section of the tt background**: An uncertainty of 13% is assigned to the tt cross section. This uncertainty is obtained with the technique used in the differential tt cross section measurement [51] for large invariant mass values of the tt system.

10 Results

Figure 11 [Figure 11: see original paper] shows the comparison between data and the expected background contributions for the single and multiple H tag event categories after all event selection criteria are applied. In the multiple H tag category only the Higgs boson candidate with the highest transverse momentum is used. The QCD multijet background has been derived from data as discussed in Section 8. Signal samples at three different mass points are also shown. In these plots only signal samples in which all T quarks decay into a top quark and a Higgs boson are shown.

Based on the expected distributions for the background and signal models for H and m_bb, a discriminating quantity L is calculated for each event, where L = ln(P_sig(H)/P_back(H) × P_sig(m_bb)/P_back(m_bb)). The P variables represent the probability densities for the signal or background hypotheses. The P_back values are obtained from the sum of the simulated tt and QCD multijet background distributions because other background contributions are found to be negligible, as discussed in Section 8. For the signal hypothesis, the P_sig values are obtained from simulated H and m_bb distributions for each signal mass point. A binned likelihood method is used where the values for the P variables are taken from histograms. The distribution of this variable is shown in Fig. 12 [Figure 12: see original paper] for data compared to the background prediction and signal hypotheses, for both the single and multiple H tag categories. As the signal model is included in the discriminator, each signal mass hypothesis has its own definition of L. The mass points 500, 700, and

1000 GeV/c² are shown in these figures. The spikes in these distributions are due to the likelihood definition, that is obtained by taking values from binned distributions.

No signal-like excess is observed in data. Bayesian upper limits [52] on the T quark production cross section are obtained with the Theta framework [53]. The nuisance parameters are assigned to the sources of systematic uncertainties reported in Section 9, which are taken into account as global normalization uncertainties and as shape uncertainties where applicable. The shape uncertainties are taken into account by interpolating between the nominal and ±1 templates of the likelihood distributions. Figure 13 [Figure 13: see original paper] shows the observed and expected limits on the T pair production cross section, for the hypothesis of an exclusive branching fraction $B(T \to tH) = 100\%$ using the combination of both the single and multiple H tag event categories. T quarks exclusively decaying into tH and with mass values below 745 GeV/c² are excluded at 95% confidence level (CL), with an expected exclusion limit of 773 GeV/c². Due to the lower background contamination, the multiple H tag event category provides the largest contribution to the achieved sensitivity.

In evaluating limits, the other decay modes of the T quark must be considered. For mixed branching fractions there are six distinct final states: tHtH, tHtZ, tHbW, bWbW, bWtZ, tZtZ. Three of these final states contain at least one tH decay. This means that the single H tag category of this analysis is sensitive also to non-exclusive branching fractions. Furthermore, we also expect some sensitivity to tZ decays because the mass of the Z boson differs from the mass of the Higgs boson by only 35 GeV/c² and because it decays into b quark pairs with a branching fraction of 15.6%. A selection efficiency of 4.5% is found for the tHtZ final state, 3% for tHbW, and 2% for tZtZ for a T quark mass of 800 GeV/c². These efficiencies are calculated in the same way as those for tHtH in Table 1.

A dedicated optimization is not performed for the non-exclusive decay modes. Nevertheless, exclusion limits are calculated for all branching fractions from a scan of all allowed values. Simulated signal samples have been produced for each set of branching fractions used in the scan. Observed and expected lower limits on the mass of the T quark for different branching fractions are listed in Table 5 and shown in Fig. 14 [Figure 14: see original paper]. Table 5 shows only those branching fractions for which actual mass limits exist (where the theory curve crosses the limit curve). A good sensitivity is achieved for T → tH branching fractions down to 80%. The observed and expected limits on the production cross section for different branching fractions are given in Table 6 and shown in Fig. 15 [Figure 15: see original paper].

11 Summary

A search for heavy resonances decaying to top quarks and Higgs bosons has been performed using proton-proton collisions recorded with the CMS detector at √s

= 8 TeV, corresponding to an integrated luminosity of 19.7 fb ^{1}. The benchmark model considered is a heavy vector-like T quark that decays into bW, tZ, and tH in all-hadronic final states. The analysis makes use of jet substructure techniques including algorithms for the identification of boosted top quarks, boosted Higgs bosons, and subjet b tagging. Results are presented for exclusive T quark decay modes as well as for non-exclusive branching fractions. If the heavy T quark has a branching fraction of 100% for T → tH, the observed (expected) exclusion limit on the mass of the T quark is 745 (773) GeV/c^2 at 95% confidence level. This limit is similar to that obtained from leptonic final states [14]. These results are the first to exploit the all-hadronic final state in the search for vector-like quarks and they facilitate the combination with other analyses to improve the mass reach.

