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Search for supersymmetry in events with one lepton and multiple jets in proton-proton collisions at $\sqrt{s} = 13$ TeV

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A search for supersymmetry is performed in events with a single electron or muon in proton-proton collisions at a center-of-mass energy of 13 TeV. The data were recorded by the CMS experiment at the LHC and correspond to an integrated luminosity of 2.3 fb^{-1}. Several exclusive search regions are defined based on the number of jets and b-tagged jets, the scalar sum of the jet transverse momenta, and the scalar sum of the missing transverse momentum and the transverse momentum of the lepton. The observed event yields in data are consistent with the expected backgrounds from standard model processes. The results are interpreted using two simplified models of supersymmetric particle spectra, both of which describe gluino pair production. In the first model, each gluino decays via a three-body process to top quarks and a neutralino, which is associated with the observed missing transverse momentum in the event. Gluinos with masses up to 1.6 TeV are excluded for neutralino masses below 600 GeV. In the second model, each gluino decays via a three-body process to two light quarks and a chargino, which subsequently decays to a W boson and a neutralino. The mass of the chargino is taken to be midway between the gluino and neutralino masses. In this model, gluinos with masses below 1.4 TeV are excluded for neutralino masses below 700 GeV.

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I. INTRODUCTION

Supersymmetry (SUSY) [1–8] is a well-motivated theoretical framework that postulates new physics beyond the standard model (SM). Models based on SUSY can address several open questions in particle physics, e.g. the cancellation of quadratically divergent loop corrections when calculating the squared mass of the Higgs boson. In R-parity [9] conserving SUSY models, the lightest SUSY particle (LSP) is stable and can be a viable dark matter candidate. An inclusive search for SUSY in the single-lepton channel was performed with 13 TeV data recorded in 2015 by the CMS experiment at the CERN LHC, corresponding to an integrated luminosity of 2.3 fb^{-1}. Similar searches were performed in 7 TeV [10–12] and in 8 TeV [13–15] data by the CMS and ATLAS experiments. First results in the single-lepton final state at 13 TeV are also available from both collaborations [16–18]. In this paper, we present a search for gluino pair production designed to be sensitive to a variety of SUSY models.

In this analysis, the main backgrounds arise from $W +$ jets events and top quark-antiquark ($t\bar{t} +$ jets) events, which also lead to W-boson production. In $W +$ jets events, or in $t\bar{t} +$ jets events with a single leptonic W-boson decay, the missing transverse momentum $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$, defined as the negative vector sum of the transverse momenta of all reconstructed particles in the event, provides a measurement of the neutrino transverse momentum. The quantity $\vec{p}_{\mathrm{T}}^{\ell} + \vec{p}_{\mathrm{T}}^{\mathrm{miss}}$, where $\vec{p}_{\mathrm{T}}^{\ell}$ is the lepton transverse momentum vector, corresponds to the transverse momentum of the W boson in background events of this type. We also define the magnitude of the missing transverse momentum, $E_{\mathrm{T}}^{\mathrm{miss}} = |\vec{p}_{\mathrm{T}}^{\mathrm{miss}}|$, and the sum $L_{\mathrm{T}} = p_{\mathrm{T}}^{\ell} + E_{\mathrm{T}}^{\mathrm{miss}}$, where p_{T}^{ℓ} is the magnitude of $\vec{p}_{\mathrm{T}}^{\ell}$.

A key analysis variable is the azimuthal angle $\Delta\Phi$, measured in the plane perpendicular to the beams, between $\vec{p}_{\mathrm{T}}^{\ell}$ and $\vec{p}_{\mathrm{T}}^{\ell} + \vec{p}_{\mathrm{T}}^{\mathrm{miss}}$. In background events with a single W-boson decay, $\Delta\Phi$ corresponds to the azimuthal angle between the transverse momentum vectors of the charged lepton and the W boson. In such events, the distribution of $\Delta\Phi$ falls rapidly and has a maximum value determined by the mass and transverse momentum of the W boson. The higher the boost of the W boson, the smaller the maximum value of $\Delta\Phi$. In SUSY events corresponding to our signal models, however, $E_{\mathrm{T}}^{\mathrm{miss}}$ typically receives a large contribution from the missing momentum of the two neutralino LSPs. As a consequence, the $\Delta\Phi$ distribution in signal events is roughly uniform. The main backgrounds can therefore be suppressed by rejecting events with a small value of $\Delta\Phi$. The primary remaining background arises from $t\bar{t} +$ jets production, where both W bosons decay into a charged lepton and a neutrino, with one lepton being not well identified or falling outside the detector acceptance. This background populates the high region of $\Delta\Phi$.

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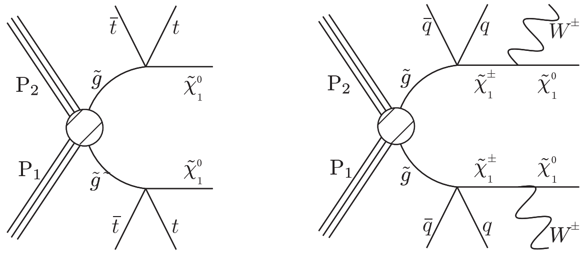

FIG. 1. Diagrams showing the simplified models (left) T1tttt and (right) T5qqqqWW. Depending on the mass difference between the chargino ($\tilde{\chi}_1^\pm$) and the neutralino ($\tilde{\chi}_1^0$), the W boson can be virtual.

Since many models of gluino pair production lead to final states with a large number of jets, the signal-to-background ratio is very small in regions with low jet multiplicity. We therefore restrict the search to regions of large jet multiplicity and use low jet multiplicity regions, dominantly populated by events from SM processes, to estimate the background. Exclusive search regions are characterized by the number of jets (n_{jet}), the number of b-tagged jets (n_b), the scalar sum of the transverse momenta p_T of the jets (H_T), and L_T.

The results are interpreted in terms of simplified models [19–22] of gluino pair production. In the first model, designated T1tttt and shown in Fig. 1 (left), gluinos are pair produced and subsequently undergo three-body decays to $t\bar{t} + \tilde{\chi}_1^0$, where $\tilde{\chi}_1^0$ is the lightest neutralino. In the second model, termed T5qqqqWW and shown in Fig. 1 (right), the gluinos undergo three-body decays to a quark-antiquark pair ($q\bar{q}$) from the first or second generation and a chargino ($\tilde{\chi}_1^\pm$). The chargino mass is taken to be $m_{\tilde{\chi}_1^\pm} = 0.5(m_{\tilde{g}} + m_{\tilde{\chi}_1^0})$. The chargino then decays to a W boson and the $\tilde{\chi}_1^0$, where the W boson can be virtual, depending on the mass difference between the chargino and the lightest neutralino.

The organization of this paper is as follows. Section II describes the CMS detector. The event reconstruction and selection are discussed in Secs. III and IV, respectively. The background estimations are given in Sec. V. An overview of the main systematic uncertainties is presented in Sec. VI. The results are discussed and interpreted in Sec. VII, and a summary is given in Sec. VIII.

II. THE CMS DETECTOR

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. 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 end-cap sections, reside within the solenoid volume. Forward calorimeters extend the pseudorapidity (η) [23] coverage provided by the barrel and end-cap detectors. Muons are measured in the range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers.

The silicon tracker measures charged particles within the range $|\eta| < 2.5$. Isolated particles with transverse momenta $p_T = 100$ GeV, emitted at $|\eta| < 1.4$, have track resolutions of 2.8% in p_T, and 10 (30)μm in the transverse (longitudinal) impact parameter [24]. The ECAL and HCAL measure energy depositions in the range $|\eta| < 3$, with quartz fiber and steel forward calorimeters extending the coverage to $|\eta| < 5$. When information from the various detector systems is combined, the resulting jet energy resolution is typically 15% at 10 GeV, 8% at 100 GeV, and 4% at 1 TeV [25]. The momentum resolution for electrons with $p_T \approx 45$ GeV from $Z \to ee$ decays ranges from 1.7% for electrons that do not shower in the barrel region to 4.5% for electrons that shower in the end caps [26]. Matching muons to tracks measured in the silicon tracker yields relative transverse momentum resolutions for muons with $20 < p_T < 100$ GeV of 1.3%–2.0% in the barrel, and less than 6% in the end caps. The p_T resolution in the barrel is below 10% for muons with p_T up to 1 TeV [27].

The CMS trigger system consists of two levels, where the first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select the most interesting events in a fixed time interval of less than 4μs. The high-level trigger (HLT) processor farm further decreases the event rate from around 100 kHz to less than 1 kHz, before data storage.

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. [23].

III. EVENT RECONSTRUCTION AND SIMULATION

All objects in the event are reconstructed using the particle-flow event reconstruction algorithm [28,29], which reconstructs and identifies each individual particle through an optimized combination of information from the various elements of the CMS detector. 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 [26]. Electron candidates are required to satisfy identification criteria designed to suppress contributions from misidentified jets, photon conversions, and electrons from heavy-flavor quark decays. Muons are reconstructed using a stand-alone muon track in the muon system serving as a seed to find a corresponding track in the silicon detector [27]. Additional criteria include requirements on the track and hit parameters. Events are vetoed if additional electrons or muons with looser identification requirements are found.

The degree of isolation of a lepton from other particles provides a strong indication of whether it was produced in a hadronic jet, such as a jet resulting from the fragmentation of a b quark, or in the leptonic decay of a W boson or other heavy particle. Lepton isolation is quantified by performing a scalar sum of the transverse momenta of all particles that lie within a cone of specified size around the lepton momentum vector, excluding the contribution of the lepton itself. To maintain high efficiency for signal events, which typically contain a large number of jets from the SUSY decay chains, we use a p_{T}-dependent cone radius $R = (0.2, 10\ \mathrm{GeV}/p_{\mathrm{T}}[\mathrm{GeV}], 0.05)$ for $(p_{\mathrm{T}} < 50\ \mathrm{GeV}, 50\ \mathrm{GeV} < p_{\mathrm{T}} < 200\ \mathrm{GeV}, p_{\mathrm{T}} > 200\ \mathrm{GeV})$, respectively. The isolation variable is defined as a relative quantity, I_{rel}, by dividing this scalar sum by the p_{T} of the lepton. For selected muons or electrons, we require $I_{\mathrm{rel}} < 0.2$ and $I_{\mathrm{rel}} < 0.1$, respectively, while for additional leptons used in the event veto, we require $I_{\mathrm{rel}} < 0.4$. When computing the isolation variable, an area-based correction is applied to remove the contribution of particles from additional proton-proton collisions within the same or neighboring bunch crossings (pileup).

The energy of charged hadrons is determined from a combination of their momenta measured in the tracker and the matching ECAL and HCAL energy depositions, corrected for zero-suppression effects in the readout electronics, 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 energies.

Jets are clustered with the anti-k_{T} algorithm [30] with a distance parameter of 0.4 [25], as implemented in the FastJet package [31]. Jet momentum is determined as the vectorial sum of all particle momenta in the jet. An offset is subtracted from the jet energies to take into account the contribution from pileup [32]. Jet energy corrections are obtained from simulation and are confirmed with *in situ* measurements of the energy balance in dijet and photon + jet events [25]. Additional selection criteria are applied to each event to remove spurious jetlike features originating from isolated noise patterns in certain HCAL regions.

To identify jets originating from b quarks, we use an inclusive combined secondary vertex tagger (CSVv2) [33,34], which employs both secondary vertex and track-based information. The working point is chosen to have about 70% b-tagging efficiency and a 1.5% light-flavor misidentification rate [35]. Double counting of objects is avoided by not considering jets that lie within a cone of radius 0.4 around a selected lepton.

While the main backgrounds are determined from data, as described in Sec. V, simulated events are used to validate the techniques and to estimate extrapolation factors as needed. In addition, some smaller backgrounds are estimated entirely from simulation. The leading-order (LO) MadGraph5 [36] event generator, using the NNPDF3.0LO [37] parton distribution functions (PDFs), is used to simulate $t\bar{t}$ + jets, W + jets, Z + jets, and multijet events. Single-top quark events in the t-channel and the tW process are generated using the next-to-leading order (NLO) POWHEGv1.0 [38–42] program, and in the s-channel process, as well as for $t\bar{t}$W and $t\bar{t}$Z production, using NLO MadGraph5_amc@nlo [43]. All signal events are generated with MadGraph5, with up to two partons in addition to the gluino pair. Both programs use the NNPDF3.0NLO [37] PDF. The gluino decays are based on a pure phase-space matrix element [44], with signal production cross sections [45–49] computed at NLO plus next-to-leading-logarithm (NLL) accuracy.

We define several benchmark points: the model T1tttt (1.2,0.8) (T1tttt(1.5,0.1)) corresponds to a gluino mass of 1.2 (1.5) TeV and neutralino mass of 0.8 (0.1) TeV, respectively. The model T5qqqqWW(1.0,0.7) (T5qqqqWW(1.2,0.8) and T5qqqqWW(1.5,0.1)) corresponds to a gluino mass of 1.0 (1.2 and 1.5) TeV and neutralino mass of 0.7 (0.8 and 0.1) TeV. For the latter, the intermediate chargino mass is fixed at 0.85 (1.0 and 0.8) TeV.

Showering and hadronization of all partons is performed using the pythia 8.2 ackage [44]. Pileup is generated for some nominal distribution of the number of proton-proton interactions per bunch crossing, which is weighted to match the corresponding distribution in data. The detector response for all backgrounds is modeled using the Geant4 [50] package, while for the signal, the CMS fast simulation program [51] is used to reduce computation time. The fast simulation has been validated against the detailed Geant4-based simulation for the variables relevant for this search, and efficiency corrections based on measurements in data are applied.

IV. TRIGGER AND EVENT SELECTION

The events are selected with an L1 trigger requiring $H_{\mathrm{T}} > 150$ GeV, followed by HLT requirements of $H_{\mathrm{T}} > 350$ GeV (online reconstruction) and at least one isolated lepton (an electron or muon) satisfying $p_{\mathrm{T}} > 15$ GeV. A trigger efficiency of $94 \pm 1\%$ is observed in the kinematic regime of the analysis, defined by lepton $p_{\mathrm{T}} > 25$ GeV and $H_{\mathrm{T}} > 500$ GeV, where the trigger efficiency reaches its maximum.

The electron or muon candidate is required to have a minimum p_{T} of 25 GeV. Events with additional electrons or muons with $p_{\mathrm{T}} > 10$ GeV, satisfying the criteria for vetoed leptons, are rejected. Jets are selected with $p_{\mathrm{T}} > 30$ GeV and $|\eta| < 2.4$. In all search regions, we require at least five jets, where the two highest-p_{T} jets must satisfy $p_{\mathrm{T}} > 80$ GeV.

