Search for pair production of heavy resonances in final states with a photon and large-radius jets in proton-proton collisions at $\sqrt{s} = 13$ TeV

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A search for the pair production of heavy spin-1/2 or spin-3/2 resonances (t^*) in proton-proton collisions at $\sqrt{s} = 13$ TeV is presented. Data collected with the CMS detector at the CERN LHC from 2016 to 2018 corresponding to an integrated luminosity of 138 fb^{-1} are used. The analysis targets benchmark signal scenarios where one t^* decays into a top quark (t) and a photon (γ), and the other into a t quark and a gluon (g), i.e., $pp \to t^*\overline{t^*} \to tt\gamma g$. All-hadronic final states from the t pair decay chain are selected using jet substructure techniques. The signal is probed as a function of the t^* candidate mass, which is reconstructed using the photon and a top quark candidate jet. No significant deviation from the background-only hypothesis is found. Observed (expected) upper limits on the signal cross section at 95% confidence level are set, excluding masses of spin-1/2 t^* particles below 930 (930) GeV and spin-3/2 t^* particles below 1330 (1390) GeV. This analysis marks the first search for heavy resonances in the $t\bar{t}\gamma g$ channel. Exploiting the high-energy photon to reduce the backgrounds, this search achieves sensitivity competitive with $pp \to t^*\overline{t^*} \to t\bar{t}gg$ searches for spin-1/2 t^* despite the small expected $t^* \to t\gamma$ branching fraction.

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I. INTRODUCTION

The standard model (SM) of particle physics has been successful in describing a large number of observations. However, it leaves several fundamental questions unanswered. For example, the SM cannot explain the vast disparity between the strengths of the electroweak (EW) force and gravity [1]. Additionally, the SM fails to elucidate the nature of dark matter. Beyond-the-SM theories, including those with extra spatial dimensions [2] and composite Higgs scenarios [3], can address these open questions. Some of these models predict that the top quark may have excited states or have vectorlike quark partners.

For a top quark vectorlike partner (T) with an electric charge of $+2/3$, the dominant decay modes are expected to be the tree-level processes $T \to bW$, $T \to tZ$, and $T \to tH$ [4]. Both the ATLAS and CMS experiments at the CERN LHC have searched for these signatures, placing lower constraints on the mass of the T of up to 1.42 TeV at 95% confidence level (CL), depending on the T branching fractions ($\mathcal{B}$) [5–13]. These decay modes could be suppressed if the mixing angle, which governs the interaction strength between T and W, Z, or H, is small. Consequently, the loop-induced decays $T \to tg$ and $T \to t\gamma$ can dominate [14–17]. These decays are similar to those of an excited top quark (t^*), which proceed via dipole operators [18]. Among these, the decay $t^* \to tg$ is expected to be dominant because of the strong coupling, while $t^* \to t\gamma$ would be suppressed by the electromagnetic coupling. Searches for t^* pair production, assuming the $t^* \to tg$ decay mode, have been performed by the CMS Collaboration using proton-proton (pp) collisions at center-of-mass energies of 8 and 13 TeV. These studies resulted in a 1050 (1700) GeV 95% CL lower mass limit for a spin-1/2 (spin-3/2) t^*, assuming $\mathcal{B}(t^* \to tg) = 100\%$ [19–21]. Despite the expected smallness of $\mathcal{B}(t^* \to t\gamma)$ with respect to $\mathcal{B}(t^* \to tg)$, the sensitivity of the $t^*\overline{t^*} \to t\bar{t}\gamma g$ channel could be similar to that of the $t\bar{t}gg$ channel because of the smaller backgrounds associated with its photon signature [22].

The interactions of spin-1/2 t^* with SM particles are described by a dipole-moment-like interaction between the t quark and t^* [22]. The interactions of a spin-3/2 t^* are described by the Rarita-Schwinger Lagrangian [23]. Although the spin-1/2 and spin-3/2 t^* are both assumed to be color-triplet particles, the $pp \to t^*\overline{t^*}$ cross sections are not the same because of the spin-dependent couplings to SM gluon fields. For example, the production cross section for a pair of spin-1/2 t^* with a mass of 1 TeV is ≈26 fb, whereas for a pair of spin-3/2 t^* particles with the same mass it is ≈260 fb. The branching fractions of the t^* depend