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A The CMS Collaboration Yerevan Physics Institute, Yerevan, Armenia V. Khachatryan, A.M. Sirunyan, A. Tumasyan Institut f ¨ur Hochenergiephysik der OeAW, Wien, Austria W. Adam, T. Bergauer, M. Dragicevic, J. Er ¨o, M. Friedl, R. Fr ¨uhwirth1, V.M. Ghete, C. Hartl, N. H ¨ormann, J. Hrubec, M. Jeitler1, W. Kiesenhofer, V. Kn ¨unz, M. Krammer1, I. Kr¨atschmer, D. Liko, I. Mikulec, D. Rabady2, B. Rahbaran, H. Rohringer, R. Sch ¨ofbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz1 National Centre for Particle and High Energy Physics, Minsk, Belarus V. Mossolov, N. Shumeiko, J. Suarez Gonzalez Universiteit Antwerpen, Antwerpen, Belgium S. Alderweireldt, S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, J. Lauwers, S. Luyckx, S. Ochesanu, R. Rougny, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck Vrije Universiteit Brussel, Brussel, Belgium F. Blekman, S. Blyweert, J. D’ Hondt, N. Daci, N. Heracleous, J. Keaveney, S. Lowette, M. Maes, A. Olbrechts, Q. Python, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella Universit´e Libre de Bruxelles, Bruxelles, Belgium C. Caillol, B. Clerbaux, G. De Lentdecker, D. Dobur, L. Favart, A.P.R. Gay, A. Grebenyuk, A. L´eonard, A. Mohammadi, L. Pernie2, A. Randle-conde, T. Reis, T. Seva, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang, F. Zenoni Ghent University, Ghent, Belgium V. Adler, K. Beernaert, L. Benucci, A. Cimmino, S. Costantini, S. Crucy, S. Dildick, A. Fagot, G. Garcia, J. Mccartin, A.A. Ocampo Rios, D. Poyraz, D. Ryckbosch, S. Salva Diblen, M. Sigamani, N. Strobbe, F. Thyssen, M. Tytgat, E. Yazgan, N. Zaganidis Universit´e Catholique de Louvain, Louvain-la-Neuve, Belgium S. Basegmez, C. Beluf 3, G. Bruno, R. Castello, A. Caudron, L. Ceard, G.G. Da Silveira, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco4, J. Hollar, A. Jafari, P. Jez, M. Komm, V. Lemaitre, C. Nuttens, L. Perrini, A. Pin, K. Piotrzkowski, A. Popov5, L. Quertenmont, M. Selvaggi, M. Vidal Marono, J.M. Vizan Garcia Universit´e de Mons, Mons, Belgium N. Beliy, T. Caebergs, E. Daubie, G.H. Hammad Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil W.L. Ald´a J ´unior, G.A. Alves, L. Brito, M. Correa Martins Junior, T. Dos Reis Martins, J. Molina, C. Mora Herrera, M.E. Pol, P. Rebello Teles Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil W. Carvalho, J. Chinellato6, A. Cust ´odio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, J. Santaolalla, A. Santoro, A. Sznajder, E.J. Tonelli Manganote6, A. Vilela Pereira A The CMS Collaboration Universidade Estadual Paulista a, Universidade Federal do ABC b, S˜ao Paulo, Brazil C.A. Bernardesb, S. Dograa,

T.R. Fernandez Perez Tomeia, E.M. Gregoresb, P.G. Mercadanteb, S.F. Novaesa, Sandra S. Padulaa Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria A. Aleksandrov, V. Genchev2, R. Hadjiiska, P. Iaydjiev, A. Marinov, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova University of Sofia, Sofia, Bulgaria A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov Institute of High Energy Physics, Beijing, China J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, T. Cheng, R. Du, C.H. Jiang, R. Plestina7, F. Romeo, J. Tao, Z. Wang State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China C. Asawatangtrakuldee, Y. Ban, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu, L. Zhang, W. Zou Universidad de Los Andes, Bogota, Colombia C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.C. Sanabria J.P. Gomez, B. Gomez Moreno, University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia N. Godinovic, D. Lelas, D. Polic, I. Puljak University of Split, Faculty of Science, Split, Croatia Z. Antunovic, M. Kovac Institute Rudjer Boskovic, Zagreb, Croatia V. Brigljevic, K. Kadija, J. Luetic, D. Mekterovic, L. Sudic University of Cyprus, Nicosia, Cyprus A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski Charles University, Prague, Czech Republic M. Bodlak, M. Finger, M. Finger Jr.8 Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt Y. Assran9, A. Ellithi Kamel10, M.A. Mahmoud11, A. Radi12,13 National Institute of Chemical Physics and Biophysics, Tallinn, Estonia M. Kadastik, M. Murumaa, M. Raidal, A. Tiko Department of Physics, University of Helsinki, Helsinki, Finland P. Eerola, M. Voutilainen Helsinki Institute of Physics, Helsinki, Finland J. Härkönen, V. Karimäki, R. Kinnunen, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, L. Wendland Lappeenranta University of Technology, Lappeenranta, Finland J. Talvitie, T. Tuuva DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, C. Favaro, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M. Titov Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France S. Baffioni, F. Beaudette, P. Busson, E. Chapon, C. Charlot, T. Dahms, M. Dalchenko, L. Dobrzynski, N. Filipovic, A. Florent, R. Granier de Cassagnac, L. Mastrolorenzo, P. Miné, I.N. Naranjo, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, S. Regnard, R. Salerno, J.B. Sauvan, Y. Sirois, C. Veelken, Y. Yilmaz, A. Zabi Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace

Mulhouse, CNRS/IN2P3, Strasbourg, France J.-L. Agram14, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte14, J.-C. Fontaine14, D. Gel´e, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, K. Skovpen, P. Van Hove Centre de Calcul de l’ Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France S. Gadrat Universit´e de Lyon, Universit´e Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucl´eaire de Lyon, Villeurbanne, France S. Beauceron, N. Beaupere, C. Bernet7, G. Boudoul2, E. Bouvier, S. Brochet, C.A. Carrillo Montoya, J. Chasserat, R. Chierici, D. Contardo2, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, J.D. Ruiz Alvarez, D. Sabes, L. Sgandurra, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret, H. Xiao Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia Z. Tsamalaidze8 RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany C. Autermann, S. Beranek, M. Bontenackels, M. Edelhoff, L. Feld, A. Heister, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, J. Sammet, S. Schael, J.F. Schulte, H. Weber, B. Wittmer, V. Zhukov5 RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany M. Ata, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, R. Fischer, A. G ¨uth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, S. Knutzen, P. Kreuzer, M. Merschmeyer, A. Meyer, P. Millet, M. Olschewski, K. Padeken, P. Papacz, H. Reithler, S.A. Schmitz, L. Sonnenschein, D. Teyssier, S. Th ¨uer, M. Weber RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany V. Cherepanov, Y. Erdogan, G. Fl ¨ugge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. K ¨unsken, J. Lingemann2, A. Nowack, I.M. Nugent, O. Pooth, A. Stahl Deutsches Elektronen-Synchrotron, Hamburg, Germany M. Aldaya Martin, I. Asin, N. Bartosik, J. Behr, U. Behrens, A.J. Bell, A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, S. Choudhury, F. Costanza, C. Diez Pardos, G. Dolinska, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, T. Eichhorn, G. Flucke, J. Garay Garcia, A. Geiser, A. Gizhko, P. Gunnellini, J. Hauk, M. Hempel15, H. Jung, A. Kalogeropoulos, O. Karacheban15, M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol, A The CMS Collaboration D. Kr ¨ucker, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann15, B. Lutz, R. Mankel, I. Mar n15, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, S. Naumann- Emme, A. Nayak, E. Ntomari, H. Perrey, D. Pitzl, R. Placakyte, A. Raspereza, P.M. Ribeiro Cipriano, B. Roland, E. Ron, M. ¨O. Sahin, J. Salfeld-Nebgen, P. Saxena, T. Schoerner-Sadenius, M. Schr ¨oder, C. Seitz, S. Spannagel, A.D.R. Vargas Trevino, R.