To separate possible new-physics signals from background, we use the L_{T} variable, which is defined as the scalar sum of the lepton p_{T} and the missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$, and reflects the leptonic energy scale of the event. A minimum L_{T} of 250 GeV is required, such that the analysis is not only sensitive to events with high $E_{\mathrm{T}}^{\mathrm{miss}}$, but also to signal events with very small $E_{\mathrm{T}}^{\mathrm{miss}}$, but higher lepton p_{T}. An additional kinematic quantity important for the

TABLE I. Expected event yields for SUSY signal benchmark models, normalized to 2.3 fb^{-1}. The baseline selection corresponds to all requirements up to and including the requirement on L_T. The last two lines are exclusive for the zero-b and the multi-b selection, respectively. The events are corrected with scale factors to account for differences in the lepton identification and isolation efficiencies, trigger efficiency, and the b-tagging efficiency between simulation and data.

Selection	T1tttt (1.2,0.8)	T1tttt (1.5,0.1)	T5qqqqWW (1.2,0.8)	T5qqqqWW (1.5,0.1)
All events	178	30	185	31
One hard lepton	55	11	51	9.3
No veto lepton	45	9.1	47	8.8
$n_\mathrm{jet} \geq 5$	44	8.9	36	8.1
$p_T(\mathrm{jet}2) > 80$ GeV	36	8.9	34	8.1
$H_\mathrm{T} > 500$ GeV	30	8.9	27	8.1
$L_\mathrm{T} > 250$ GeV	15	8.4	21	7.8
$n_b = 0$ and $\Delta\Phi > 0.75$	0.47	0.26	11	3.5
$n_b \geq 1$, $n_\mathrm{jet} \geq 6$ and $\Delta\Phi > 0.75$	9.3	5.1	2.9	1.2

search is given by the hadronic energy scale of the event H_T. A cutflow for the benchmark signal models is given in Table I.

After imposing the minimum requirements on L_T and H_T, several search regions are defined in bins of n_jet, n_b, L_T, and H_T, where n_jet and n_b are the numbers of jets and b-tagged jets, respectively. Defining search bins in b-jet multiplicity enables the analysis to target specific event topologies and to separate them from SM backgrounds. The phase space is divided into exclusive [0, 1, 2, ≥ 3] b-tagged jet categories when defining search bins, with a minimum b-jet p_T of 30 GeV.

All search bins with at least one b-tagged jet, called "multi-b" bins in the following, are sensitive to the T1tttt model, while the search bins requiring zero b-tagged jets, called "zero-b" bins, are sensitive to the T5qqqqWW model. The baseline selection and the background estimation method differ for these two b-tag categories. For T1tttt, we expect a large number of jets and find in simulation that the n_jet distribution peaks at eight jets for most mass points. We require at least six jets for the multi-b analysis and define two independent categories with 6–8 and ≥ 9 jets. For the zero-b analysis, where the investigated simplified T5qqqqWW model has fewer jets, we require, in the search region, 5, 6–7, or ≥ 8 jets. Depending on the specific SUSY particle masses, the hadronic event activity varies. To accommodate this, we define search bins in H_T. Figure 2 shows the H_T distributions for the multi-b and the zero-b selection. To exploit the strong separation power associated with the L_T variable, we divide the search region into four bins in L_T, such that sufficient statistical accuracy is given in each control bin to predict the background in the corresponding search bin.

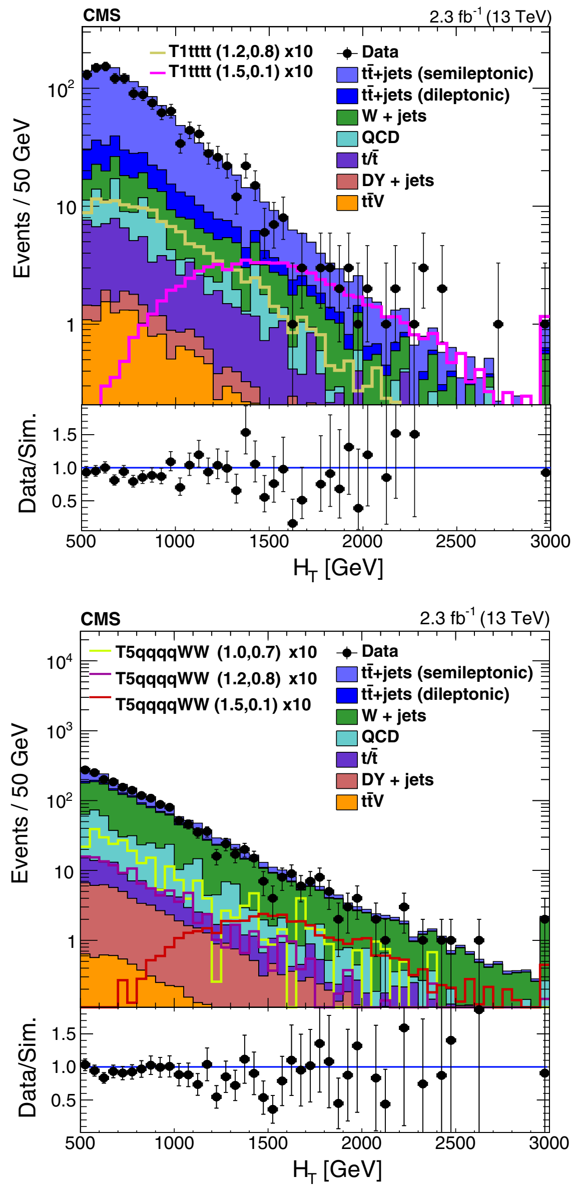

FIG. 2. The H_T distribution for (left) the multi-b analysis and (right) the zero-b analysis, both after the baseline selection. The simulated background events are stacked on top of each other, and several signal points are overlaid for illustration, but without stacking. Overflows are included in the last bin. The label DY refers to $q\bar{q} \to \mathrm{Z}/\gamma^* \to \ell^+\ell^-$ events, and QCD refers to multijet events. The event yields for the benchmark models have been scaled up by a factor of 10. The ratio of data to simulation is given below each of the panels. All uncertainties are statistical only.

After these selections, the main backgrounds are leptonically decaying W + jets and semileptonic $t\bar{t}$ events. These backgrounds, both of which contain one lepton and one neutrino (from the W boson decay) in the final state, are mostly located at small $\Delta\Phi$ values due to the correlation between the lepton and the neutrino. Therefore, the region with large $\Delta\Phi$ is defined as the search region, while the events with small $\Delta\Phi$ are used as the control sample.

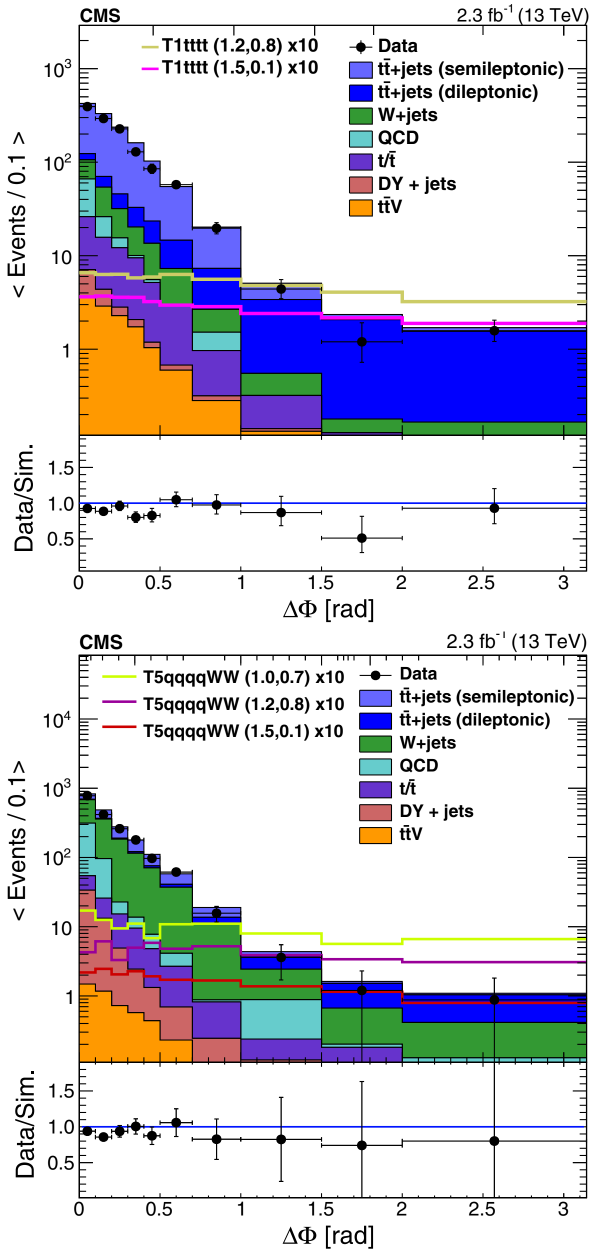

FIG. 3. Comparison of the $\Delta\Phi$ distribution for (left) the multi-b and (right) the zero-b analysis after the baseline selection. The simulated background events are stacked on top of each other, and several signal points are overlaid for illustration, but without stacking. The wider bins are normalized to a bin width of 0.1. The label DY refers to $q\bar{q} \to Z/\gamma^* \to \ell^+\ell^-$ events, and QCD refers to multijet events. The event yields for the benchmark models have been scaled up by a factor of 10. The ratio of data to simulation is given below each of the panels.

Figure 3 shows the $\Delta\Phi$ distributions for the zero-b and multi-b search regions. The ratio of the background event yield in the search region to that in the control region is determined in the corresponding signal-depleted sideband regions, which have smaller values of n_{jet}, as discussed in Sec. V. Since the angle between the W boson and the lepton depends on the W momentum, being smaller for W bosons with higher boost, the $\Delta\Phi$ requirement for the signal region is chosen depending on L_{T}, which is a measure of the W boson p_{T}. For the zero-b analysis, $\Delta\Phi$ is required to be larger than 1.0 for most regions except for those with large L_{T}, where the requirement is relaxed to 0.75, while the multi-b analysis has a relaxed $\Delta\Phi$ requirement of 0.75 and 0.5 for medium- and high-L_{T} regions, respectively.

In total, we define 30 search bins in the multi-b analysis and 13 search bins in the zero-b analysis, as described in detail in Table II.

V. BACKGROUND ESTIMATION

The dominant backgrounds in this search are from $t\bar{t}+$ jets and $W+$ jets events, whose contributions vary with the multiplicity of b-tagged jets and the kinematic region in H_{T} and L_{T}. To determine these backgrounds, we define two regions for each bin in L_{T}, H_{T}, and n_b: the search region (SR) with large values of $\Delta\Phi$, and the control region (CR) with low values of $\Delta\Phi$, with the separation requirement depending on the L_{T} value, as shown in Table II. We further divide each of these bins into low-n_{jet} sideband (SB) and high-n_{jet} main band (MB) regions.

About 10%–15% of the SM background events in the CR are expected to be multijet events (denoted in the following as QCD) and are predicted as described in Sec. V C. Since the multijet background is negligible in the SR, it is subtracted from the number of background events in the CR when calculating the transfer factor $R_{\mathrm{CS}}^{\mathrm{data}}$ to extrapolate from CR (low-$\Delta\Phi$) to SR (high-$\Delta\Phi$). This transfer factor $R_{\mathrm{CS}}^{\mathrm{data}}$ is determined from data in the low-n_{jet} SB regions, separately for each L_{T}, H_{T}, and n_b search region:

$$R_{\mathrm{CS}}^{\mathrm{data}} = \frac{N_{\mathrm{data}}^{\mathrm{SB}}(\mathrm{SR})}{N_{\mathrm{data}}^{\mathrm{SB}}(\mathrm{CR}) - N_{\mathrm{QCD\,pred}}^{\mathrm{SB}}(\mathrm{CR})}, \tag{1}$$

where $N_{\mathrm{data}}^{\mathrm{SB}}(\mathrm{SR})$ is the number of events in the low-n_{jet} SB high-$\Delta\Phi$ signal region, $N_{\mathrm{data}}^{\mathrm{SB}}(\mathrm{CR})$ the number of events in the low-n_{jet} SB low-$\Delta\Phi$ control region, and $N_{\mathrm{QCD\,pred}}^{\mathrm{SB}}(\mathrm{CR})$ the predicted number of QCD multijet events in the SB CR.

In the regions with one b tag and four or five jets, about 80% $t\bar{t}+$ jets events and 15%–20% $W+$ jets and single top quark events are expected, while in all other multi-b regions, $t\bar{t}$ background is completely dominant. Because only a single SM background dominates in the multi-b analysis, just one R_{CS} factor is needed for each L_{T}, H_{T}, and n_b range. In the zero-b bins, the contributions from $W+$ jets and $t\bar{t}+$ jets are roughly equal. Here, an extension of the multi-b strategy is employed, which takes into account differences in the R_{CS} values for these two backgrounds.

An overview of the (n_{jet}, n_b) regions used in this analysis, as discussed in detail in Secs. V A–V C, is given in Table III.