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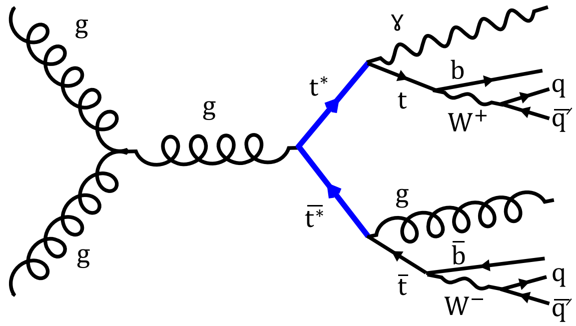

FIG. 1. Representative LO Feynman diagram for pair production of t^* in the $t\bar{t}\gamma g$ channel.

on the coupling strength to gluons and photons. Simple coupling ratio arguments suggest absolute branching fractions of $\mathcal{B}(t^* \to t\gamma) = 3\%$ and $\mathcal{B}(t^* \to tg) = 97\%$. These and other theoretical assumptions adopted in this analysis follow Ref. [22].

This paper describes the first search at the LHC for pair-produced t^* with spin-1/2 or spin-3/2 in the $t\bar{t}\gamma g$ channel in pp collisions at $\sqrt{s} = 13$ TeV. The data used in the analysis correspond to an integrated luminosity of 138 fb^{-1}, collected by the CMS experiment at the LHC during 2016–2018. The large expected mass of the t^* implies that the partons produced in its decay will have very large momenta, resulting in a photon and top quark of high transverse momentum (p_T). Because of the large Lorentz boost of the top quark, its decay products are typically expected to be merged into one large radius particle jet. Thus, events characterized by an isolated photon with high-p_T and multiple large-radius jets are used in this analysis.

This search utilizes a state-of-the-art machine-learning algorithm, known as the PARTICLENET tagger, to identify the large-radius jets as originating from top quarks [24]. In this study, we employ the reconstruction of the mass of a single t^* candidate, using a photon and a top quark jet, to search for an excess of events in the mass distribution that would correspond to the presence of a t^*. The corresponding leading-order (LO) Feynman diagram for the search channel targeted in this paper is shown in Fig. 1.

II. THE CMS DETECTOR

The CMS apparatus is a multipurpose, nearly hermetic detector, designed to trigger on [25–27] and identify electrons, muons, photons, and (charged and neutral) hadrons [28–30]. Its central feature is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two end cap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and end cap detectors. Muons are reconstructed using gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. More detailed descriptions of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, are reported in Refs. [31,32].

III. DATA AND SIMULATED EVENT SAMPLES

Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about 4 μs [25]. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [26]. Collision events are selected using a high-p_T photon trigger. The p_T thresholds for the photon trigger are 175 GeV for data collected during 2016, and 200 GeV for data collected in 2017 and 2018, reflecting adjustments to account for the changing LHC luminosity conditions. The trigger efficiencies, measured in $Z \to ee$ samples, are greater than 99% for photons with $p_\mathrm{T} > 240$ GeV [33].

Monte Carlo (MC) simulated events are used to model most of the background processes and the t^* signals. The next-to-next-to-leading order NNPDF3.1 [34] parton distribution function (PDF) set is used in event production. Parton showering and hadronization are performed with PYTHIA v8.240 [35] using the underlying event tune CP5 [36]. All the MC generated samples are passed through the full simulation of the CMS detector based on GEANT4 [37]. Simulated samples include additional pp interactions occurring within the same or nearby bunch crossings (pileup). Events in these samples are reweighted so that the pileup distribution matches that of the data.

Signal samples for the pair production of spin-1/2 and spin-3/2 t^* along with their decays, $pp \to t^*\overline{t^*} \to t\bar{t}\gamma g$, are generated at LO with the MADGRAPH5_aMC@NLO v.2.6.5 generator [38]. The narrow-width approximation is assumed to be valid in the mass range considered in this analysis [22]. In practice, the signal samples are generated with a fixed t^* width of 10 GeV, which is much smaller than the experimental resolution of the reconstructed t^* mass (m_{t^*}). Under this approximation, signal samples are produced for m_{t^*} values ranging from 700 GeV to 2 TeV in 100 GeV steps, with four additional mass points at 2.25, 2.5, 2.75, and 3 TeV. All signal samples are normalized to the cross section of $t^*\overline{t^*}$ production, calculated at LO, times the product of $\mathcal{B}(t^* \to tg) = 0.97$ and $\mathcal{B}(t^* \to t\gamma) = 0.03$ [22].