Walsh, C. Wissing University of Hamburg, Hamburg, Germany V. Blobel, M. Centis Vignali, A.R. Draeger, J. Er e, E. Garutti, K. Goebel, M. G ¨orner, J. Haller, M. Hoffmann, R.S. H ¨oing, A. Junkes, H. Kirschenmann, R. Klanner, R. Kogler, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, J. Ott, T. Peiffer, A. Perieanu, N. Pietsch, J. Poehlsen, T. Poehlsen, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Seidel, V. Sola, H. Stadie, G. Steinbr ¨uck, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer Institut f ¨ur Experimentelle Kernphysik, Karlsruhe, Germany C. Barth, C. Baus, J. Berger, C. B ¨oser, E. Butz, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, F. Frensch, M. Giffels, A. Gilbert, F. Hartmann2, T. Hauth, U. Husemann, I. Katkov5, A. Kornmayer2, P. Lobelle Pardo, M.U. Mozer, T. M ¨uller, Th. M ¨uller, A. N ¨urnberg, G. Quast, K. Rabbertz, S. R ¨ocker, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, R. Wolf Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece G. Anagnostou, G. Daskalakis, T. Geralis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, A. Markou, C. Markou, A. Psallidas, I. Topsis-Giotis University of Athens, Athens, Greece A. Agapitos, S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Stiliaris University of Io´annina, Io´annina, Greece X. Aslanoglou, I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas Wigner Research Centre for Physics, Budapest, Hungary G. Bencze, C. Hajdu, P. Hidas, D. Horvath16, F. Sikler, V. Veszpremi, G. Vesztergombi17, A.J. Zsigmond Institute of Nuclear Research ATOMKI, Debrecen, Hungary N. Beni, S. Czellar, J. Karancsi18, J. Molnar, J. Palinkas, Z. Szillasi University of Debrecen, Debrecen, Hungary A. Makovec, P. Raics, Z.L. Trocsanyi, B. Ujvari National Institute of Science Education and Research, Bhubaneswar, India S.K. Swain Panjab University, Chandigarh, India S.B. Beri, V. Bhatnagar, R. Gupta, U.Bhawandeep, A.K. Kalsi, M. Kaur, R. Kumar, M. Mittal, N. Nishu, J.B. Singh University of Delhi, Delhi, India Ashok Kumar, Arun Kumar, S. Ahuja, A. Bhardwaj, B.C. Choudhary, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, V. Sharma Saha Institute of Nuclear Physics, Kolkata, India S. Banerjee, S. Bhattacharya, K. Chatterjee, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, A. Modak, S. Mukherjee, D. Roy, S. Sarkar, M. Sharan Bhabha Atomic Research Centre, Mumbai, India A. Abdulsalam, D. Dutta, V. Kumar, A.K. Mohanty2, L.M. Pant, P. Shukla, A. Topkar Tata Institute of Fundamental Research, Mumbai, India T. Aziz, S. Banerjee, S. Bhowmik19, R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu20, G. Kole, S. Kumar, M. Maity19, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage21 Indian Institute of Science Education and Research (IISER), Pune, India S. Sharma Institute for Research in Fundamental Sciences (IPM), Tehran, Iran H. Bakhshiansohi, H. Behnamian, S.M. Etesami22, A. Fahim23, R. Goldouzian, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh24, M. Zeinali University College Dublin, Dublin, Ireland M. Felcini, M. Grunewald INFN Sezione di Bari a, Universita di Bari b, Politecnico di Bari c, Bari, Italy M. Abbresciaa,b, C. Calabriaa,b, S.S. Chhibraa,b, A. Colaleoa, D. Creanzaa,c, L. Cristellaa,b, N. De Filippisa,c, M. De Palmaa,b, L. Fiorea, G. Iasellia,c, G. Maggia,c, M. Maggia, S. Mya,c, S. Nuzzoa,b, A. Pompilia,b, G. Pugliesea,c, R. Radognaa,b,2, G. Selvaggia,b, A. Sharmaa, L. Silvestrisa,2, R. Vendittia,b, P. Verwilligena INFN Sezione di Bologna a, Universita di Bologna b, Bologna, Italy G. Abbiendia, A.C. Benvenutia, D. Bonacorsia,b, S. Braibant-Giacomellia,b, L. Brigliadoria,b, R. Campaninia,b, P. Capiluppia,b, A. Castroa,b, F.R. Cavalloa, G. Codispotia,b, M. Cuffiania,b, G.M. Dallavallea, F. Fabbria, A. Fanfania,b, D. Fasanellaa,b, P. Giacomellia, C. Grandia, L. Guiduccia,b, S. Marcellinia, G. Masettia, A. Montanaria, F.L. Navarriaa,b, A. Perrottaa, A.M. Rossia,b, T. Rovellia,b, G.P. Sirolia,b, N. Tosia,b, R. Travaglinia,b INFN Sezione di Catania a, Universita di Catania b, CSFNSM c, Catania, Italy S. Albergoa,b, G. Cappelloa, M. Chiorbolia,b, S. Costaa,b, F. Giordanoa,2, R. Potenzaa,b, A. Tricomia,b, C. Tuvea,b INFN Sezione di Firenze a, Universita di Firenze b, Firenze, Italy G. Barbaglia, V. Ciullia,b, C. Civininia, R. D' Alessandroa,b, E. Focardia,b, E. Galloa, S. Gonzia,b, V. Goria,b, P. Lenzia,b, M. Meschinia, S. Paolettia, G. Sguazzonia, A. Tropianoa,b INFN Laboratori Nazionali di Frascati, Frascati, Italy L. Benussi, S. Bianco, F. Fabbri, D. Piccolo INFN Sezione di Genova a, Universita di Genova b, Genova, Italy R. Ferrettia,b, F. Ferroa, M. Lo Veterea,b, E. Robuttia, S. Tosia,b INFN Sezione di Milano-Bicocca a, Universita di Milano-Bicocca b, Milano, Italy M.E. Dinardoa,b, S. Fiorendia,b, S. Gennaia,2, R. Gerosaa,b,2, A. Ghezzia,b, P. Govonia,b, M.T. Lucchinia,b,2, S. Malvezzia, R.A. Manzonia,b, A. Martellia,b, B. Marzocchia,b,2, D. Menascea, L. Moronia, M. Paganonia,b, D. Pedrinia, S. Ragazzia,b, N. Redaellia, T. Tabarelli de Fatisa,b A The CMS Collaboration INFN Sezione di Napoli a, Universita di Napoli ' Federico II' b, Napoli, Italy, Universita della Basilicata c, Potenza, Italy, Universita G. Marconi d, Roma, Italy S. Buontempoa, N. Cavalloa,c, S. Di Guidaa,d,2, F. Fabozzia,c, A.O.M. Iorioa,b, L. Listaa, S. Meolaa,d,2, M. Merolaa, P. Paoluccia,2 INFN Sezione di Padova a, Universita di Padova b, Padova, Italy, Universita di Trento c, Trento, Italy P. Azzia, N. Bacchettaa, D. Biselloa,b, A. Brancaa,b, R. Carlina,b, P. Checchiaa, M. Dall' Ossoa,b, T. Dorigoa, U. Dossellia, F. Gasparinia,b, U. Gasparinia,b, A. Gozzelinoa, K. Kanishcheva,c, S. Lacapraraa, M. Margonia,b, A.T. Meneguzzoa,b, J. Pazzinia,b, N. Pozzobona,b, P. Ronchesea,b, F. Simonettoa,b, E. Torassaa, M. Tosia,b, P. Zottoa,b, A. Zucchettaa,b, G. Zumerlea,b INFN Sezione di Pavia a, Universita di Pavia b, Pavia, Italy M. Gabusia,b, S.P. Rattia,b, V. Rea, C. Riccardia,b, P. Salvinia, P. Vituloa,b INFN Sezione di Perugia a, Universita di Perugia b, Perugia, Italy M. Biasinia,b, G.M. Bileia, D. Ciangottinia,b,2, L. Fan oa,b, P. Laricciaa,b, G. Mantovania,b, M. Menichellia, A. Sahaa, A. Santocchiaa,b, A. Spieziaa,b,2 INFN Sezione di Pisa a, Universita di Pisa b, Scuola Normale Superiore di Pisa c, Pisa, Italy K. Androsova,25, P. Azzurria, G. Bagliesia, J. Bernardinia, T. Boccalia, G. Broccoloa,c, R. Castaldia, M.A. Cioccia,25, R. Dell' Orsoa, S. Donatoa,c,2, G. Fedi, F. Fioria,c, L. Foaa,c, A. Giassia, M.T. Grippoa,25, F. Ligabuea,c, T. Lomtadzea, L. Martinia,b, A. Messineoa,b, C.S. Moona,26, F. Pallaa,2, A. Rizzia,b, A. Savoy-Navarroa,27, A.T. Serbana, P. Spagnoloa, P. Squillaciotia,25, R. Tenchinia, G. Tonellia,b, A. Venturia, P.G. Verdinia, C. Vernieria,c INFN Sezione di Roma a, Universita di Roma b, Roma, Italy L. Baronea,b, F. Cavallaria, G. D' imperioa,b, D. Del Rea,b, M. Diemoza, C. Jordaa, E. Longoa,b, F. Margarolia,b, P. Meridiania, F. Michelia,b,2, G. Organtinia,b, R. Paramattia, S. Rahatloua,b, C. Rovellia, F. Santanastasioa,b, L. Soffia,b, P. Traczyka,b,2 INFN Sezione di Torino a, Universita di Torino b, Torino, Italy, Universita del Piemonte Orientale c, Novara, Italy N. Amapanea,b, R. Arcidiaconoa,c, S. Argiroa,b, M. Arneodoa,c, R. Bellana,b, C. Biinoa, N. Cartigliaa, S. Casassoa,b,2, M. Costaa,b, R. Covarelli, A. Deganoa,b, N. Demariaa, L. Fincoa,b,2, C. Mariottia, S. Masellia, E. Migliorea,b, V. Monacoa,b, M. Musicha, M.M. Obertinoa,c, L. Pachera,b, N. Pastronea, M. Pelliccionia, G.L. Pinna Angionia,b, A. Potenzaa,b, A. Romeroa,b, M. Ruspaa,c, R. Sacchia,b, A. Solanoa,b, A. Staianoa, U. Tamponia INFN Sezione di Trieste a, Universita di Trieste b, Trieste, Italy S. Belfortea, V. Candelisea,b,2, M. Casarsaa, F. Cossuttia, G. Della Riccaa,b, B. Gobboa, C. La Licataa,b, M. Maronea,b, A. Schizzia,b, T. Umera,b, A. Zanettia Kangwon National University, Chunchon, Korea S. Chang, A. Kropivnitskaya, S.K. Nam Kyungpook National University, Daegu, Korea D.H. Kim, G.N. Kim, M.S. Kim, D.J. Kong, S. Lee, Y.D. Oh, H. Park, A. Sakharov, D.C. Son Chonbuk National University, Jeonju, Korea T.J. Kim, M.S. Ryu Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea J.Y. Kim, D.H. Moon, S. Song Korea University, Seoul, Korea S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, Y. Kim, B. Lee, K.S. Lee, S.K. Park, Y. Roh Seoul National University, Seoul, Korea H.D. Yoo University of Seoul, Seoul, Korea M. Choi, J.H. Kim, I.C. Park, G. Ryu Sungkyunkwan University, Suwon, Korea Y. Choi, Y.K. Choi, J. Goh, D. Kim, E. Kwon, J. Lee, I. Yu Vilnius University, Vilnius, Lithuania A. Juodagalvis National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia J.R. Komaragiri, M.A.B. Md Ali Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico E. Casimiro Linares, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, A. Hernandez-Almada, R. Lopez-Fernandez, A. Sanchez-Hernandez Universidad Iberoamericana, Mexico City, Mexico S. Carrillo Moreno, F. Vazquez Valencia Benemerita Universidad Autonoma de Puebla, Puebla, Mexico I. Pedraza, H.A. Salazar Ibarguen Universidad Aut ´onoma de San Luis Potos´ı, San Luis Potos´ı, Mexico A. Morelos Pineda University of Auckland, Auckland, New Zealand D. Krofcheck University of Canterbury, Christchurch, New Zealand P.H. Butler, S. Reucroft National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, T. Khurshid, M. Shoaib National Centre for Nuclear Research, Swierk, Poland H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. G ´orski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, P. Zalewski Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland G. Brona, K. Bunkowski, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski Laborat ´orio de Instrumenta¸c˜ao e F´ısica Experimental de Part´ıculas, Lisboa, Portugal P. Bargassa, C. Beir˜ao Da Cruz E Silva, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, L. Lloret Iglesias, F. Nguyen, J. Rodrigues Antunes, J. Seixas, J. Varela, P. Vischia Joint Institute for Nuclear Research, Dubna, Russia P. Bunin, I. Golutvin, I. Gorbunov, V. Karjavin, V. Konoplyanikov, G. Kozlov, A. Lanev, A. Malakhov, V. Matveev28, P. Moisenz, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, A. Zarubin A The CMS Collaboration Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia V. Golovtsov, Y. Ivanov, V. Kim29, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev Institute for Nuclear Research, Moscow, Russia Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin Institute for Theoretical and Experimental Physics, Moscow, Russia V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, S. Semenov, A. Spiridonov, V. Stolin, E. Vlasov, A. Zhokin P.N. Lebedev Physical Institute, Moscow, Russia V. Andreev, M. Azarkin30, I. Dremin30, M. Kirakosyan, A. Leonidov30, G. Mesyats, S.V. Rusakov, A. Vinogradov Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia A. Belyaev, E. Boos, V. Bunichev, M. Dubinin31, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, V. Savrin, A. Snigirev State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia P. Adzic32, M.