TABLE II. Search regions and the corresponding minimum $\Delta\Phi$ requirements.

n_{jet}	n_b	L_{T}[GeV]	H_{T}[GeV]	$\Delta\Phi$ [rad]
	$=1$, $=2$, ≥ 3	[250, 350]	[500, 750], ≥ 750	1.0
		[350, 450]	[500, 750], ≥ 750	0.75
[6,8]	$=1$, ≥ 2	[450, 600]	[500, 1250], ≥ 1250	
		≥ 600	[500, 1250], ≥ 1250	0.5
	$=1$, $=2$	[250, 350]	[500, 1250], ≥ 1250	1.0
	≥ 3		≥ 500	
≥ 9	$=1$, $=2$, ≥ 3	[350, 450]	≥ 500	0.75
	$=1$, ≥ 2	≥ 450	≥ 500	
5	0	[250, 350], [350, 450], ≥ 450	≥ 500	1.0
[6,7]		[250, 350], [350, 450]	[500, 750], ≥ 750	
		≥ 450	[500, 1000], ≥ 1000	0.75
≥ 8		[250, 350]	[500, 750], ≥ 750	1.0
		[350, 450], ≥ 450	≥ 500	0.75

A. Estimate of the leading backgrounds for $n_b \geq 1$

For the multi-b analysis, the SB region, where R_{CS} is determined, is required to have four or five jets, while the MB region must satisfy $n_{\text{jet}} \in [6-8]$ or $n_{\text{jet}} \geq 9$. To account for possible differences in this extrapolation from SB to MB as a function of jet multiplicity, we apply multiplicative correction factors κ_{EW}, determined from simulation. The predicted number $N^{\text{MB}}_{\text{pred}}(\text{SR})$ of background events in each MB SR is then given by

$$N^{\text{MB}}_{\text{pred}}(\text{SR}) = R^{\text{data}}_{\text{CS}} \kappa_{\text{EW}} [N^{\text{MB}}_{\text{data}}(\text{CR}) - N^{\text{MB}}_{\text{QCD pred}}(\text{CR})], \quad (2)$$

with

$$\kappa_{\text{EW}} = \frac{R^{\text{MC}}_{\text{CS}}(\text{MB}, \text{EW})}{R^{\text{MC}}_{\text{CS}}(\text{SB}, \text{EW})}. \quad (3)$$

Here $R^{\text{data}}_{\text{CS}}$ is determined from Eq. (1), $N^{\text{MB}}_{\text{data}}(\text{CR})$ is the number of data events in the CR of the MB region, and $N^{\text{MB}}_{\text{QCD pred}}(\text{CR})$ is the predicted number of multijet events in the MB. The label EW refers to all backgrounds other than multijets. The residual difference of the values of R_{CS} between the SB and MB regions is evaluated in simulation as the correction factor κ_{EW} given by Eq. (3), where $R^{\text{MC}}_{\text{CS}}(\text{MB}, \text{EW})$ is the R_{CS} in a search MB region from simulation and $R^{\text{MC}}_{\text{CS}}(\text{SB}, \text{EW})$ is the R_{CS} in the corresponding SB region in simulation for the EW background.

The κ_{EW} factor is determined separately for each search bin, except that an overall κ_{EW} factor is applied for the $n_b \geq 2$ search bins with the same H_{T} and L_{T}, since the κ_{EW} factors are found to be nearly independent of n_b. Similarly, R_{CS} at very high H_{T} is determined jointly across all three n_b bins to increase the number of events, as the overall uncertainty of the background prediction for several of the search bins is dominated by the statistical uncertainty of the yield in the SR of the side band.

The value of R_{CS} for the total background is equal to the sum of the R_{CS} values of each background component, weighted with the relative contributions of the components. For semileptonic $t\bar{t}$ and $W+$jets events, which contain both one neutrino from the hard interaction, R_{CS} typically has values of 0.01 to 0.04, depending on the search bin. In events with more than one neutrino, e.g. in $t\bar{t}$ events in which both W bosons decay leptonically, R_{CS} is higher, with values of around 0.5. This is visible in Fig. 3, where at high $\Delta\Phi$ a large fraction of events is due to dileptonic $t\bar{t}+$jets background, while the low-$\Delta\Phi$ region is dominated by events with only one neutrino. A larger R_{CS} is also expected for events with three neutrinos, such as $t\bar{t}$Z, when the $t\bar{t}$ system decays semileptonically and the Z boson decays to

TABLE III. Overview of the definitions of sideband and main band regions. For the multijet (QCD) fit, the electron (e) sample is used, while for the determination (det.) of $R_{\text{CS}}(\text{W}^{\pm})$, the muon ($\mu$) sample is used. Empty cells are not used in this analysis.

Analysis	Multi-b analysis		Zero-b analysis	
	$n_b = 0$	$n_b \geq 1$	$n_b = 0$	$n_b = 1$
$n_{\text{jet}} = 3$	QCD bkg. fit (e sample)	R_{CS} det.	$R_{\text{CS}}(\text{W}^{\pm})$ det. (μ sample),	
$n_{\text{jet}} = 4$	QCD bkg. fit (e sample)	R_{CS} det.	QCD bkg. fit (e sample)	$R_{\text{CS}}(t\bar{t}+\text{jets})$ det.
$n_{\text{jet}} = 5$			MB	$R_{\text{CS}}(t\bar{t}+\text{jets})$ det.
$n_{\text{jet}} \geq 6$		MB	MB	

two neutrinos. The influence of these latter processes is small since their relative contribution to the background is minor. Most of the SRs with six or more jets are dominated by semileptonic $t\bar{t}$ events, and therefore this background dominates the total R_{CS} value of ≈ 0.05. As the R_{CS} for dileptonic $t\bar{t}$ events is an order of magnitude larger than for semileptonic $t\bar{t}$ events, a slight change in composition in the CR from low- to high-n_{jet} multiplicity translates into κ_{EW} slightly different from unity. This change in the dileptonic $t\bar{t}$ contribution is accounted for by assigning an uncertainty on the n_{jet} extrapolation based on a dileptonic control sample in data, as discussed in Sec. VI.

B. Estimate of the leading backgrounds for $n_b = 0$

For search bins in which b-tagged jets are vetoed, the background contributions from $W +$ jets and $t\bar{t} +$ jets events are estimated by applying the R_{CS} method separately to each of the two components. This strategy implies the use of two sidebands enriched in $W +$ jets and $t\bar{t} +$ jets events, respectively. We write the total background in each search region $n_{\mathrm{jet}}^{\mathrm{SR}}$ (with a $\Delta\Phi$ requirement as shown in Table II) as

$$N_{\mathrm{MB}}^{\mathrm{SR}}(0b) = N_{W}^{\mathrm{SR}}(0b) + N_{t\bar{t}}^{\mathrm{SR}}(0b) + N_{\mathrm{other}}^{\mathrm{SR(MC)}}(0b), \quad (4)$$

where the predicted yields of $W +$ jets and $t\bar{t} +$ jets background events are denoted by N_{W}^{SR} and $N_{t\bar{t}}^{\mathrm{SR}}$, respectively. Additional backgrounds from rare sources are estimated from simulation and denoted by $N_{\mathrm{other}}^{\mathrm{SR(MC)}}$.

The expected number of events for each of the background components can be described by

$$N_{i}^{\mathrm{SR}} = N_{\mathrm{data}}^{\mathrm{CR}} f_i R_{\mathrm{CS}}^{i}, \quad \text{with} \quad i = [W, t\bar{t}], \quad (5)$$

where $N_{\mathrm{data}}^{\mathrm{CR}}$ is the total number of events in the CR of the MB region and f_i is the relative yield of component i. The relative contributions of the two components are determined by a fit of templates obtained from simulation to the n_b multiplicity distribution in the CR of the MB region. The contribution of the QCD multijet background in the CR is fixed to the yield estimated from data as described in Sec. V C. The contribution of other rare background components is obtained from simulation as well, as is done in the SR. Uncertainties in these two components are propagated as systematic uncertainties to the final prediction. Examples of these fits are shown in Fig. 4.

The two R_{CS} values, for $W +$ jets and $t\bar{t} +$ jets, are measured in two different low-n_{jet} SB regions. For the $t\bar{t} +$ jets estimate, a sideband with the requirements $4 \le n_{\mathrm{jet}} \le 5$ and $n_b = 1$ is used. The value of $R_{\mathrm{CS}}^{t\bar{t}}$ is then given by

$$R_{\mathrm{CS}}^{t\bar{t}}(0b, n_{\mathrm{jet}}^{\mathrm{SR}}) = \kappa_b \kappa_{t\bar{t}} R_{\mathrm{CS}}^{\mathrm{data}}(1b, n_{\mathrm{jet}} \in [4, 5]). \quad (6)$$

The correction factors κ_b and $\kappa_{t\bar{t}}$ are determined from simulation. The factor κ_b corrects for a potential difference of $R_{\mathrm{CS}}^{t\bar{t}}$ between samples with zero or one b jet and for the small contributions of backgrounds other than $t\bar{t} +$ jets or QCD multijet events. The factor $\kappa_{t\bar{t}}$ corrects for a residual dependence of $R_{\mathrm{CS}}^{t\bar{t}}$ on n_{jet}, in analogy to the κ_{EW} factor defined in Sec. V A. Both values, κ_b and $\kappa_{t\bar{t}}$, are close to unity, and statistical uncertainties from the simulation are propagated to the predicted yields.

Similarly, the $W +$ jets contribution is estimated using R_{CS} values from a sideband with $3 \le n_{\mathrm{jet}} \le 4$ and $n_b = 0$. With respect to the SB used for the estimate of $R_{\mathrm{CS}}^{t\bar{t}}$, a lower jet multiplicity is chosen in order to limit the contamination from $t\bar{t} +$ jets events. Only the muon channel is used since it has a negligible contamination from QCD multijet events, contrary to the electron channel. A systematic uncertainty is derived from simulation to cover potential differences between the μ and the combined e and μ samples. The

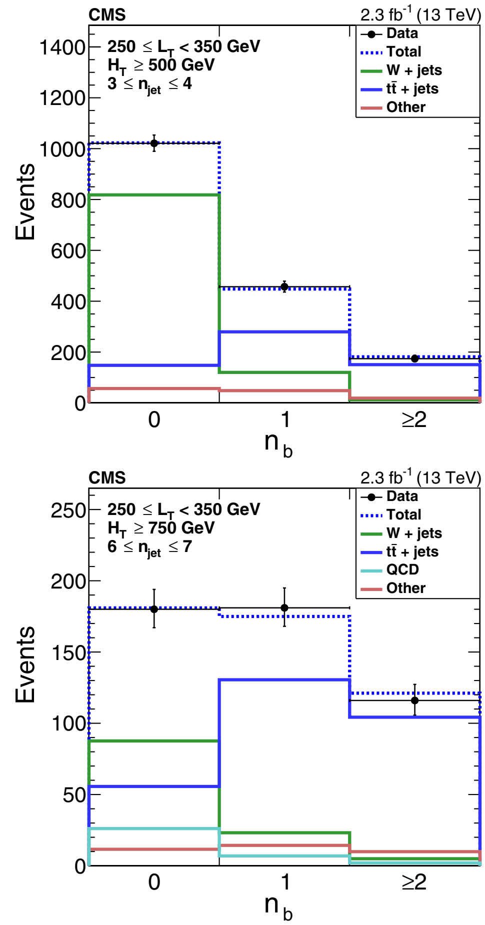

FIG. 4. Fits to the n_b multiplicity for control regions in (left) $3 \le n_{\mathrm{jet}} \le 4$ ($250 \le L_{\mathrm{T}} < 350$ GeV, $H_{\mathrm{T}} \ge 500$ GeV, $\Delta\Phi < 1$) and (right) $6 \le n_{\mathrm{jet}} \le 7$ ($250 \le L_{\mathrm{T}} < 350$ GeV, $H_{\mathrm{T}} \ge 750$ GeV, $\Delta\Phi < 1$) in data (muon channel). The solid lines represent the templates scaled according to the fit result (blue for $t\bar{t} +$ jets, green for $W +$ jets, turquoise for QCD, and red for the remaining backgrounds), the dashed line shows the sum after the fit, and the points with error bars represent data.

value of R_{CS}^{W} is given by

$$R_{\mathrm{CS}}^{W}(0b, n_{\mathrm{jet}}^{\mathrm{SR}}) = \kappa_W R_{\mathrm{CS}}^{\mathrm{data(corr)}}(0b, n_{\mathrm{jet}} \in [3,4]). \quad (7)$$

Again, the factor κ_W corrects for a residual dependence of R_{CS}^{W} on the jet multiplicity. The raw value of $R_{\mathrm{CS}}^{\mathrm{data}}$ measured in the SB has to be corrected for the contamination of $t\bar{t}+$jets events. The $t\bar{t}+$jets yields are subtracted in the numerator and denominator according to

$$R_{\mathrm{CS}}^{\mathrm{data(corr)}}(0b, n_{\mathrm{jet}} \in [3,4]) = \frac{N_{\mathrm{data}}^{\mathrm{SR}} - R_{\mathrm{CS}}^{t\bar{t},\mathrm{MC}} f_{t\bar{t}} N_{\mathrm{data}}^{\mathrm{CR}}}{(1-f_{t\bar{t}})N_{\mathrm{data}}^{\mathrm{CR}}}. \quad (8)$$

The event yields $N_{\mathrm{data}}^{\mathrm{CR}}$ and $N_{\mathrm{data}}^{\mathrm{SR}}$ are measured in the SB CRs and SRs. The fraction of $t\bar{t}+$jets events $f_{t\bar{t}}$ is again obtained by a fit to the n_b multiplicity in the SB CR. The R_{CS} value for $t\bar{t}+$jets in this SB is obtained from simulation.

Systematic uncertainties are assigned to $\kappa_{t\bar{t}}$ and κ_W according to the difference between the R_{CS} values in the sideband and the result of a linear fit over the full range of n_{jet}. The uncertainties vary from 3% to 43% for $\kappa_{t\bar{t}}$ and from 1% to 49% for κ_W. The two sources are treated as being independent.

C. Estimate of the multijet background

Multijet events enter this analysis mostly when reconstructed electrons originate from misidentified jets or from photon conversion in the inner detector. This background is estimated from the yield of "antiselected" electron candidates in each region, which pass looser identification and isolation requirements, and fail the tighter criteria for selected electrons. These events are scaled by the ratio of jets and photons that pass the tight electron identification requirements to the number of antiselected electron candidates in a multijet-enriched control sample with no b-tagged jets and three or four other jets. The assumption is that this sample is devoid of genuine prompt electrons. The estimation method was introduced previously [10,52], and it relies on the L_{P} variable:

$$L_{\mathrm{P}} = \frac{p_{\mathrm{T}}^{\ell}}{p_{\mathrm{T}}^{W}} \cos(\Delta\Phi). \quad (9)$$

For the dominant SM backgrounds, $t\bar{t}+$jets and $W+$jets, the distribution of L_{P} is a well-understood consequence of the W boson polarization and falls from 0 to 1. In contrast, the distribution of L_{P} for multijet events peaks near $L_{\mathrm{P}} = 1$.

The ratio of selected to antiselected electron candidates is obtained from a fit to the L_{P} distribution in bins of L_{T}. The shape of the QCD multijet contribution used in the fit is taken from the antiselected sample, while the shape of all other contributions is taken from simulation, as the behavior due to W polarization is well understood. The ratios are found to be in the range 0.1–0.2.

In principle, the background estimation with the R_{CS} method requires knowledge of the multijet contribution in the SR and CR separately. Since the multijet background estimation is performed inclusively with respect to $\Delta\Phi$, an R_{CS} factor for multijet events is determined as well. In practice, since the resulting R_{CS} values are all found to be below 2%, the multijet contamination is negligible for the SR. Therefore, the previously described R_{CS} method takes into account only the QCD multijet contribution in the CR, as written in Eq. (1). For the muon channel, the contribution from QCD multijet background is typically of the order of 1% of the total background. To estimate this contribution, a procedure similar to the one outlined above is applied and assigned a 100% uncertainty.