The background processes considered in this analysis include several key contributions. These encompass SM top quark-antiquark pair production ($t\bar{t}$), as well as $t\bar{t}$ produced in association with a photon ($t\bar{t}\gamma$). Additionally, single top quark production occuring through the t-channel, tW-channel (associated with a W boson), and s-channel is considered. Other important backgrounds include multijet production and processes involving the production of a photon, Z, or W boson in association with jets ($\gamma+$jet, $Z+$jets, and $W+$jets). Processes where a Z or a W boson is produced alongside a photon ($Z\gamma$ and $W\gamma$) are also included. The SM $t\bar{t}$, and single top quark production processes in the t channel and tW channel are simulated with POWHEG v2.0 at next-to-leading order (NLO) [39–41]. The MADGRAPH5_aMC@NLO v.2.6.5 generator is used to simulate other processes. The multijets, $\gamma+$jet, $W+$jets, $W\gamma$, and $t\bar{t}\gamma$ samples are generated at LO; other MC samples are generated at NLO. Jets produced at the matrix element level are matched with those generated by PYTHIA parton shower using the MLM and FxFx merging schemes for LO and NLO samples, respectively [42]. Possible overlaps between events with a photon generated at the matrix element level in the $t\bar{t}\gamma$, $\gamma+$jet, $Z\gamma$, and $W\gamma$ processes and events with a photon generated by PYTHIA at the showering step in the $t\bar{t}$, multijet, $Z+$jets, and $W+$jets processes are removed [43].

IV. EVENT RECONSTRUCTION

The global event description based on the particle-flow (PF) algorithm [44] aims to reconstruct and identify each individual particle in an event, with an optimized combination of all subdetector information. In this process, the identification of the particle type (photon, electron, muon, charged or neutral hadron) plays an important role in the determination of the particle direction and energy. Photons are identified as ECAL energy clusters not linked to the extrapolation of any trajectory of a charged particle originating from the primary vertex. Electrons are identified as a primary charged-particle track and potentially multiple ECAL energy clusters corresponding to this track extrapolation to the ECAL and to possible bremsstrahlung photons emitted along the way through the tracker material. Muons are identified as tracks in the central tracker consistent with either a track or several hits in the muon system, and associated with energy deposits in calorimeters compatible with the muon hypothesis. Charged hadrons are identified as charged-particle tracks identified neither as electrons, nor as muons. Finally, neutral hadrons are identified as HCAL energy clusters not linked to any charged-hadron trajectory, or as a combined ECAL and HCAL energy excess with respect to the expected charged-hadron energy deposit.

The primary vertex (PV) is taken to be the vertex corresponding to the highest-momentum scattering in the event, evaluated using tracking information alone, as described in Sec. 9.4.1 of Ref. [45]. The PV is used to associate the reconstructed objects in the event, such as jets and photons, and to calculate kinematic variables such as p_{T} and η relative to the PV.

The energy of photons is obtained from the ECAL measurement. The energy of electrons is determined from a combination of the track momentum at the main interaction vertex, the corresponding ECAL cluster energy, and the energy sum of all bremsstrahlung photons attached to the track. The energy of muons is obtained from the corresponding track curvature. The energy of charged hadrons is determined from a combination of the track momentum and the corresponding ECAL and HCAL energies, corrected 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.

In the barrel section of the ECAL, an energy resolution of about 1% is achieved for unconverted or late-converting photons in the tens of GeV energy range. The energy resolution of the remaining barrel photons is about 1.3% up to $|\eta|=1$, changing to about 2.5% at $|\eta|=1.4$ [28]. A standard identification (ID) working point, called "medium ID" in Ref. [28], with an average efficiency of 80% for selecting genuine photons is used in this analysis. The photon ID is based on requirements on the ratio of the energy deposited in the closest HCAL tower to that of the ECAL and shower profile of the photon ($\sigma_{i\eta i\eta}$). The $\sigma_{i\eta i\eta}$ observable, defined as the energy-weighted root-mean-square of the electromagnetic shower profile along the η direction, quantifies the lateral spread of the shower in units of the ECAL crystal size [46]. Selected photons must also satisfy the photon isolation requirement based on the scalar p_{T} sum of charged hadron (I_{chg}), neutral hadron, and additional photon candidates reconstructed by the PF algorithm within a cone of $\Delta R=\sqrt{(\Delta\eta)^2+(\Delta\phi)^2}<0.3$ around its axis [28], where ϕ is azimuthal angle in radians. The photon is distinguished from identified electrons in the detector by requiring no hits in the inner tracker layers close to the photon direction. The photon ID and isolation efficiencies are measured separately in data and simulation with $Z\to ee$ events, with the electron tracks removed to emulate photonlike ECAL superclusters except in cases where photon conversions occur. Scale factors (SF) are applied to simulated events to correct for differences between the behavior of reconstructed photons in the simulation and those observed in collision data. The same $Z\to ee$ events are utilized to calibrate the photon energy scale and resolution [28].