Ekmedzic, J. Milosevic, V. Rekovic Centro de Investigaciones Energ´eticas Medioambientales y Tecnol ´ogicas (CIEMAT), Madrid, Spain J. Alcaraz Maestre, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Dom´ınguez V´azquez, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fern´andez Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, E. Navarro De Martino, A. P´erez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares Universidad Aut ´onoma de Madrid, Madrid, Spain C. Albajar, J.F. de Troc ´oniz, M. Missiroli, D. Moran Universidad de Oviedo, Oviedo, Spain H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero Instituto de F´ısica de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, G. Gomez, A. Graziano, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez, T. Rodrigo, A.Y. Rodr´ıguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, R. Vilar Cortabitarte CERN, European Organization for Nuclear Research, Geneva, Switzerland D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, A. Benaglia, J. Bendavid, L. Benhabib, J.F. Benitez, P. Bloch, A. Bocci, A. Bonato, O. Bondu, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, S. Colafranceschi33, M. D’ Alfonso, D. d’ Enterria, A. Dabrowski, A. David, F. De Guio, A. De Roeck, S. De Visscher, E. Di Marco, M. Dobson, M. Dordevic, B. Dorney, N. Dupont-Sagorin, A. Elliott-Peisert, G. Franzoni, W. Funk, D. Gigi, K. Gill, D. Giordano, M. Girone, F. Glege, R. Guida, S. Gundacker, M. Guthoff, J. Hammer, M. Hansen, P. Harris, J. Hegeman, V. Innocente, P. Janot, K. Kousouris, K. Krajczar, P. Lecoq, C. Lourenc¸o, N. Magini, L. Malgeri, M. Mannelli, J. Marrouche, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, L. Orsini, L. Pape, E. Perez, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pimi¨a, D. Piparo, M. Plagge, A. Racz, G. Rolandi34, M. Rovere, H. Sakulin, C. Sch¨afer, C. Schwick, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas35, D. Spiga, J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Tsirou, G.I. Veres17, N. Wardle, H.K. W ¨ohri, H. Wollny, W.D. Zeuner Paul Scherrer Institut, Villigen, Switzerland W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, D. Renker, T. Rohe Institute for Particle Physics, ETH Zurich, Zurich, Switzerland F. Bachmair, L. B¨ani, L. Bianchini, M.A. Buchmann, B. Casal, N. Chanon, G. Dissertori, M. Dittmar, M. Donega, M. D ¨unser, P. Eller, C. Grab, D. Hits, J. Hoss, W. Lustermann, B. Mangano, A.C. Marini, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio,