VI. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties either influence κ, and thereby the predictions for the background, or modify the expected signal yield.

The main systematic uncertainty on the background arises from the extrapolation of R_{CS} from the low n_{jet} region, where it is measured, to the MB regions of higher jet multiplicities, where it is applied. Therefore, a systematic uncertainty on R_{CS} is determined in a dedicated control region with dileptonic events. The ratio of the semileptonic to dileptonic $t\bar{t}+$jets final states for different numbers of reconstructed jets is of major importance since the total R_{CS} is based on the fraction of the two channels and their corresponding R_{CS} values, which differ significantly in $t\bar{t}+$jets events. To ensure that the data are described well by simulation, a high-purity dilepton $t\bar{t}+$jets control sample is selected from the data by requiring two leptons of opposite charge. For same-flavor leptons, it is also required that the invariant mass of the lepton pair be more than 10 GeV away from the Z boson mass peak. To study the behavior of the dileptonic events in the single-lepton selection, one of the two leptons is removed from the event. Since these "lost leptons" are principally from $\tau \to$ hadrons $+ \nu$ decays, we replace the removed lepton by a jet with $2/3$ of the original lepton's p_{T} to accommodate for the missing energy due to the neutrino from the τ decay, and we recalculate the L_{T}, $\Delta\Phi$, and H_{T} values of the now "single-lepton" event. In order to maximize the number of events, no $\Delta\Phi$ requirement is applied, and all events are used twice, with each reconstructed lepton being considered as the lost lepton. We refer to the samples produced using this procedure as the dilepton CRs.

A key test is performed by comparing the jet multiplicity distribution in the sample resulting from single-lepton baseline selection (excluding the SRs) with the corresponding simulated event sample, and by comparing the dilepton CRs with the corresponding simulated event sample. Both comparisons show the same trend, a slight overprediction by simulation of the rate of high jet multiplicity events. The ratio of event yields in data-to-simulation is computed for each comparison, and the two ratios are then divided to see whether the behavior in data relative to simulation is the same in both pairs of samples. This double ratio is consistent with unity within statistical uncertainty. The systematic uncertainty in the description of the n_{jet} distribution in simulation is determined from this double ratio and is mainly due to the statistical uncertainty of the data samples, which is within 8%–40%, and therefore larger than the observed slope of the double ratio vs n_{jet}.

The remaining uncertainties are smaller than the one from the dileptonic $t\bar{t}+$jets fraction. In particular, the applied jet energy scale (JES) factors are varied up and down according to their uncertainty [25] as a function of jet p_{T} and η, and these changes are propagated to $E_{\mathrm{T}}^{\mathrm{miss}}$. The scale factors applied to the efficiencies for the identification of b-quark jets and for the misidentification of c-quark, light-quark, or gluon jets are also varied up and down according to their uncertainties [34]. Uncertainties for the efficiency of lepton reconstruction and identification are handled in the same way. For pileup, a 5% uncertainty in the inelastic cross section [53] is used to obtain its impact on the uncertainty in the pileup. In a few bins with a low number of simulated events, the reweighting leads to a large uncertainty. All these uncertainties apply to both the background prediction and the signal yield. The luminosity is measured with the pixel cluster counting method, and the absolute luminosity scale calibration is derived from an analysis of van der Meer scans performed in August 2015, resulting in an uncertainty of 2.7% [54].

The $W+$jets and $t\bar{t}+$jets cross sections are changed by 30% [55] to cover possible biases in the estimation of the background composition in terms of $W+$jets vs $t\bar{t}+$jets events, which would lead to a slight change in the κ value. These changes have only a small impact on the zero-b analysis, where the relative fraction of the two processes is determined from a fit. Also, the following changes in the simulation are performed, with differences between the values of κ in the reweighted and original samples defining the uncertainties. Motivated by measurements at $\sqrt{s}=8$ TeV, simulated $t\bar{t}+$jets events are reweighted by a factor $\sqrt{F(p_{\mathrm{T}}^{t})F(p_{\mathrm{T}}^{\bar{t}})}$, with $F(p_{\mathrm{T}}^{t})=\min(0.5,\exp(0.156-0.00137p_{\mathrm{T}}^{t}))$, to improve the modeling of the top quark p_{T} spectrum [56]. The reweighting preserves the normalization of the sample, and the difference relative to the results obtained with the unweighted sample is assigned as a systematic uncertainty. The polarization of W bosons is varied by reweighting events by the factor $w(\cos\theta^{*})=1+\alpha(1-\cos\theta^{*})^{2}$, where θ^{*} is the angle between the charged lepton and W boson in the W boson rest frame. In $W+$jets events, we take α to be 0.1, guided by the theoretical uncertainty and measurements found in Refs. [52,57–59]. For $t\bar{t}+$jets events, we take $\alpha=0.05$. For $W+$jets events, where the initial state can have different polarizations for W^{+} vs W^{-} bosons, we take, as the uncertainty, the larger change in κ resulting from reweighting only the W^{+} bosons in the sample, and from reweighting all W bosons. The $t\bar{t}$V cross section is varied by 100%. The systematic uncertainty in the multijet estimation depends on n_{jet} and n_{b}, and ranges from 25% to 100%.

For the zero-b analysis, an additional systematic uncertainty is applied, based on linear fits of R_{CS} as a function of n_{jet} as described in Sec. V B, and a 50% cross-section uncertainty is used for all backgrounds other than $W+$jets, $t\bar{t}+$jets, $t\bar{t}$V, and multijets.

For the signal, an uncertainty in initial-state radiation (ISR) is applied, based on the p_{T} of the gluino-gluino system, which corresponds to a 15% uncertainty at p_{T} between 400 and 600 GeV, and 30% at larger p_{T}. This

TABLE IV. Summary of systematic uncertainties in the total background prediction for the multi-b and for the zero-b analyses.

Source	Uncertainty for multi-b [%]	Uncertainty for zero-b [%]
Dilepton control sample	5.8–20	7.5–40
JES	0.2–11	0.6–8.2
Tagging of b-jets	0.1–17	1.4–4.5
$\sigma(W+\mathrm{jets})$	0.3–6.4	<2.5
W polarization	0.1–2	0.2–3.4
$\sigma(t\bar{t}\ \mathrm{V})$	0.1–5	0.2–2.9
Reweighting of top quark p_{T}	0.1–10	0.1–7.1
Pileup	0.3–23	0.1–10
Fit to R_{CS} (n_{jet}) ($W+$jets and $t\bar{t}+$jets)	---	3.3–35
Total	8.0–28	10–54
Statistical uncertainty in MC events	3.0–30	8.2–48

TABLE V. Summary of the systematic uncertainties and their average effect on the yields of the benchmark signals. The values are very similar for the multi-b and the zero-b analyses, and are usually larger for compressed scenarios, where the mass difference between the gluino and the neutralino is small.

Source	Uncertainty [%]
Trigger	1
Pileup	5
Lepton efficiency	5
Luminosity	2.7
ISR	3–20
Tagging of b-jets (heavy flavors)	6–10
Tagging of b-jets (light flavors)	2–3
JES	3–10
Factorization/renormalization scale	<3
Total	12–26

uncertainty is based on measurements of ISR in $Z+$jets and $t\bar{t}+$jets events [16,60]. The factorization and renormalization scales are each changed by a factor of 0.5 and 2. Uncertainties in the signal cross section are also taken into account.

The impact of the systematic uncertainties in the total background prediction for the multi-b and zero-b analyses is summarized in Table IV. While the systematic uncertainty is determined for each signal point, the uncertainties typical for most signals are summarized, for illustration, in Table V.

VII. RESULTS AND INTERPRETATION

The backgrounds for all SRs are determined, as described previously, in different SB regions with lower jet or b-jet multiplicities. The results of the background prediction and the observed data are shown in Table VI and Fig. 5 for the multi-b events. In this figure, the outline of the filled histogram represents the total number of background events from the prediction. For illustration, the relative amount of $t\bar{t}+$jets, $W+$jets, and of other backgrounds is shown as well, based on the fractions estimated in simulation. Table VII and Fig. 6 show the results for the zero-b events. Here, the filled histogram represents the predictions from data for $t\bar{t}+$jets and $W+$jets events, and for the remaining backgrounds, where the latter include the multijet prediction determined from data and rare backgrounds taken from simulation. The data agree with SM expectations, and no excess is observed.

To set limits, separate likelihood functions, one for the multi-b analysis and one for the zero-b analysis, are constructed from the Poisson probability functions for all four data regions (the CRs and SRs in the SB as well in the MB) to determine the background in the MB SR. In addition, the κ values from simulation are included to correct any residual differences between the SB and MB regions, with uncertainties incorporated through log-normal constraints. The estimated contribution from multijet events in the two CRs is also included. A possible signal contamination is taken into account by including signal terms in the fit for both the sideband and the control

TABLE VI. Summary of the results in the multi-b search.

n_{jet}	L_{T} [GeV]	H_{T} [GeV]	n_b	Bin name	Expected signal T1tttt $m_{\tilde{g}}/m_{\tilde{\chi}^0}$ [TeV] (1.5,0.1)	(1.2,0.8)	Predicted background	Observed
[6, 8]	[250, 350]	[500, 750]	= 1	LT1, HT0, NB1	<0.01	0.41 ±0.02	9.0 ±2.1	9
			= 2	LT1, HT0, NB2	<0.01	0.67 ±0.03	8.4 ±2.1	2
			≥3	LT1, HT0, NB3i	<0.01	0.67 ±0.03	1.23 ±0.39	1
		≥750	= 1	LT1, HT1i, NB1	0.03 ±0.00	0.15 ±0.01	9.8 ±3.0	14
			= 2	LT1, HT1i, NB2	0.07 ±0.00	0.27 ±0.02	7.1 ±2.7	6
			≥3	LT1, HT1i, NB3i	0.07 ±0.00	0.22 ±0.02	0.85 ±0.40	1
	[350, 450]	[500, 750]	= 1	LT2, HT0, NB1	<0.01	0.19 ±0.02	2.42 ±0.96	4
			= 2	LT2, HT0, NB2	0.01 ±0.00	0.28 ±0.02	0.89 ±0.56	2
			≥3	LT2, HT0, NB3i	0.01 ±0.00	0.24 ±0.02	0.10 ±0.08	0
		≥750	= 1	LT2, HT1i, NB1	0.08 ±0.00	0.16 ±0.01	3.6 ±1.8	5
			= 2	LT2, HT1i, NB2	0.12 ±0.01	0.24 ±0.02	3.8 ±1.9	2
			≥3	LT2, HT1i, NB3i	0.13 ±0.01	0.19 ±0.01	0.54 ±0.35	0
	[450, 600]	[500, 1250]	= 1	LT3, HT01, NB1	0.07 ±0.00	0.18 ±0.02	4.1 ±1.6	1
			≥2	LT3, HT01, NB2i	0.19 ±0.01	0.42 ±0.02	4.0 ±2.1	0
		≥1250	= 1	LT3, HT2i, NB1	0.08 ±0.00	0.02 ±0.00	0.62 ±0.69	1
			≥2	LT3, HT2i, NB2i	0.29 ±0.01	0.08 ±0.01	0.59 ±0.66	1
	≥600	[500, 1250]	= 1	LT4i, HT01, NB1	0.18 ±0.01	0.05 ±0.01	0.60 ±0.51	0
			≥2	LT4i, HT01, NB2i	0.57 ±0.01	0.16 ±0.01	0.25 ±0.39	0
		≥1250	= 1	LT4i, HT2i, NB1	0.26 ±0.01	0.07 ±0.01	0.20 ±0.27	0
			≥2	LT4i, HT2i, NB2i	0.95 ±0.02	0.16 ±0.01	0.42 ±0.53	0
≥9	[250, 350]	[500, 1250]	= 1	LT1, HT01, NB1	0.01 ±0.00	0.22 ±0.02	0.52 ±0.19	0
			= 2	LT1, HT01, NB2	0.01 ±0.00	0.55 ±0.03	0.23 ±0.14	0
		≥500	≥3	LT1, HT0i, NB3i	0.08 ±0.00	0.74 ±0.03	0.32 ±0.16	0
		≥1250	= 1	LT1, HT2i, NB1	0.02 ±0.00	0.02 ±0.01	0.17 ±0.16	0
			= 2	LT1, HT2i, NB2	0.04 ±0.00	0.05 ±0.01	0.24 ±0.31	0
	[350, 450]	≥500	= 1	LT2, HT0i, NB1	0.04 ±0.00	0.23 ±0.02	0.28 ±0.14	0
			= 2	LT2, HT0i, NB2	0.10 ±0.01	0.41 ±0.02	0.05 ±0.06	1
			≥3	LT2, HT0i, NB3i	0.12 ±0.01	0.51 ±0.02	0.04 ±0.05	0
	≥450	≥500	= 1	LT3i, HT0i, NB1	0.29 ±0.01	0.23 ±0.02	0.31 ±0.20	0
			≥2	LT3i, HT0i, NB2i	1.42 ±0.02	0.99 ±0.03	0.15 ±0.13	0

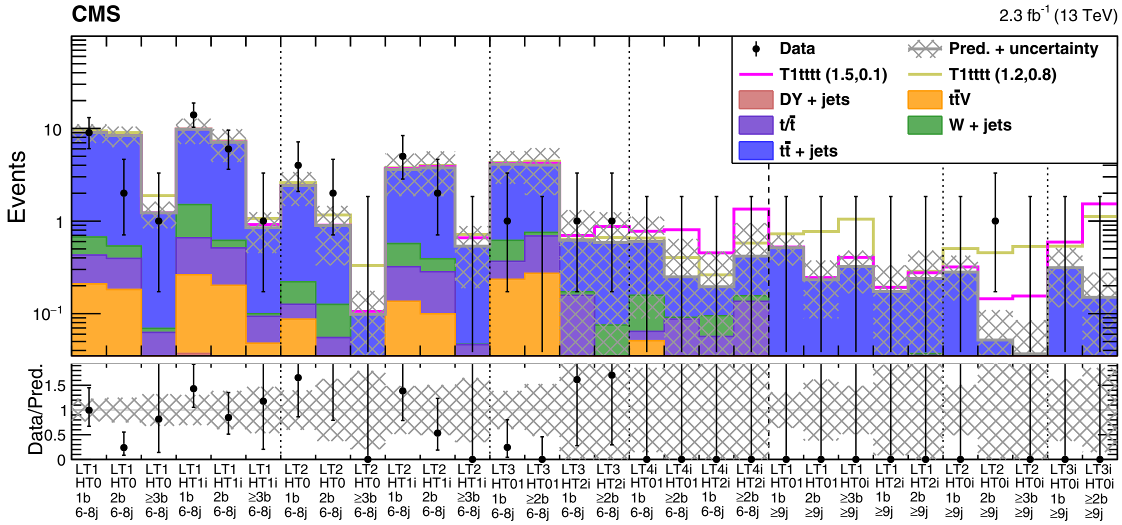

FIG. 5. Multi-b search: Comparison of observed and predicted background event yields in the 30 search regions. Upper panel: The data are shown by black points with error bars, while the total SM background predictions are shown by a grey line, with a hatched region representing its uncertainty. For illustration, the relative fraction of the different SM background contributions, as determined from simulation, is shown by the stacked, colored histograms, whose total normalization is set by the total background yields obtained from the control samples in the data. The expected event yields for two T1tttt SUSY benchmark models are shown by open histograms, each of which is shown stacked on the total background prediction. The vertical dashed and dotted lines separate different $n_{\rm jet}$ and $L_{\rm T}$ bins, respectively, as indicated by the x-axis labels. Lower panel: The ratio of the yield observed in data to the predicted background yield is shown for each bin. The error bars on the data points indicate the combined statistical and systematic uncertainty in the ratio. The grey hatched region indicates the uncertainty on the ratio that arises from the uncertainty on the background prediction.

regions. For the zero-b analysis, the relative contributions of $W+$jets and $t\bar{t}+$jets events as determined in the fits to the n_b distribution in the CRs are treated as external measurements. The correlation between the $W+$jets and $t\bar{t}+$jets yields introduced by these fits is taken into account. A profile likelihood ratio in the asymptotic approximation [61] is used as the test statistic. Limits are then calculated at the 95% confidence level (CL) using the asymptotic CL$_s$ criterion [62,63].