In each event, hadronic jets are formed by clustering the reconstructed PF candidates using the infrared- and collinear-safe anti-k_{T} algorithm [47], as implemented in the FASTJET package [48]. Large-radius jets ("AK8 jets"), with a distance parameter of 0.8, are used to reconstruct hadronically decaying, highly Lorentz-boosted top quark candidates. The jet momentum is determined as the vectorial sum of the jet constituents, and is found from simulation to be, on average, within 5% to 10% of the true momentum over the entire p_{T} spectrum and detector acceptance [49]. Pileup interactions can contribute additional tracks and calorimetric energy depositions to the jet momentum. The pileup-per-particle identification algorithm [50,51] is used to mitigate the effect of pileup at the reconstructed-particle level, making use of local shape information, event pileup properties, and tracking information. A local shape variable is defined, which distinguishes between collinear and soft diffuse distributions of other particles surrounding the particle under consideration. The former is attributed to particles originating from the hard scatter and the latter to particles originating from pileup interactions. Charged particles identified to be originating from pileup vertices are discarded. For each neutral particle, a local shape variable is computed using the surrounding charged particles compatible with the PV within the tracker acceptance ($|\eta| < 2.5$), and using both charged and neutral particles in the region outside of the tracker coverage. The momenta of the neutral particles are then rescaled according to their probability to originate from the PV deduced from the local shape variable, superseding the need for jet-based pileup corrections [50].

Jet energy corrections are derived from simulation studies so that the average measured energy of jets becomes identical to that of particle-level jets. *In situ* measurements of the momentum balance in dijet, $\gamma + +$jet, $Z + +$jet, and multijet events are used to determine any residual differences between the jet energy scale in data and in simulation, and appropriate corrections are made [49]. Additional selection criteria are applied to each jet to remove those potentially dominated by instrumental effects or reconstruction failures [50]. The groomed jet mass is calculated after applying a modified mass-drop algorithm [52,53], known as the soft-drop mass (m_{SD}) [54], to AK8 jets with parameters $\beta = 0$, $z_{\mathrm{cut}} = 0.1$, and $R_0 = 0.8$.

Hadronic decays of top quarks are identified using the PARTICLENET tagger, a graph neural network based jet tagging algorithm [24]. The PF candidates and secondary vertices associated with the AK8 jets are used as input to the algorithm, which is designed to identify different jet types. In this search, the discrimination of t jets against other jet types is utilized. The AK8 jets with a PARTICLENET tagger score above a specific threshold are classified as "t-tagged" jets. For the selected thresholds on the PARTICLENET score, the efficiency for identifying AK8 jets originating from the hadronic decays of top quarks within the kinematic range $400 < p_{\mathrm{T}} < 600$ GeV (where p_{T} denotes the transverse momentum of the AK8 jet) is approximately 82%. Meanwhile, the misidentification rate for jets originating from the hadronization of gluons or light-flavor quarks (u, d, s) is about 0.1%. The m_{SD} and t tagging SFs are derived using $t\bar{t}$ events where one top quark decays into a lepton, neutrino, and a b jet, while the other decays to three jets.

Isolated muon and electron candidates are reconstructed to veto events containing them. Muons are identified using dedicated selection criteria for high-momentum muons, as described in Ref. [55]. The electron identification is performed using a multivariate analysis discriminant that combines various measured properties from the tracker and ECAL [56]. Muons (electrons) must satisfy $|\eta| < 2.4$ and $p_{\mathrm{T}} > 55(40)$ GeV. Electrons in the gap between the ECAL barrel and endcap calorimeters ($1.44 < |\eta| < 1.56$) are excluded, because the reconstruction of an electron object in this region is not optimal. Selected leptons must be separated from the photons and jets by $\Delta R > 0.4$ and 0.8, respectively.