D. Meister, N. Mohr, P. Musella, C. N¨ageli36, F. Nessi-Tedaldi, F. Pandolfi, F. Pauss, L. Perrozzi, M. Peruzzi, M. Quittnat, L. Rebane, M. Rossini, A. Starodumov37, M. Takahashi, K. Theofilatos, R. Wallny, H.A. Weber Universit¨at Z ¨urich, Zurich, Switzerland C. Amsler38, M.F. Canelli, V. Chiochia, A. De Cosa, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, J. Ngadiuba, D. Pinna, P. Robmann, F.J. Ronga, S. Taroni, M. Verzetti, Y. Yang National Central University, Chung-Li, Taiwan M. Cardaci, K.H. Chen, C. Ferro, C.M. Kuo, W. Lin, Y.J. Lu, R. Volpe, S.S. Yu National Taiwan University (NTU), Taipei, Taiwan P. Chang, Y.H. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, U. Grundler, W.-S. Hou, Y.F. Liu, R.-S. Lu, M. Mi ˜nano Moya, E. Petrakou, Y.M. Tzeng, R. Wilken Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand B. Asavapibhop, G. Singh, N. Srimanobhas, N. Suwonjandee Cukurova University, Adana, Turkey A. Adiguzel, M.N. Bakirci39, S. Cerci40, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal41, A. Kayis Topaksu, G. Onengut42, K. Ozdemir43, S. Ozturk39, A. Polatoz, D. Sunar Cerci40, B. Tali40, H. Topakli39, M. Vergili, C. Zorbilmez Middle East Technical University, Physics Department, Ankara, Turkey I.V. Akin, B. Bilin, S. Bilmis, H. Gamsizkan44, B. Isildak45, G. Karapinar46, K. Ocalan47, S. Sekmen, U.E. Surat, M. Yalvac, M. Zeyrek Bogazici University, Istanbul, Turkey E.A. Albayrak48, E. G ¨ulmez, M. Kaya49, O. Kaya50, T. Yetkin51 Istanbul Technical University, Istanbul, Turkey K. Cankocak, F.I. Vardarlı National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine L. Levchuk, P. Sorokin A The CMS Collaboration University of Bristol, Bristol, United Kingdom J.J. Brooke, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, Z. Meng, D.M. Newbold52, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, S. Senkin, V.J. Smith Rutherford Appleton Laboratory, Didcot, United Kingdom K.W. Bell, A. Belyaev53, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley, S.D. Worm Imperial College, London, United Kingdom M. Baber, R. Bainbridge, O. Buchmuller, D. Burton, D. Colling, N. Cripps, P. Dauncey, G. Davies, M. Della Negra, P. Dunne, A. Elwood, W. Ferguson, J. Fulcher, D. Futyan, G. Hall, G. Iles, M. Jarvis, G. Karapostoli, M. Kenzie, R. Lane, R. Lucas52, L. Lyons, A.-M. Magnan, S. Malik, B. Mathias, J. Nash, A. Nikitenko37, J. Pela, M. Pesaresi, K. Petridis, D.M. Raymond, S. Rogerson, A. Rose, C. Seez, P. Sharp†, A. Tapper, M. Vazquez Acosta, T. Virdee, S.C. Zenz Brunel University, Uxbridge, United Kingdom J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leggat, D. Leslie, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner Baylor University, Waco, USA J. Dittmann, K. Hatakeyama, A. Kasmi, H. Liu, N. Pastika, T. Scarborough, Z. Wu The University of Alabama, Tuscaloosa, USA O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio Boston University, Boston, USA A. Avetisyan, T. Bose, C. Fantasia, P. Lawson, C. Richardson, J. Rohlf, J. St. John, L. Sulak Brown University, Providence, USA J. Alimena, E. Berry, S. Bhattacharya, G. Christopher, D. Cutts, Z. Demiragli,