The cross-section limits obtained for the T1tttt model using the multi-b analysis, and for the T5qqqqWW model using the zero-b analysis, are shown in Fig. 7 as a function of $m(\tilde{g})$ and $m(\tilde{\chi}_1^0)$, assuming branching fractions of 100% as shown in Fig. 1. Using the $\tilde{g}\tilde{g}$ pair production cross section calculated at next-to-leading order within next-to-leading-logarithmic accuracy, exclusion limits are set as a function of the $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0})$ mass hypothesis.

TABLE VII. Summary of the results of the zero-b search.

$n_{\rm jet}$	$L_{\rm T}$ [GeV]	$H_{\rm T}$ [GeV]	Bin name	Expected signal T5qqqqWW $m_{\tilde{g}}/m_{\tilde{\chi}^0}$ [TeV] (1.0,0.7)	(1.2,0.8)	(1.5,0.1)	Predicted background	Observed
5	[250, 350]	≥500	LT1, HTi	1.67 ±0.27	0.68 ±0.07	0.03 ±0.01	12.8 ±2.9	13
	[350, 450]	≥500	LT2, HTi	1.13 ±0.22	0.68 ±0.07	0.04 ±0.01	4.5 ±2.2	4
	≥450	≥500	LT3, HTi	1.48 ±0.26	0.79 ±0.08	0.51 ±0.02	3.9 ±2.0	1
[6,7]	[250, 350]	[500, 750]	LT1, HT1	3.03 ±0.36	1.06 ±0.09	<0.01	4.2 ±1.4	8
		≥750	LT1, HT23	0.92 ±0.20	0.36 ±0.05	0.08 ±0.01	4.8 ±1.6	4
	[350, 450]	[500, 750]	LT2, HT1	1.54 ±0.26	0.90 ±0.08	<0.01	1.4 ±1.1	0
		≥750	LT2, HT23	1.15 ±0.21	0.41 ±0.05	0.13 ±0.01	1.29 ±0.74	2
	≥450	[500, 1000]	LT3, HT12	1.99 ±0.29	1.83 ±0.12	0.11 ±0.01	2.25 ±0.93	0
		≥1000	LT3, HT3	1.33 ±0.23	0.55 ±0.06	1.38 ±0.04	1.5 ±1.0	2
≥8	[250, 350]	[500, 750]	LT1, HT1	0.90 ±0.20	0.26 ±0.04	<0.01	0.34 ±0.22	0
		≥750	LT1, HT23	0.85 ±0.19	0.41 ±0.05	0.06 ±0.01	1.10 ±0.61	1
	[350, 450]	≥500	LT2, HTi	1.41 ±0.23	0.75 ±0.07	0.09 ±0.01	0.45 ±0.28	0
	≥450	≥500	LT3, HTi	2.44 ±0.31	1.27 ±0.09	0.84 ±0.03	0.39 ±0.26	0

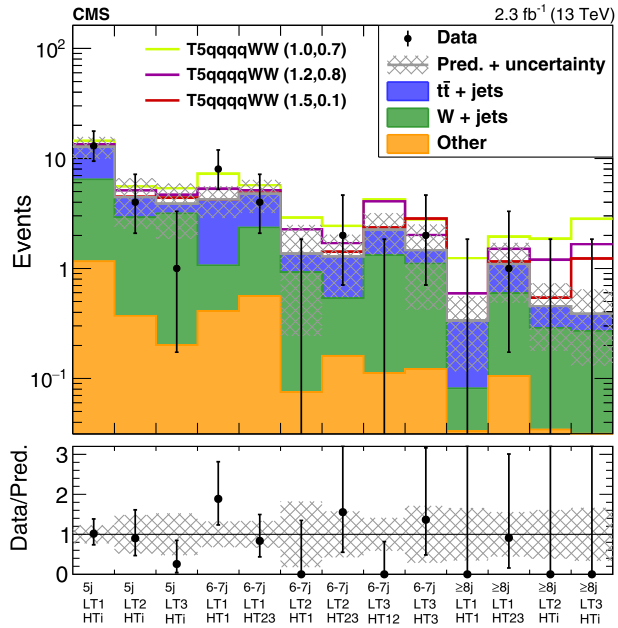

FIG. 6. Zero-b search: Observed and predicted event counts in the 13 search regions. Upper panel: The black points with error bars show the number of observed events. The filled, stacked histograms represent the predictions for $t\bar{t}$ + jets, W + jets events, and the remaining backgrounds. The uncertainty on the background prediction is shown as a grey hatched region. The expected yields from three T5qqqqWW model points, added to the SM background, are shown as solid lines. Lower panel: The ratio of the yield observed in data to the predicted background yield is shown for each bin. The error bars on the data points indicate the combined statistical and systematic uncertainty in the ratio. The grey hatched region indicates the uncertainty on the ratio that arises from the uncertainty on the background prediction.

VIII. SUMMARY

A search for supersymmetry has been performed with 2.3 fb^{-1} of proton-proton collision data recorded by the CMS experiment at $\sqrt{s} = 13$ TeV in 2015. The data are analyzed in several exclusive categories, differing in the number of jets and b-tagged jets, the scalar sum of all jet transverse momenta, and the scalar sum of the missing transverse momentum and the transverse momentum of the lepton. The main background is significantly reduced by requiring a large azimuthal angle between the directions of the momenta of the lepton and of the reconstructed W boson. No significant excess is observed, and the results are interpreted in terms of two simplified models that describe gluino pair production.

For the simplified model T1tttt, in which each gluino decays through an off-shell top squark to a $t\bar{t}$ pair and the lightest neutralino, gluino masses up to 1.6 TeV are excluded for neutralino masses below 600 GeV. Neutralino masses below 850 GeV can be excluded for a gluino mass up to 1.4 TeV. Similar to Ref. [16], these results extend the limits obtained from the 8 TeV searches [13–15] by about 250 GeV.

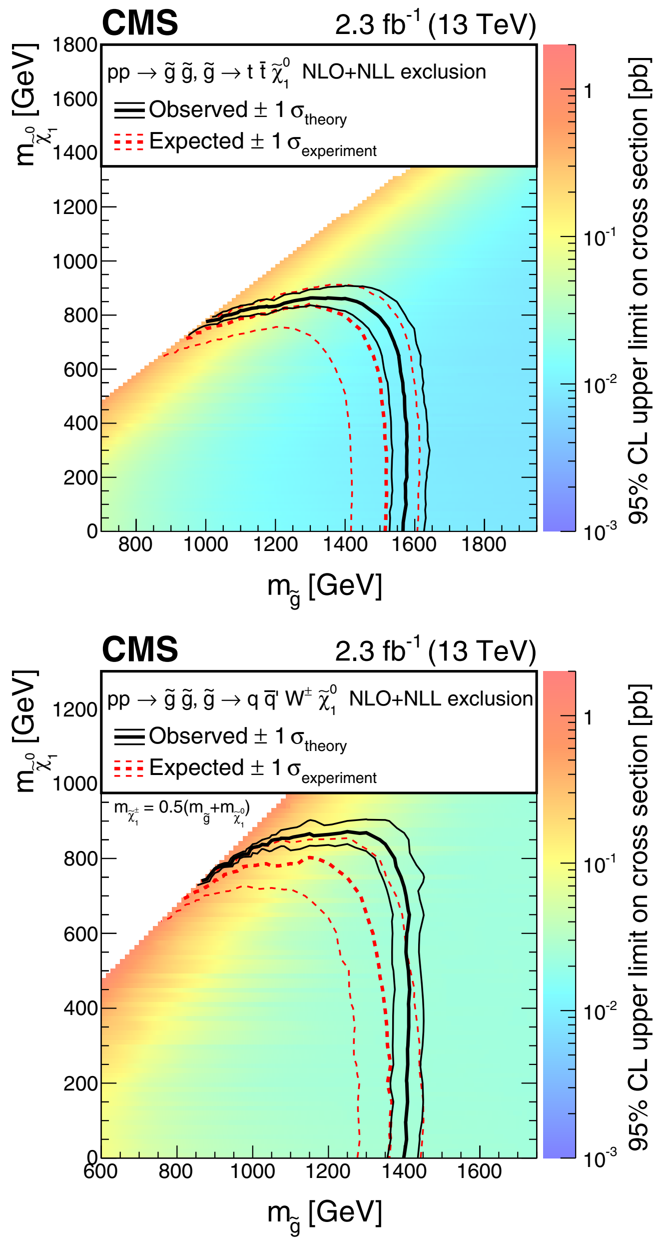

FIG. 7. Cross-section limits at a 95% C.L. for the (left) T1tttt and (right) T5qqqqWW models, as a function of the gluino and LSP masses. In T5qqqqWW, the pair-produced gluinos each decay to a quark-antiquark pair of the first or second generation ($q\bar{q}$), and a chargino ($\tilde{\chi}_1^{\pm}$) with its mass taken to be $m_{\tilde{\chi}_1^{\pm}} = 0.5(m_{\tilde{g}} + m_{\tilde{\chi}_1^0})$. The solid black (dashed red) lines correspond to the observed (expected) mass limits, with the thicker lines representing the central values and the thinner lines representing the $\pm 1\sigma$ uncertainty bands related to the theoretical (experimental) uncertainties.

The second simplified model T5qqqqWW also contains gluino pair production, with the gluinos decaying to first or second generation squarks and a chargino, which then decays to a W boson and the lightest neutralino. The chargino mass in this decay chain is taken to be $m_{\tilde{\chi}_1^\pm} = 0.5(m_{\tilde{g}} + m_{\tilde{\chi}_1^0})$. In this model, gluino masses below 1.4 TeV are excluded for neutralino masses below 700 GeV. For a gluino mass of 1.3 TeV, neutralinos with masses up to 850 GeV can be excluded. These results improve existing limits [17] on the neutralino mass in this channel for gluino masses between 900 GeV and 1.4 TeV.