V. EVENT SELECTION AND ANALYSIS STRATEGY

The analysis selection requires exactly one photon in the ECAL barrel region, i.e., $|\eta| < 1.44$, with $p_{\mathrm{T}} > 240$ GeV. Events with photons reconstructed in the endcap regions are excluded due to negligible signal sensitivity. Photons are required to be separated from AK8 jets by $\Delta R > 0.8$. Events containing muons or electrons are excluded, as described above. The AK8 jets are required to be within the region $|\eta| < 2.4$ and must have $p_{\mathrm{T}} > 300$ GeV. Signal events may contain three AK8 jets originating from the top quark, top antiquark, and gluon produced in $t^*\overline{t^*}$ decays, provided all jets fall within the defined acceptance. Events in the signal region (SR) are required to contain at least two AK8 jets, of which one (j_1) must be t tagged with $125 < m_{\mathrm{SD}}^{\mathrm{j}_1} < 225$ GeV and another (j_2) must satisfy $m_{\mathrm{SD}}^{\mathrm{j}_2} > 50$ GeV. No additional requirement is imposed on the total number of AK8 jets in the event. With these selection criteria, most background events that do not contain a top quark are removed. Consequently, additional signal characteristics, such as the presence of high-p_{T} jets from gluons or b quarks, are not utilized. This approach maintains generality and preserves high signal efficiency. The efficiency for the spin-3/2 signal is up to 5% higher than that of the spin-1/2 case, in the mass range 700–2000 GeV, with absolute efficiencies ranging from approximately 8% to 15%. This difference arises because spin-3/2 t^* events are produced more centrally than those of spin-1/2.

We search for the top quarks from t^* decays by requiring at least one t-tagged AK8 jet. The probability of successfully reconstructing both t candidates is less than 20% for t^* particles with masses below 2 TeV in the SR. In events with one t-tagged AK8 jet, there is an ambiguity in the t^* reconstruction since the selected top quark and photon candidates can originate from different t^* parents. For events with two t-tagged AK8 jets, the t-tagged jet with the lower m_{SD} is chosen to associate to the photon and reconstruct the t^* mass ($m_{\gamma \mathrm{j}_1}$). This approach achieves a correct pairing efficiency between the t and γ candidates of about 50%–60% for $m_{t^*} < 2$ TeV. Importantly, the effectiveness of this assignment choice is largely independent of the t^* mass and spin, ensuring consistency across different signal scenarios.

Figure 2 shows the $m_{\gamma \mathrm{j}_1}$ distribution for $t^*\overline{t^*}$ signal events in the SR, for different m_{t^*}. The peak shape is similar for both the spin-1/2 and spin-3/2 signals.

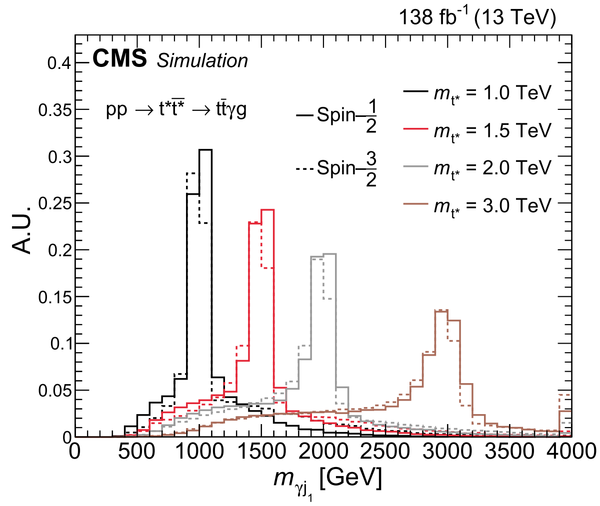

FIG. 2. Shape comparison of the $m_{\gamma j_1}$ distribution for $t^*\overline{t^*}$ signal events generated at different m_{t^*}, for the spin-1/2 (solid) and spin-3/2 (dashed) cases.

VI. BACKGROUND ESTIMATION

After applying the selection criteria, the $\gamma+\text{jet}$ background is substantially reduced by requiring a t-tagged AK8 jet, yet it still accounts for approximately 45% of the remaining total background. The $t\bar{t}\gamma$ process constitutes roughly 50%, with all remaining backgrounds contributing less than 5% in total. Background events are categorized based on their photon origin into three groups:

(i) events with a prompt photon, mostly from the $\gamma+\text{jet}$ and $t\bar{t}\gamma$ processes;
(ii) events with hadrons misidentified as photons, mostly from fully hadronic $t\bar{t}$ decays, referred to hereafter as "$\text{h}\to\gamma$";
(iii) events with electrons misidentified as photons, mostly from $t\bar{t}$ events in the lepton + jets channel, referred to hereafter as "$e\to\gamma$."