N. Dhingra, A. Ferapontov, A. Garabedian, U. Heintz, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, M. Segala, T. Sinthuprasith, T. Speer, J. Swanson University of California, Davis, Davis, USA R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, M. Gardner, W. Ko, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, F. Ricci-Tam, S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay University of California, Los Angeles, USA R. Cousins, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, G. Rakness, E. Takasugi, V. Valuev, M. Weber University of California, Riverside, Riverside, USA K. Burt, R. Clare, J. Ellison, J.W. Gary, G. Hanson, J. Heilman, M. Ivova Rikova, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, A. Luthra, M. Malberti, M. Olmedo Negrete, A. Shrinivas, S. Sumowidagdo, S. Wimpenny University of California, San Diego, La Jolla, USA J.G. Branson, G.B. Cerati, S. Cittolin, R.T. D' Agnolo, A. Holzner, R. Kelley, D. Klein, J. Letts, I. Macneill, D. Olivito, S. Padhi, C. Palmer, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, Y. Tu, A. Vartak, C. Welke, F. W ¨urthwein, A. Yagil, G. Zevi Della Porta University of California, Santa Barbara, Santa Barbara, USA D. Barge, J. Bradmiller-Feld, C. Campagnari, T. Danielson, A. Dishaw, V. Dutta, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Incandela, C. Justus, N. Mccoll, S.D. Mullin, J. Richman, D. Stuart, W. To, C. West, J. Yoo California Institute of Technology, Pasadena, USA A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, J. Duarte, A. Mott, H.B. Newman, C. Pena, M. Pierini, M. Spiropulu, J.R. Vlimant, R. Wilkinson, S. Xie, R.Y. Zhu Carnegie Mellon University, Pittsburgh, USA V. Azzolini, A. Calamba, B. Carlson, T. Ferguson, Y. Iiyama, M. Paulini, J. Russ, H. Vogel, I. Vorobiev University of Colorado at Boulder, Boulder, USA J.P. Cumalat, W.T. Ford, A. Gaz, M. Krohn, E. Luiggi Lopez, U. Nauenberg, J.G. Smith, K. Stenson, S.R. Wagner Cornell University, Ithaca, USA J. Alexander, A. Chatterjee, J. Chaves, J. Chu, S. Dittmer, N. Eggert, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Ryd, E. Salvati, L. Skinnari, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Tucker, Y. Weng, L. Winstrom, P. Wittich Fairfield University, Fairfield, USA D. Winn Fermi National Accelerator Laboratory, Batavia, USA S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, H.W.K. Cheung, F. Chlebana, S. Cihangir, V.D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Gr ¨unendahl, O. Gutsche, J. Hanlon, D. Hare, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Kwan†, J. Linacre, D. Lincoln, R. Lipton, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, V.I. Martinez Outschoorn, S. Maruyama, D. Mason, P. McBride, P. Merkel, K. Mishra, S. Mrenna, S. Nahn, C. Newman-Holmes, V. O' Dell, O. Prokofyev, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, A. Whitbeck, J. Whitmore, F. Yang University of Florida, Gainesville, USA D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, M. Carver, D. Curry, S. Das, M. De Gruttola, G.P. Di Giovanni, R.D. Field, M. Fisher, I.K. Furic, J. Hugon, J. Konigsberg, A. Korytov, T. Kypreos, J.F. Low, K. Matchev, H. Mei, P. Milenovic54, G. Mitselmakher, L. Muniz, A. Rinkevicius, L. Shchutska, M. Snowball, D. Sperka, J. Yelton, M. Zakaria Florida International University, Miami, USA S. Hewamanage, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez Florida State University, Tallahassee, USA J.R. Adams, T. Adams, A. Askew, J. Bochenek, B. Diamond, J. Haas, S. Hagopian, V. Hagopian, K.F. Johnson, H. Prosper, V. Veeraraghavan, M. Weinberg Florida Institute of Technology, Melbourne, USA M.M. Baarmand, M. Hohlmann, H. Kalakhety, F. Yumiceva University of Illinois at Chicago (UIC), Chicago, USA M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, A The CMS Collaboration L. Gauthier, C.E. Gerber, D.J. Hofman, P. Kurt, C. O' Brien, C. Silkworth, P. Turner, N. Varelas I.D. Sandoval Gonzalez, The University of Iowa, Iowa City, USA B. Bilki55, W. Clarida, K. Dilsiz, M. Haytmyradov, J.-P. Merlo, H. Mermerkaya56, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok48, A. Penzo, R. Rahmat, S. Sen, P. Tan, E. Tiras, J. Wetzel, K. Yi Johns Hopkins University, Baltimore, USA I. Anderson, B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, A.V. Gritsan, P. Maksimovic, C. Martin, M. Swartz, M. Xiao The University of Kansas, Lawrence, USA P. Baringer, A. Bean, G. Benelli, C. Bruner, J. Gray, R.P. Kenny III, D. Majumder, M. Malek, M. Murray, D. Noonan, S. Sanders, J. Sekaric, R. Stringer, Q. Wang, J.S. Wood Kansas State University, Manhattan, USA I. Chakaberia, A. Ivanov, K. Kaadze, S. Khalil, M. Makouski, Y. Maravin, L.K. Saini, N. Skhirtladze, I. Svintradze Lawrence Livermore National Laboratory, Livermore, USA J. Gronberg, D. Lange, F. Rebassoo, D. Wright University of Maryland, College Park, USA A. Baden, A. Belloni, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Kolberg, Y. Lu, A.C. Mignerey, K. Pedro, A. Skuja, M.B. Tonjes, S.C. Tonwar Massachusetts Institute of Technology, Cambridge, USA A. Apyan, R. Barbieri, K. Bierwagen, W. Busza, I.A. Cali, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Gulhan, M. Klute, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, C. Paus, D. Ralph, C. Roland, G. Roland, G.S.F. Stephans, K. Sumorok, D. Velicanu, J. Veverka, B. Wyslouch, M. Yang, M. Zanetti, V. Zhukova University of Minnesota, Minneapolis, USA B. Dahmes, A. Gude, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, S. Nourbakhsh, R. Rusack, A. Singovsky, N. Tambe, J. Turkewitz University of Mississippi, Oxford, USA J.G. Acosta, S. Oliveros University of Nebraska-Lincoln, Lincoln, USA E. Avdeeva, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, R. Gonzalez Suarez, J. Keller, D. Knowlton, I. Kravchenko, J. Lazo-Flores, F. Meier, F. Ratnikov, G.R. Snow, M. Zvada State University of New York at Buffalo, Buffalo, USA J. Dolen, A. Godshalk, I. Iashvili, A. Kharchilava, A. Kumar, S. Rappoccio Northeastern University, Boston, USA G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, D. Trocino, R.-J. Wang, D. Wood, J. Zhang Northwestern University, Evanston, USA K.A. Hahn, A. Kubik, N. Mucia, N. Odell, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, K. Sung, M. Velasco, S. Won University of Notre Dame, Notre Dame, USA A. Brinkerhoff, K.M. Chan, A. Drozdetskiy, M. Hildreth, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, S. Lynch, N. Marinelli,