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Fan,[34] J. Fay,[34] S. Gascon,[34] M. Gouzevitch,[34] G. Grenier,[34] B. Ille,[34] F. Lagarde,[34] I. B. Laktineh,[34] M. Lethuillier,[34] L. Mirabito,[34] A. L. Pequegnot,[34] S. Perries,[34] A. Popov,[34,n] D. Sabes,[34] V. Sordini,[34] M. Vander Donckt,[34] P. Verdier,[34] S. Viret,[34] T. Toriashvili,[35,o] Z. Tsamalaidze,[36,i] C. Autermann,[37] S. Beranek,[37] L. Feld,[37] A. Heister,[37] M. K. Kiesel,[37] K. Klein,[37] M. Lipinski,[37] A. Ostapchuk,[37] M. Preuten,[37] F. Raupach,[37] S. Schael,[37] C. Schomakers,[37] J. F. Schulte,[37] J. Schulz,[37] T. Verlage,[37] H. Weber,[37] V. Zhukov,[37,n] M. Brodski,[38] E. Dietz-Laursonn,[38] D. Duchardt,[38] M. Endres,[38] M. Erdmann,[38] S. Erdweg,[38] T. Esch,[38] R. Fischer,[38] A. Güth,[38] M. Hamer,[38] T. Hebbeker,[38] C. Heidemann,[38] K. Hoepfner,[38] S. Knutzen,[38] M. Merschmeyer,[38] A. Meyer,[38] P. Millet,[38] S. Mukherjee,[38] M. Olschewski,[38] K. Padeken,[38] T. Pook,[38] M. Radziej,[38] H. Reithler,[38] M. Rieger,[38] F. Scheuch,[38] L. Sonnenschein,[38] D. Teyssier,[38] S. Thüer,[38] V. Cherepanov,[39] G. Flügge,[39] W. Haj Ahmad,[39] F. Hoehle,[39] B. Kargoll,[39] T. Kress,[39] A. Künsken,[39] J. Lingemann,[39] A. Nehrkorn,[39] A. Nowack,[39] I. M. Nugent,[39] C. Pistone,[39] O. Pooth,[39] A. Stahl,[39,m] M. Aldaya Martin,[40] C. Asawatangtrakuldee,[40] K. Beernaert,[40] O. Behnke,[40] U. Behrens,[40] A. A. Bin Anuar,[40] K. Borras,[40,p] A. Campbell,[40] P. Connor,[40] C. Contreras-Campana,[40] F. Costanza,[40] C. Diez Pardos,[40] G. Dolinska,[40] G. Eckerlin,[40] D. Eckstein,[40] E. Eren,[40] E. Gallo,[40,q] J. Garay Garcia,[40] A. Geiser,[40] A. Gizhko,[40] J. M. Grados Luyando,[40] P. Gunnellini,[40] A. Harb,[40] J. Hauk,[40] M. Hempel,[40,r] H. Jung,[40] A. Kalogeropoulos,[40] O. Karacheban,[40,r] M. Kasemann,[40] J. Keaveney,[40] J. Kieseler,[40] C. Kleinwort,[40] I. Korol,[40] D. Krücker,[40] W. Lange,[40] A. Lelek,[40] J. Leonard,[40] K. Lipka,[40] A. Lobanov,[40] W. Lohmann,[40,r] R. Mankel,[40] I.-A. Melzer-Pellmann,[40] A. B. Meyer,[40] G. Mittag,[40] J. Mnich,[40] A. Mussgiller,[40] E. Ntomari,[40] D. Pitzl,[40] R. Placakyte,[40] A. Raspereza,[40] B. Roland,[40] M. Ö. Sahin,[40] P. Saxena,[40] T. Schoerner-Sadenius,[40] C. Seitz,[40] S. Spannagel,[40] N. Stefaniuk,[40] K. D. Trippkewitz,[40] G. P. Van Onsem,[40] R. Walsh,[40] C. Wissing,[40] V. Blobel,[41] M. Centis Vignali,[41] A. R. Draeger,[41] T. Dreyer,[41] E. Garutti,[41] D. Gonzalez,[41] J. Haller,[41] M. Hoffmann,[41] A. Junkes,[41] R. Klanner,[41] R. Kogler,[41] N. Kovalchuk,[41] T. Lapsien,[41] T. Lenz,[41] I. Marchesini,[41] D. Marconi,[41] M. Meyer,[41] M. Niedziela,[41] D. Nowatschin,[41] F. Pantaleo,[41,m] T. Peiffer,[41] A. Perieanu,[41] J. Poehlsen,[41] C. Sander,[41] C. Scharf,[41] P. Schleper,[41] A. Schmidt,[41] S. Schumann,[41] J. Schwandt,[41] H. Stadie,[41] G. Steinbrück,[41] F. M. Stober,[41] M. Stöver,[41] H. Tholen,[41] D. Troendle,[41] E. Usai,[41] L. Vanelderen,[41] A. Vanhoefer,[41] B. Vormwald,[41] C. Barth,[42] C. Baus,[42] J. Berger,[42] E. Butz,[42] T. Chwalek,[42] F. Colombo,[42] W. De Boer,[42] A. Dierlamm,[42] S. Fink,[42] R. Friese,[42] M. Giffels,[42] A. Gilbert,[42] P. Goldenzweig,[42] D. Haitz,[42] F. Hartmann,[42,m] S. M. Heindl,[42] U. Husemann,[42] I. Katkov,[42,n] P. Lobelle Pardo,[42] B. Maier,[42] H. Mildner,[42] M. U. Mozer,[42] T. Müller,[42] Th. Müller,[42] M. Plagge,[42] G. Quast,[42] K. Rabbertz,[42] S. Röcker,[42] F. Roscher,[42] M. Schröder,[42] I. Shvetsov,[42] G. Sieber,[42] H. J. Simonis,[42] R. Ulrich,[42] J. Wagner-Kuhr,[42] S. Wayand,[42] M. Weber,[42] T. Weiler,[42] S. Williamson,[42] C. Wöhrmann,[42] R. Wolf,[42] G. Anagnostou,[43] G. Daskalakis,[43] T. Geralis,[43] V. A. Giakoumopoulou,[43] A. Kyriakis,[43] D. Loukas,[43] I. Topsis-Giotis,[43] A. Agapitos,[44] S. Kesisoglou,[44] A. Panagiotou,[44] N. Saoulidou,[44] E. Tziaferi,[44] I. Evangelou,[45] G. Flouris,[45] C. Foudas,[45] P. Kokkas,[45] N. Loukas,[45] N. Manthos,[45] I. Papadopoulos,[45] E. Paradas,[45] N. Filipovic,[46] G. Bencze,[47] C. Hajdu,[47] P. Hidas,[47] D. Horvath,[47,s] F. Sikler,[47] V. Veszpremi,[47] G. Vesztergombi,[47,t] A. J. Zsigmond,[47] N. Beni,[48] S. Czellar,[48] J. Karancsi,[48,u] A. Makovec,[48] J. Molnar,[48] Z. Szillasi,[48] M. Bartók,[49,t] P. Raics,[49] Z. L. Trocsanyi,[49] B. Ujvari,[49] S. Bahinipati,[50] S. Choudhury,[50,v] P. Mal,[50] K. Mandal,[50] A. Nayak,[50,w] D. K. Sahoo,[50] N. Sahoo,[50] S. K. Swain,[50] S. Bansal,[51] S. B. Beri,[51] V. Bhatnagar,[51] R. Chawla,[51] U. Bhawandeep,[51] A. K. Kalsi,[51]

A. Kaur,[51] M. Kaur,[51] R. Kumar,[51] A. Mehta,[51] M. Mittal,[51] J. B. Singh,[51] G. Walia,[51] Ashok Kumar,[52] A. Bhardwaj,[52] B. C. Choudhary,[52] R. B. Garg,[52] S. Keshri,[52] S. Malhotra,[52] M. Naimuddin,[52] N. Nishu,[52] K. Ranjan,[52] R. Sharma,[52] V. Sharma,[52] R. Bhattacharya,[53] S. Bhattacharya,[53] K. Chatterjee,[53] S. Dey,[53] S. Dutt,[53] S. Dutta,[53] S. Ghosh,[53] N. Majumdar,[53] A. Modak,[53] K. Mondal,[53] S. Mukhopadhyay,[53] S. Nandan,[53] A. Purohit,[53] A. Roy,[53] D. Roy,[53] S. Roy Chowdhury,[53] S. Sarkar,[53] M. Sharan,[53] S. Thakur,[53] P. K. Behera,[54] R. Chudasama,[55] D. Dutta,[55] V. Jha,[55] V. Kumar,[55] A. K. Mohanty,[55,m] P. K. Netrakanti,[55] L. M. Pant,[55] P. Shukla,[55] A. Topkar,[55] T. Aziz,[56] S. Dugad,[56] G. Kole,[56] B. Mahakud,[56] S. Mitra,[56] G. B. Mohanty,[56] B. Parida,[56] N. Sur,[56] B. Sutar,[56] S. Banerjee,[57] S. Bhowmik,[57,x] R. K. Dewanjee,[57] S. Ganguly,[57] M. Guchait,[57] Sa. Jain,[57] S. Kumar,[57] M. Maity,[57,x] G. Majumder,[57] K. Mazumdar,[57] T. Sarkar,[57,x] N. Wickramage,[57,y] S. Chauhan,[58] S. Dube,[58] V. Hegde,[58] A. Kapoor,[58] K. Kothekar,[58] A. Rane,[58] S. Sharma,[58] H. Behnamian,[59] S. Chenarani,[59,z] E. Eskandari Tadavani,[59] S. M. Etesami,[59,z] A. Fahim,[59,aa] M. Khakzad,[59] M. Mohammadi Najafabadi,[59] M. Naseri,[59] S. Paktinat Mehdiabadi,[59] F. Rezaei Hosseinabadi,[59] B. Safarzadeh,[59,bb] M. Zeinali,[59] M. Felcini,[60] M. Grunewald,[60] M. Abbrescia,[61a,61b] C. Calabria,[61a,61b] C. Caputo,[61a,61b] A. Colaleo,[61a] D. Creanza,[61a,61c] L. Cristella,[61a,61b] N. De Filippis,[61a,61c] M. De Palma,[61a,61b] L. Fiore,[61a] G. Iaselli,[61a,61c] G. Maggi,[61a,61c] M. Maggi,[61a] G. Miniello,[61a,61b] S. My,[61a,61b] S. Nuzzo,[61a,61b] A. Pompili,[61a,61b] G. Pugliese,[61a,61c] R. Radogna,[61a,61b] A. Ranieri,[61a] G. Selvaggi,[61a,61b] L. Silvestris,[61a,m] R. Venditti,[61a,61b] P. Verwilligen,[61a] G. Abbiendi,[62a] C. Battilana,[62a] D. Bonacorsi,[62a,62b] S. Braibant-Giacomelli,[62a,62b] L. Brigliadori,[62a,62b] R. Campanini,[62a,62b] P. Capiluppi,[62a,62b] A. Castro,[62a,62b] F. R. Cavallo,[62a] S. S. Chhibra,[62a,62b] G. Codispoti,[62a,62b] M. Cuffiani,[62a,62b] G. M. Dallavalle,[62a] F. Fabbri,[62a] A. Fanfani,[62a,62b] D. Fasanella,[62a,62b] P. Giacomelli,[62a] C. Grandi,[62a] L. Guiducci,[62a,62b] S. Marcellini,[62a] G. Masetti,[62a] A. Montanari,[62a] F. L. Navarria,[62a,62b] A. Perrotta,[62a] A. M. Rossi,[62a,62b] T. Rovelli,[62a,62b] G. P. Siroli,[62a,62b] N. Tosi,[62a,62b,m] S. Albergo,[63a,63b] M. Chiorboli,[63a,63b] S. Costa,[63a,63b] A. Di Mattia,[63a] F. Giordano,[63a,63b] R. Potenza,[63a,63b] A. Tricomi,[63a,63b] C. Tuve,[63a,63b] G. Barbagli,[64a] V. Ciulli,[64a,64b] C. Civinini,[64a] R. D'Alessandro,[64a,64b] E. Focardi,[64a,64b] V. Gori,[64a,64b] P. Lenzi,[64a,64b] M. Meschini,[64a] S. Paoletti,[64a] G. Sguazzoni,[64a] L. Viliani,[64a,64b,m] L. Benussi,[65] S. Bianco,[65] F. Fabbri,[65] D. Piccolo,[65] F. Primavera,[65,m] V. Calvelli,[66a,66b] F. Ferro,[66a] M. Lo Vetere,[66a,66b] M. R. Monge,[66a,66b] E. Robutti,[66a] S. Tosi,[66a,66b] L. Brianza,[67a,m] M. E. Dinardo,[67a,67b] S. Fiorendi,[67a,67b] S. Gennai,[67a] A. Ghezzi,[67a,67b] P. Govoni,[67a,67b] M. Malberti,[67a] S. Malvezzi,[67a] R. A. Manzoni,[67a,67b,m] B. Marzocchi,[67a,67b] D. Menasce,[67a] L. Moroni,[67a] M. Paganoni,[67a,67b] D. Pedrini,[67a] S. Pigazzini,[67a] S. Ragazzi,[67a,67b] T. Tabarelli de Fatis,[67a,67b] S. Buontempo,[68a] N. Cavallo,[68a,68c] G. De Nardo,[68a] S. Di Guida,[68a,68d,m] M. Esposito,[68a,68b] F. Fabozzi,[68a,68c] A. O. M. Iorio,[68a,68b] G. Lanza,[68a] L. Lista,[68a] S. Meola,[68a,68d,m] P. Paolucci,[68a,m] C. Sciacca,[68a,68b] F. Thyssen,[68a] P. Azzi,[69a,m] N. Bacchetta,[69a] M. Bellato,[69a] L. Benato,[69a,69b] A. Boletti,[69a,69b] R. Carlin,[69a,69b] A. Carvalho Antunes De Oliveira,[69a,69b] M. Dall'Osso,[69a,69b] P. De Castro Manzano,[69a] T. Dorigo,[69a] U. Dosselli,[69a] F. Gasparini,[69a,69b] A. Gozzelino,[69a] S. Lacaprara,[69a] M. Margoni,[69a,69b] A. T. Meneguzzo,[69a,69b] F. Montecassiano,[69a] J. Pazzini,[69a,69b,m] N. Pozzobon,[69a,69b] P. Ronchese,[69a,69b] F. Simonetto,[69a,69b] E. Torassa,[69a] S. Ventura,[69a] M. Zanetti,[69a] P. Zotto,[69a,69b] A. Zucchetta,[69a,69b] G. Zumerle,[69a,69b] A. Braghieri,[70a] A. Magnani,[70a,70b] P. Montagna,[70a,70b] S. P. Ratti,[70a,70b] V. Re,[70a] C. Riccardi,[70a,70b] P. Salvini,[70a] I. Vai,[70a,70b] P. Vitulo,[70a,70b] L. Alunni Solestizi,[71a,71b] G. M. Bilei,[71a] D. Ciangottini,[71a,71b] L. Fanò,[71a,71b] P. Lariccia,[71a,71b] R. Leonardi,[71a,71b] G. Mantovani,[71a,71b] M. Menichelli,[71a] A. Saha,[71a] A. Santocchia,[71a,71b] K. Androsov,[72a,cc] P. Azzurri,[72a,m] G. Bagliesi,[72a] J. Bernardini,[72a] T. Boccali,[72a] R. Castaldi,[72a] M. A. Ciocci,[72a,cc] R. Dell'Orso,[72a] S. Donato,[72a,72c] G. Fedi,[72a] A. Giassi,[72a] M. T. Grippo,[72a,cc] F. Ligabue,[72a,72c] T. Lomtadze,[72a] L. Martini,[72a,72b] A. Messineo,[72a,72b] F. Palla,[72a] A. Rizzi,[72a,72b] A. Savoy-Navarro,[72a,dd] P. Spagnolo,[72a] R. Tenchini,[72a] G. Tonelli,[72a,72b] A. Venturi,[72a] P. G. Verdini,[72a] L. Barone,[73a,73b] F. Cavallari,[73a] M. Cipriani,[73a,73b] G. D'imperio,[73a,73b,m] D. Del Re,[73a,73b,m] M. Diemoz,[73a] S. Gelli,[73a,73b] C. Jorda,[73a] E. Longo,[73a,73b] F. Margaroli,[73a,73b] P. Meridiani,[73a] G. Organtini,[73a,73b] R. Paramatti,[73a] F. Preiato,[73a,73b] S. Rahatlou,[73a,73b] C. Rovelli,[73a] F. Santanastasio,[73a,73b] N. Amapane,[74a,74b] R. Arcidiacono,[74a,74c,m] S. Argiro,[74a,74b] M. Arneodo,[74a,74c] N. Bartosik,[74a] R. Bellan,[74a,74b] C. Biino,[74a] N. Cartiglia,[74a] F. Cenna,[74a,74b] M. Costa,[74a,74b] R. Covarelli,[74a,74b] A. Degano,[74a,74b] N. Demaria,[74a] L. Finco,[74a,74b] B. Kiani,[74a,74b] C. Mariotti,[74a] S. Maselli,[74a] E. Migliore,[74a,74b] V. Monaco,[74a,74b] E. Monteil,[74a,74b] M. M. Obertino,[74a,74b] L. Pacher,[74a,74b] N. Pastrone,[74a] M. Pelliccioni,[74a] G. L. Pinna Angioni,[74a,74b] F. Ravera,[74a,74b] A. Romero,[74a,74b] M. Ruspa,[74a,74c] R. Sacchi,[74a,74b] K. Shchelina,[74a,74b] V. Sola,[74a] A. Solano,[74a,74b] A. Staiano,[74a] P. Traczyk,[74a,74b] S. Belforte,[75a] M. Casarsa,[75a] F. Cossutti,[75a] G. Della Ricca,[75a,75b] C. La Licata,[75a,75b] A. Schizzi,[75a,75b] A. Zanetti,[75a] D. H. Kim,[76] G. N. Kim,[76] M. S. Kim,[76] S. Lee,[76] S. W. Lee,[76] Y. D. Oh,[76] S. Sekmen,[76] D. C. Son,[76] Y. C. Yang,[76] A. Lee,[77] J. A. Brochero Cifuentes,[78] T. J. Kim,[78] S. Cho,[79] S. Choi,[79] Y. Go,[79] D. Gyun,[79] S. Ha,[79] B. Hong,[79] Y. Jo,[79] Y. Kim,[79] B. Lee,[79] K. Lee,[79] K. S. Lee,[79] S. Lee,[79] J. Lim,[79]

S. K. Park,[79] Y. Roh,[79] J. Almond,[80] J. Kim,[80] H. Lee,[80] S. B. Oh,[80] B. C. Radburn-Smith,[80] S. h. Seo,[80] U. K. Yang,[80] H. D. Yoo,[80] G. B. Yu,[80] M. Choi,[81] H. Kim,[81] H. Kim,[81] J. H. Kim,[81] J. S. H. Lee,[81] I. C. Park,[81] G. Ryu,[81] M. S. Ryu,[81] Y. Choi,[82] J. Goh,[82] C. Hwang,[82] J. Lee,[82] I. Yu,[82] V. Dudenas,[83] A. Juodagalvis,[83] J. Vaitkus,[83] I. Ahmed,[84] Z. A. Ibrahim,[84] J. R. Komaragiri,[84] M. A. B. Md Ali,[84,ee] F. Mohamad Idris,[84,ff] W. A. T. Wan Abdullah,[84] M. N. Yusli,[84] Z. Zolkapli,[84] H. Castilla-Valdez,[85] E. De La Cruz-Burelo,[85] I. Heredia-De La Cruz,[85,gg] A. Hernandez-Almada,[85] R. Lopez-Fernandez,[85] R. Magaña Villalba,[85] J. Mejia Guisao,[85] A. Sanchez-Hernandez,[85] S. Carrillo Moreno,[86] C. Oropeza Barrera,[86] F. Vazquez Valencia,[86] S. Carpinteyro,[87] I. Pedraza,[87] H. A. Salazar Ibarguen,[87] C. Uribe Estrada,[87] A. Morelos Pineda,[88] D. Krofcheck,[89] P. H. Butler,[90] A. Ahmad,[91] M. Ahmad,[91] Q. Hassan,[91] H. R. Hoorani,[91] W. A. Khan,[91] M. A. Shah,[91] M. Shoaib,[91] M. Waqas,[91] H. Bialkowska,[92] M. Bluj,[92] B. Boimska,[92] T. Frueboes,[92] M. Górski,[92] M. Kazana,[92] K. Nawrocki,[92] K. Romanowska-Rybinska,[92] M. Szleper,[92] P. Zalewski,[92] K. Bunkowski,[93] A. Byszuk,[93,hh] K. Doroba,[93] A. Kalinowski,[93] M. Konecki,[93] J. Krolikowski,[93] M. Misiura,[93] M. Olszewski,[93] M. Walczak,[93] P. Bargassa,[94] C. Beirão Da Cruz E Silva,[94] A. Di Francesco,[94] P. Faccioli,[94] P. G. Ferreira Parracho,[94] M. Gallinaro,[94] J. Hollar,[94] N. Leonardo,[94] L. Lloret Iglesias,[94] M. V. Nemallapudi,[94] J. Rodrigues Antunes,[94] J. Seixas,[94] O. Toldaiev,[94] D. Vadruccio,[94] J. Varela,[94] P. Vischia,[94] S. Afanasiev,[95] V. Alexakhin,[95] M. Gavrilenko,[95] I. Golutvin,[95] I. Gorbunov,[95] A. Kamenev,[95] V. Karjavin,[95] G. Kozlov,[95] A. Lanev,[95] A. Malakhov,[95] V. Matveev,[95,ii,jj] P. Moisenz,[95] V. Palichik,[95] V. Perelygin,[95] M. Savina,[95] S. Shmatov,[95] N. Skatchkov,[95] V. Smirnov,[95] A. Zarubin,[95] L. Chtchipounov,[96] V. Golovtsov,[96] Y. Ivanov,[96] V. Kim,[96,kk] E. Kuznetsova,[96,ll] V. Murzin,[96] V. Oreshkin,[96] V. Sulimov,[96] A. Vorobyev,[96] Yu. Andreev,[97] A. Dermenev,[97] S. Gninenko,[97] N. Golubev,[97] A. Karneyeu,[97] M. Kirsanov,[97] N. Krasnikov,[97] A. Pashenkov,[97] D. Tlisov,[97] A. Toropin,[97] V. Epshteyn,[98] V. Gavrilov,[98] N. Lychkovskaya,[98] V. Popov,[98] I. Pozdnyakov,[98] G. Safronov,[98] A. Spiridonov,[98] M. Toms,[98] E. Vlasov,[98] A. Zhokin,[98] A. Bylinkin,[99,jj] M. Chadeeva,[100,mm] O. Markin,[100] E. Tarkovskii,[100] V. Andreev,[101] M. Azarkin,[101,jj] I. Dremin,[101,jj] M. Kirakosyan,[101] A. Leonidov,[101,jj] S. V. Rusakov,[101] A. Terkulov,[101] A. Baskakov,[102] A. Belyaev,[102] E. Boos,[102] M. Dubinin,[102,nn] L. Dudko,[102] A. Ershov,[102] A. Gribushin,[102] V. Klyukhin,[102] O. Kodolova,[102] I. Lokhtin,[102] I. Miagkov,[102] S. Obraztsov,[102] S. Petrushanko,[102] V. Savrin,[102] A. Snigirev,[102] V. Blinov,[103,oo] Y. Skovpen,[103,oo] I. Azhgirey,[104] I. Bayshev,[104] S. Bitioukov,[104] D. Elumakhov,[104] V. Kachanov,[104] A. Kalinin,[104] D. Konstantinov,[104] V. Krychkine,[104] V. Petrov,[104] R. Ryutin,[104] A. Sobol,[104] S. Troshin,[104] N. Tyurin,[104] A. Uzunian,[104] A. Volkov,[104] P. Adzic,[105,pp] P. Cirkovic,[105] D. Devetak,[105] M. Dordevic,[105] J. Milosevic,[105] V. Rekovic,[105] J. Alcaraz Maestre,[106] M. Barrio Luna,[106] E. Calvo,[106] M. Cerrada,[106] M. Chamizo Llatas,[106] N. Colino,[106] B. De La Cruz,[106] A. Delgado Peris,[106] A. Escalante Del Valle,[106] C. Fernandez Bedoya,[106] J. P. Fernández Ramos,[106] J. Flix,[106] M. C. Fouz,[106] P. Garcia-Abia,[106] O. Gonzalez Lopez,[106] S. Goy Lopez,[106] J. M. Hernandez,[106] M. I. Josa,[106] E. Navarro De Martino,[106] A. Pérez-Calero Yzquierdo,[106] J. Puerta Pelayo,[106] A. Quintario Olmeda,[106] I. Redondo,[106] L. Romero,[106] M. S. Soares,[106] J. F. de Trocóniz,[107] M. Missiroli,[107] D. Moran,[107] J. Cuevas,[108] J. Fernandez Menendez,[108] I. Gonzalez Caballero,[108] J. R. González Fernández,[108] E. Palencia Cortezon,[108] S. Sanchez Cruz,[108] I. Suárez Andrés,[108] J. M. Vizan Garcia,[108] I. J. Cabrillo,[109] A. Calderon,[109] J. R. Castiñeiras De Saa,[109] E. Curras,[109] M. Fernandez,[109] J. Garcia-Ferrero,[109] G. Gomez,[109] A. Lopez Virto,[109] J. Marco,[109] C. Martinez Rivero,[109] F. Matorras,[109] J. Piedra Gomez,[109] T. Rodrigo,[109] A. Ruiz-Jimeno,[109] L. Scodellaro,[109] N. Trevisani,[109] I. Vila,[109] R. Vilar Cortabitarte,[109] D. Abbaneo,[110] E. Auffray,[110] G. Auzinger,[110] M. Bachtis,[110] P. Baillon,[110] A. H. Ball,[110] D. Barney,[110] P. Bloch,[110] A. Bocci,[110] A. Bonato,[110] C. Botta,[110] T. Camporesi,[110] R. Castello,[110] M. Cepeda,[110] G. Cerminara,[110] M. D'Alfonso,[110] D. d'Enterria,[110] A. Dabrowski,[110] V. Daponte,[110] A. David,[110] M. De Gruttola,[110] F. De Guio,[110] A. De Roeck,[110] E. Di Marco,[110,qq] M. Dobson,[110] B. Dorney,[110] T. du Pree,[110] D. Duggan,[110] M. Dünser,[110] N. Dupont,[110] A. Elliott-Peisert,[110] S. Fartoukh,[110] G. Franzoni,[110] J. Fulcher,[110] W. Funk,[110] D. Gigi,[110] K. Gill,[110] M. Girone,[110] F. Glege,[110] D. Gulhan,[110] S. Gundacker,[110] M. Guthoff,[110] J. Hammer,[110] P. Harris,[110] J. Hegeman,[110] V. Innocente,[110] P. Janot,[110] H. Kirschenmann,[110] V. Knünz,[110] A. Kornmayer,[110,m] M. J. Kortelainen,[110] K. Kousouris,[110] M. Krammer,[110,b] P. Lecoq,[110] C. Lourenço,[110] M. T. Lucchini,[110] L. Malgeri,[110] M. Mannelli,[110] A. Martelli,[110] F. Meijers,[110] S. Mersi,[110] E. Meschi,[110] F. Moortgat,[110] S. Morovic,[110] M. Mulders,[110] H. Neugebauer,[110] S. Orfanelli,[110] L. Orsini,[110] L. Pape,[110] E. Perez,[110] M. Peruzzi,[110] A. Petrilli,[110] G. Petrucciani,[110] A. Pfeiffer,[110] M. Pierini,[110] A. Racz,[110] T. Reis,[110] G. Rolandi,[110,rr] M. Rovere,[110] M. Ruan,[110] H. Sakulin,[110] J. B. Sauvan,[110] C. Schäfer,[110] C. Schwick,[110] M. Seidel,[110] A. Sharma,[110] P. Silva,[110] M. Simon,[110] P. Sphicas,[110,ss] J. Steggemann,[110] M. Stoye,[110] Y. Takahashi,[110] M. Tosi,[110] D. Treille,[110] A. Triossi,[110] A. Tsirou,[110] V. Veckalns,[110,tt] G. I. Veres,[110,t] N. Wardle,[110] H. K. Wöhri,[110] A. Zagozdzinska,[110,hh] W. D. Zeuner,[110] W. Bertl,[111] K. Deiters,[111] W. Erdmann,[111] R. Horisberger,[111] Q. Ingram,[111] H. C. Kaestli,[111] D. Kotlinski,[111] U. Langenegger,[111]