Y. Musienko28, T. Pearson, M. Planer, R. Ruchti, G. Smith, N. Valls, M. Wayne, M. Wolf, A. Woodard The Ohio State University, Columbus, USA L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, A. Hart, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, W. Luo, D. Puigh, M. Rodenburg, B.L. Winer, H. Wolfe, H.W. Wulsin Princeton University, Princeton, USA O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S.A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Pirou´e, X. Quan, H. Saka, D. Stickland2, C. Tully, J.S. Werner, A. Zuranski University of Puerto Rico, Mayaguez, USA E. Brownson, S. Malik, H. Mendez, J.E. Ramirez Vargas Purdue University, West Lafayette, USA V.E. Barnes, D. Benedetti, D. Bortoletto, M. De Mattia, L. Gutay, Z. Hu, M.K. Jha, M. Jones, K. Jung, M. Kress, N. Leonardo, D.H. Miller, N. Neumeister, F. Primavera, B.C. Radburn-Smith, X. Shi, I. Shipsey, D. Silvers, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu, J. Zablocki Purdue University Calumet, Hammond, USA N. Parashar, J. Stupak Rice University, Houston, USA A. Adair, B. Akgun, K.M. Ecklund, F.J.M. Geurts, W. Li, B. Michlin, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel University of Rochester, Rochester, USA B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, M. Galanti, A. Garcia- Bellido, P. Goldenzweig, J. Han, A. Harel, O. Hindrichs, A. Khukhunaishvili, S. Korjenevski, G. Petrillo, D. Vishnevskiy The Rockefeller University, New York, USA R. Ciesielski, L. Demortier, K. Goulianos, C. Mesropian Rutgers, The State University of New Jersey, Piscataway, USA S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, S. Kaplan, A. Lath, S. Panwalkar, M. Park, R. Patel, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker University of Tennessee, Knoxville, USA K. Rose, S. Spanier, A. York Texas A&M University, College Station, USA O. Bouhali57, A. Castaneda Hernandez, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon58, V. Khotilovich, V. Krutelyov, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Rose, A. Safonov, I. Suarez, A. Tatarinov, K.A. Ulmer Texas Tech University, Lubbock, USA N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Dudero, J. Faulkner, K. Kovitanggoon, S. Kunori, S.W. Lee, T. Libeiro, I. Volobouev A The CMS Collaboration Vanderbilt University, Nashville, USA E. Appelt, A.G. Delannoy, S. Greene, A. Gurrola, W. Johns, C. Maguire, Y. Mao, A. Melo, M. Sharma, P. Sheldon, B. Snook, S. Tuo, J. Velkovska University of Virginia, Charlottesville, USA M.W. Arenton, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Lin, C. Neu, E. Wolfe, J. Wood Wayne State University, Detroit, USA C. Clarke, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, J. Sturdy University of Wisconsin, Madison, USA D.A. Belknap, D. Carlsmith, M. Cepeda, S. Dasu, L. Dodd, S. Duric, E. Friis, R. Hall- Wilton, M. Herndon, A. Herv´e, P. Klabbers, A. Lanaro, C. Lazaridis, A. Levine, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, I. Ross, T. Sarangi, A. Savin, W.H. Smith, D. Taylor, C. Vuosalo, N. Woods †: Deceased 1: Also at Vienna University of Technology, Vienna, Austria 2: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland 3: Also at Institut Pluridisciplinaire

Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France 4: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia 5: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia 6: Also at Universidade Estadual de Campinas, Campinas, Brazil 7: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France 8: Also at Joint Institute for Nuclear Research, Dubna, Russia 9: Also at Suez University, Suez, Egypt 10: Also at Cairo University, Cairo, Egypt 11: Also at Fayoum University, El-Fayoum, Egypt 12: Also at Ain Shams University, Cairo, Egypt 13: Now at British University in Egypt, Cairo, Egypt 14: Also at Université de Haute Alsace, Mulhouse, France 15: Also at Brandenburg University of Technology, Cottbus, Germany 16: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary 17: Also at Eötvös Loránd University, Budapest, Hungary 18: Also at University of Debrecen, Debrecen, Hungary 19: Also at University of Visva-Bharati, Santiniketan, India 20: Now at King Abdulaziz University, Jeddah, Saudi Arabia 21: Also at University of Ruhuna, Matara, Sri Lanka 22: Also at Isfahan University of Technology, Isfahan, Iran 23: Also at University of Tehran, Department of Engineering Science, Tehran, Iran 24: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran 25: Also at Universita degli Studi di Siena, Siena, Italy 26: Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France 27: Also at Purdue University, West Lafayette, USA 28: Also at Institute for Nuclear Research, Moscow, Russia 29: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia 30: Also at National Research Nuclear University ’ Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia 31: Also at California Institute of Technology, Pasadena, USA 32: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia 33: Also at Facolta Ingegneria, Università di Roma, Roma, Italy 34: Also at Scuola Normale e Sezione dell’ INFN, Pisa, Italy 35: Also at University of Athens, Athens, Greece 36: Also at Paul Scherrer Institut, Villigen, Switzerland 37: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia 38: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland 39: Also at Gaziosmanpasa University, Tokat, Turkey 40: Also at Adiyaman University, Adiyaman, Turkey 41: Also at Mersin University, Mersin, Turkey 42: Also at Cag University, Mersin, Turkey 43: Also at Piri Reis University, Istanbul, Turkey 44: Also at Anadolu University, Eskisehir, Turkey 45: Also at Ozyegin University, Istanbul, Turkey 46: Also at Izmir Institute of Technology, Izmir, Turkey 47: Also at Necmettin Erbakan University, Konya, Turkey 48: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey 49: Also at Marmara University, Istanbul, Turkey 50: Also at Kafkas University, Kars, Turkey 51: Also at Yildiz Technical University, Istanbul, Turkey 52: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom 53: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom 54: Also at University of Belgrade, Faculty of Physics and

Vinca Institute of Nuclear Sciences, Belgrade, Serbia 55: Also at Argonne National Laboratory, Argonne, USA 56: Also at Erzincan University, Erzincan, Turkey 57: Also at Texas A&M University at Qatar, Doha, Qatar 58: Also at Kyungpook National University, Daegu, Korea

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