T. Rohe,[111] F. Bachmair,[112] L. Bäni,[112] L. Bianchini,[112] B. Casal,[112] G. Dissertori,[112] M. Dittmar,[112] M. Donegà,[112] P. Eller,[112] C. Grab,[112] C. Heidegger,[112] D. Hits,[112] J. Hoss,[112] G. Kasieczka,[112] P. Lecomte,[112,a] W. Lustermann,[112] B. Mangano,[112] M. Marionneau,[112] P. Martinez Ruiz del Arbol,[112] M. Masciovecchio,[112] M. T. Meinhard,[112] D. Meister,[112] F. Micheli,[112] P. Musella,[112] F. Nessi-Tedaldi,[112] F. Pandolfi,[112] J. Pata,[112] F. Pauss,[112] G. Perrin,[112] L. Perrozzi,[112] M. Quittnat,[112] M. Rossini,[112] M. Schönenberger,[112] A. Starodumov,[112,uu] V. R. Tavolaro,[112] K. Theofilatos,[112] R. Wallny,[112] T. K. Aarrestad,[113] C. Amsler,[113,vv] L. Caminada,[113] M. F. Canelli,[113] A. De Cosa,[113] C. Galloni,[113] A. Hinzmann,[113] T. Hreus,[113] B. Kilminster,[113] C. Lange,[113] J. Ngadiuba,[113] D. Pinna,[113] G. Rauco,[113] P. Robmann,[113] D. Salerno,[113] Y. Yang,[113] V. Candelise,[114] T. H. Doan,[114] Sh. Jain,[114] R. Khurana,[114] M. Konyushikhin,[114] C. M. Kuo,[114] W. Lin,[114] Y. J. Lu,[114] A. Pozdnyakov,[114] S. S. Yu,[114] Arun Kumar,[115] P. Chang,[115] Y. H. Chang,[115] Y. W. Chang,[115] Y. Chao,[115] K. F. Chen,[115] P. H. Chen,[115] C. Dietz,[115] F. Fiori,[115] W.-S. Hou,[115] Y. Hsiung,[115] Y. F. Liu,[115] R.-S. Lu,[115] M. Miñano Moya,[115] E. Paganis,[115] A. Psallidas,[115] J. f. Tsai,[115] Y. M. Tzeng,[115] B. Asavapibhop,[116] G. Singh,[116] N. Srimanobhas,[116] N. Suwonjandee,[116] A. Adiguzel,[117] S. Cerci,[117,ww] S. Damarseckin,[117] Z. S. Demiroglu,[117] C. Dozen,[117] I. Dumanoglu,[117] S. Girgis,[117] G. Gokbulut,[117] Y. Guler,[117] E. Gurpinar,[117] I. Hos,[117] E. E. Kangal,[117,xx] O. Kara,[117] A. Kayis Topaksu,[117] U. Kiminsu,[117] M. Oglakci,[117] G. Onengut,[117,yy] K. Ozdemir,[117,zz] B. Tali,[117,ww] H. Topakli,[117,aaa] S. Turkcapar,[117] I. S. Zorbakir,[117] C. Zorbilmez,[117] B. Bilin,[118] S. Bilmis,[118] B. Isildak,[118,bbb] G. Karapinar,[118,ccc] M. Yalvac,[118] M. Zeyrek,[118] E. Gülmez,[119] M. Kaya,[119,ddd] O. Kaya,[119,eee] E. A. Yetkin,[119,fff] T. Yetkin,[119,ggg] A. Cakir,[120] K. Cankocak,[120] S. Sen,[120,hhh] B. Grynyov,[121] L. Levchuk,[122] P. Sorokin,[122] R. Aggleton,[123] F. Ball,[123] L. Beck,[123] J. J. Brooke,[123] D. Burns,[123] E. Clement,[123] D. Cussans,[123] H. Flacher,[123] J. Goldstein,[123] M. Grimes,[123] G. P. Heath,[123] H. F. Heath,[123] J. Jacob,[123] L. Kreczko,[123] C. Lucas,[123] D. M. Newbold,[123,iii] S. Paramesvaran,[123] A. Poll,[123] T. Sakuma,[123] S. Seif El Nasr-storey,[123] D. Smith,[123] V. J. Smith,[123] K. W. Bell,[124] A. Belyaev,[124,jjj] C. Brew,[124] R. M. Brown,[124] L. Calligaris,[124] D. Cieri,[124] D. J. A. Cockerill,[124] J. A. Coughlan,[124] K. Harder,[124] S. Harper,[124] E. Olaiya,[124] D. Petyt,[124] C. H. Shepherd-Themistocleous,[124] A. Thea,[124] I. R. Tomalin,[124] T. Williams,[124] M. Baber,[125] R. Bainbridge,[125] O. Buchmuller,[125] A. Bundock,[125] D. Burton,[125] S. Casasso,[125] M. Citron,[125] D. Colling,[125] L. Corpe,[125] P. Dauncey,[125] G. Davies,[125] A. De Wit,[125] M. Della Negra,[125] R. Di Maria,[125] P. Dunne,[125] A. Elwood,[125] D. Futyan,[125] Y. Haddad,[125] G. Hall,[125] G. Iles,[125] T. James,[125] R. Lane,[125] C. Laner,[125] R. Lucas,[125,iii] L. Lyons,[125] A.-M. Magnan,[125] S. Malik,[125] L. Mastrolorenzo,[125] J. Nash,[125] A. Nikitenko,[125,uu] J. Pela,[125] B. Penning,[125] M. Pesaresi,[125] D. M. Raymond,[125] A. Richards,[125] A. Rose,[125] C. Seez,[125] S. Summers,[125] A. Tapper,[125] K. Uchida,[125] M. Vazquez Acosta,[125,kkk] T. Virdee,[125,m] J. Wright,[125] S. C. Zenz,[125] J. E. Cole,[126] P. R. Hobson,[126] A. Khan,[126] P. Kyberd,[126] D. Leslie,[126] I. D. Reid,[126] P. Symonds,[126] L. Teodorescu,[126] M. Turner,[126] A. Borzou,[127] K. Call,[127] J. Dittmann,[127] K. Hatakeyama,[127] H. Liu,[127] N. Pastika,[127] O. Charaf,[128] S. I. Cooper,[128] C. Henderson,[128] P. Rumerio,[128] D. Arcaro,[129] A. Avetisyan,[129] T. Bose,[129] D. Gastler,[129] D. Rankin,[129] C. Richardson,[129] J. Rohlf,[129] L. Sulak,[129] D. Zou,[129] G. Benelli,[130] E. Berry,[130] D. Cutts,[130] A. Garabedian,[130] J. Hakala,[130] U. Heintz,[130] J. M. Hogan,[130] O. Jesus,[130] E. Laird,[130] G. Landsberg,[130] Z. Mao,[130] M. Narain,[130] S. Piperov,[130] S. Sagir,[130] E. Spencer,[130] R. Syarif,[130] R. Breedon,[131] G. Breto,[131] D. Burns,[131] M. Calderon De La Barca Sanchez,[131] S. Chauhan,[131] M. Chertok,[131] J. Conway,[131] R. Conway,[131] P. T. Cox,[131] R. Erbacher,[131] C. Flores,[131] G. Funk,[131] M. Gardner,[131] W. Ko,[131] R. Lander,[131] C. Mclean,[131] M. Mulhearn,[131] D. Pellett,[131] J. Pilot,[131] F. Ricci-Tam,[131] S. Shalhout,[131] J. Smith,[131] M. Squires,[131] D. Stolp,[131] M. Tripathi,[131] S. Wilbur,[131] R. Yohay,[131] R. Cousins,[132] P. Everaerts,[132] A. Florent,[132] J. Hauser,[132] M. Ignatenko,[132] D. Saltzberg,[132] E. Takasugi,[132] V. Valuev,[132] M. Weber,[132] K. Burt,[133] R. Clare,[133] J. Ellison,[133] J. W. Gary,[133] G. Hanson,[133] J. Heilman,[133] P. Jandir,[133] E. Kennedy,[133] F. Lacroix,[133] O. R. Long,[133] M. Olmedo Negrete,[133] M. I. Paneva,[133] A. Shrinivas,[133] H. Wei,[133] S. Wimpenny,[133] B. R. Yates,[133] J. G. Branson,[134] G. B. Cerati,[134] S. Cittolin,[134] M. Derdzinski,[134] R. Gerosa,[134] A. Holzner,[134] D. Klein,[134] V. Krutelyov,[134] J. Letts,[134] I. Macneill,[134] D. Olivito,[134] S. Padhi,[134] M. Pieri,[134] M. Sani,[134] V. Sharma,[134] S. Simon,[134] M. Tadel,[134] A. Vartak,[134] S. Wasserbaech,[134,lll] C. Welke,[134] J. Wood,[134] F. Würthwein,[134] A. Yagil,[134] G. Zevi Della Porta,[134] R. Bhandari,[135] J. Bradmiller-Feld,[135] C. Campagnari,[135] A. Dishaw,[135] V. Dutta,[135] K. Flowers,[135] M. Franco Sevilla,[135] P. Geffert,[135] C. George,[135] F. Golf,[135] L. Gouskos,[135] J. Gran,[135] R. Heller,[135] J. Incandela,[135] N. Mccoll,[135] S. D. Mullin,[135] A. Ovcharova,[135] J. Richman,[135] D. Stuart,[135] I. Suarez,[135] C. West,[135] J. Yoo,[135] D. Anderson,[136] A. Apresyan,[136] J. Bendavid,[136] A. Bornheim,[136] J. Bunn,[136] Y. Chen,[136] J. Duarte,[136] J. M. Lawhorn,[136] A. Mott,[136] H. B. Newman,[136] C. Pena,[136] M. Spiropulu,[136] J. R. Vlimant,[136] S. Xie,[136] R. Y. Zhu,[136] M. B. Andrews,[137] V. Azzolini,[137] T. Ferguson,[137] M. Paulini,[137] J. Russ,[137] M. Sun,[137] H. Vogel,[137] I. Vorobiev,[137] J. P. Cumalat,[138] W. T. Ford,[138] F. Jensen,[138] A. Johnson,[138] M. Krohn,[138] T. Mulholland,[138] K. Stenson,[138] S. R. Wagner,[138] J. Alexander,[139]

J. Chaves,[139] J. Chu,[139] S. Dittmer,[139] K. Mcdermott,[139] N. Mirman,[139] G. Nicolas Kaufman,[139] J. R. Patterson,[139] A. Rinkevicius,[139] A. Ryd,[139] L. Skinnari,[139] L. Soffi,[139] S. M. Tan,[139] Z. Tao,[139] J. Thom,[139] J. Tucker,[139] P. Wittich,[139] M. Zientek,[139] D. Winn,[140] S. Abdullin,[141] M. Albrow,[141] G. Apollinari,[141] S. Banerjee,[141] L. A. T. Bauerdick,[141] A. Beretvas,[141] J. Berryhill,[141] P. C. Bhat,[141] G. Bolla,[141] K. Burkett,[141] J. N. Butler,[141] H. W. K. Cheung,[141] F. Chlebana,[141] S. Cihangir,[141,a] M. Cremonesi,[141] V. D. Elvira,[141] I. Fisk,[141] J. Freeman,[141] E. Gottschalk,[141] L. Gray,[141] D. Green,[141] S. Grünendahl,[141] O. Gutsche,[141] D. Hare,[141] R. M. Harris,[141] S. Hasegawa,[141] J. Hirschauer,[141] Z. Hu,[141] B. Jayatilaka,[141] S. Jindariani,[141] M. Johnson,[141] U. Joshi,[141] B. Klima,[141] B. Kreis,[141] S. Lammel,[141] J. Linacre,[141] D. Lincoln,[141] R. Lipton,[141] T. Liu,[141] R. Lopes De Sá,[141] J. Lykken,[141] K. Maeshima,[141] N. Magini,[141] J. M. Marraffino,[141] S. Maruyama,[141] D. Mason,[141] P. McBride,[141] P. Merkel,[141] S. Mrenna,[141] S. Nahn,[141] C. Newman-Holmes,[141,a] V. O'Dell,[141] K. Pedro,[141] O. Prokofyev,[141] G. Rakness,[141] L. Ristori,[141] E. Sexton-Kennedy,[141] A. Soha,[141] W. J. Spalding,[141] L. Spiegel,[141] S. Stoynev,[141] N. Strobbe,[141] L. Taylor,[141] S. Tkaczyk,[141] N. V. Tran,[141] L. Uplegger,[141] E. W. Vaandering,[141] C. Vernieri,[141] M. Verzocchi,[141] R. Vidal,[141] M. Wang,[141] H. A. Weber,[141] A. Whitbeck,[141] D. Acosta,[142] P. Avery,[142] P. Bortignon,[142] D. Bourilkov,[142] A. Brinkerhoff,[142] A. Carnes,[142] M. Carver,[142] D. Curry,[142] S. Das,[142] R. D. Field,[142] I. K. Furic,[142] J. Konigsberg,[142] A. Korytov,[142] P. Ma,[142] K. Matchev,[142] H. Mei,[142] P. Milenovic,[142,mmm] G. Mitselmakher,[142] D. Rank,[142] L. Shchutska,[142] D. Sperka,[142] L. Thomas,[142] J. Wang,[142] S. Wang,[142] J. Yelton,[142] S. Linn,[143] P. Markowitz,[143] G. Martinez,[143] J. L. Rodriguez,[143] A. Ackert,[144] J. R. Adams,[144] T. Adams,[144] A. Askew,[144] S. Bein,[144] B. Diamond,[144] S. Hagopian,[144] V. Hagopian,[144] K. F. Johnson,[144] A. Khatiwada,[144] H. Prosper,[144] A. Santra,[144] M. Weinberg,[144] M. M. Baarmand,[145] V. Bhopatkar,[145] S. Colafranceschi,[145,nnn] M. Hohlmann,[145] D. Noonan,[145] T. Roy,[145] F. Yumiceva,[145] M. R. Adams,[146] L. Apanasevich,[146] D. Berry,[146] R. R. Betts,[146] I. Bucinskaite,[146] R. Cavanaugh,[146] O. Evdokimov,[146] L. Gauthier,[146] C. E. Gerber,[146] D. J. Hofman,[146] P. Kurt,[146] C. O'Brien,[146] I. D. Sandoval Gonzalez,[146] P. Turner,[146] N. Varelas,[146] H. Wang,[146] Z. Wu,[146] M. Zakaria,[146] J. Zhang,[146] B. Bilki,[147,ooo] W. Clarida,[147] K. Dilsiz,[147] S. Durgut,[147] R. P. Gandrajula,[147] M. Haytmyradov,[147] V. Khristenko,[147] J.-P. Merlo,[147] H. Mermerkaya,[147,ppp] A. Mestvirishvili,[147] A. Moeller,[147] J. Nachtman,[147] H. Ogul,[147] Y. Onel,[147] F. Ozok,[147,qqq] A. Penzo,[147] C. Snyder,[147] E. Tiras,[147] J. Wetzel,[147] K. Yi,[147] I. Anderson,[148] B. Blumenfeld,[148] A. Cocoros,[148] N. Eminizer,[148] D. Fehling,[148] L. Feng,[148] A. V. Gritsan,[148] P. Maksimovic,[148] M. Osherson,[148] J. Roskes,[148] U. Sarica,[148] M. Swartz,[148] M. Xiao,[148] Y. Xin,[148] C. You,[148] A. Al-bataineh,[149] P. Baringer,[149] A. Bean,[149] S. Boren,[149] J. Bowen,[149] C. Bruner,[149] J. Castle,[149] L. Forthomme,[149] R. P. Kenny III,[149] A. Kropivnitskaya,[149] D. Majumder,[149] W. Mcbrayer,[149] M. Murray,[149] S. Sanders,[149] R. Stringer,[149] J. D. Tapia Takaki,[149] Q. Wang,[149] A. Ivanov,[150] K. Kaadze,[150] S. Khalil,[150] M. Makouski,[150] Y. Maravin,[150] A. Mohammadi,[150] L. K. Saini,[150] N. Skhirtladze,[150] S. Toda,[150] F. Rebassoo,[151] D. Wright,[151] C. Anelli,[152] A. Baden,[152] O. Baron,[152] A. Belloni,[152] B. Calvert,[152] S. C. Eno,[152] C. Ferraioli,[152] J. A. Gomez,[152] N. J. Hadley,[152] S. Jabeen,[152] R. G. Kellogg,[152] T. Kolberg,[152] J. Kunkle,[152] Y. Lu,[152] A. C. Mignerey,[152] Y. H. Shin,[152] A. Skuja,[152] M. B. Tonjes,[152] S. C. Tonwar,[152] D. Abercrombie,[153] B. Allen,[153] A. Apyan,[153] R. Barbieri,[153] A. Baty,[153] R. Bi,[153] K. Bierwagen,[153] S. Brandt,[153] W. Busza,[153] I. A. Cali,[153] Z. Demiragli,[153] L. Di Matteo,[153] G. Gomez Ceballos,[153] M. Goncharov,[153] D. Hsu,[153] Y. Iiyama,[153] G. M. Innocenti,[153] M. Klute,[153] D. Kovalskyi,[153] K. Krajczar,[153] Y. S. Lai,[153] Y.-J. Lee,[153] A. Levin,[153] P. D. Luckey,[153] A. C. Marini,[153] C. Mcginn,[153] C. Mironov,[153] S. Narayanan,[153] X. Niu,[153] C. Paus,[153] C. Roland,[153] G. Roland,[153] J. Salfeld-Nebgen,[153] G. S. F. Stephans,[153] K. Sumorok,[153] K. Tatar,[153] M. Varma,[153] D. Velicanu,[153] J. Veverka,[153] J. Wang,[153] T. W. Wang,[153] B. Wyslouch,[153] M. Yang,[153] V. Zhukova,[153] A. C. 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