In simulation, a reconstructed photon is classified as "prompt" if it is matched to a radiated photon from a primary lepton, quark, or heavy boson. If the selected photon is matched to an electron, it is classified as "$e\to\gamma$." If it comes from other types of particles (e.g., photons from $\pi^0\to\gamma\gamma$ decays or any other hadrons), or no match is found (e.g., photons from pileup interactions), it is classified as "$\text{h}\to\gamma$."

Nontop quark jets, defined as AK8 jets not originating from the hadronic decays of a top quark, can be misidentified as t-tagged jets, and thus pass the SR selection criteria. Among background events with nontop quark AK8 jets in the SR, the $\gamma+\text{jet}$ process is dominant, contributing more than 99% of events. Therefore, we hereafter call the sum of all background processes with a prompt photon and nontop quark AK8 jets the $\gamma+\text{jet}$ background. Detector simulations cannot accurately replicate the top quark mistag rate observed in data; this mistag rate depends not only on the detector performance, but also on the event topology. Additionally, the $\gamma+\text{jet}$ sample is generated at LO, and precise higher-order cross section calculations for the restricted phase space of our analysis are not available. Therefore, we estimate the contribution of the $\gamma+\text{jet}$ background directly from data. Similarly, the $\text{h}\to\gamma$ background is not precisely simulated in the MC-generated samples. Thus, we also estimate the $\text{h}\to\gamma$ background from data, although it is a small background. Contributions of other processes are estimated from simulation.

The $\gamma+\text{jet}$ background is estimated with the following strategy. First, the probability of an AK8 jet not originating from a top quark to be t tagged, which is called the top quark mistag rate (r), is measured. Then, the contribution of the $\gamma+\text{jet}$ background in the SR is estimated using data events in a $\gamma+\text{jet}$ application region (AR). The $\gamma+\text{jet}$ AR is defined by requiring the same selection as the SR except for the number of t-tagged jets, which must be equal to zero. The mistag rate r depends only on the p_T and m_SD of the jet. The probability for an event without any top quarks, containing n AK8 jets, to have exactly zero t-tagged jets is expressed as,

$$P = P_{\text{zero}\,t\text{-tagger jets}}(p_\text{T}, m_\text{SD}) = \prod_{i=1}^{n}(1 - r_i(p_\text{T}, m_\text{SD})). \tag{1}$$

The $\gamma+\text{jet}$ background in the SR is estimated by applying a weight of $(1-P)/P$ to events in the AR.

The top quark mistag rate r is measured using data events in a region with low signal contamination defined by the presence of one photon that passes a looser photon ID condition compared with the medium ID criteria but fails the medium ID selection, together with an AK8 jet. This region is enriched with multijet events featuring a similar proportion of b and c quark jets, as well as the combined contribution from jets originating from light-flavor quarks and gluons (u, d, s quarks and g), as seen in $\gamma+\text{jet}$ events in simulation. The mistag rate r is defined as the ratio of the number of events in which the AK8 jet is t tagged to the total number of selected events. The contribution from processes involving top quarks is subtracted from the data using simulated samples, accounting for less than 10% of events with one t-tagged AK8 jet. The mistag ratio r is extracted in bins of AK8 jet p_T and m_SD.

The $\gamma+\text{jet}$ background estimation is validated in a region with a photon and exactly one AK8 jet that is identified as t tagged. We divide this validation region into two subregions based on the $m_\text{SD}^{j_1}$: $125 < m_\text{SD}^{j_1} < 225$ GeV (VR1), similar to the SR, and $m_\text{SD}^{j_1} < 125$ GeV or $m_\text{SD}^{j_1} > 225$ GeV (VR2). Both VR1 and VR2 have a large $\gamma+\text{jet}$ contribution and minimal signal contamination. The VR2 is used to perform a closure test of the $\gamma+\text{jet}$ estimation, whereas VR1 is included in the final fit to constrain the $\gamma+\text{jet}$ background.

The h → γ background consists of fully hadronic $t\bar{t}$ decay events, where energy deposits from hadrons in the detector are misidentified as originating from a prompt photon. These hadrons tend to have abnormally high fractions of energy deposited in the ECAL. This background is estimated from data using the misidentification rate method [57]. To use the method, we measure the probability (f) that a nonprompt photon passes the medium photon ID selection criteria in a multijet sample. The value f is defined as the ratio of the number of events with a nonprompt photon candidate where

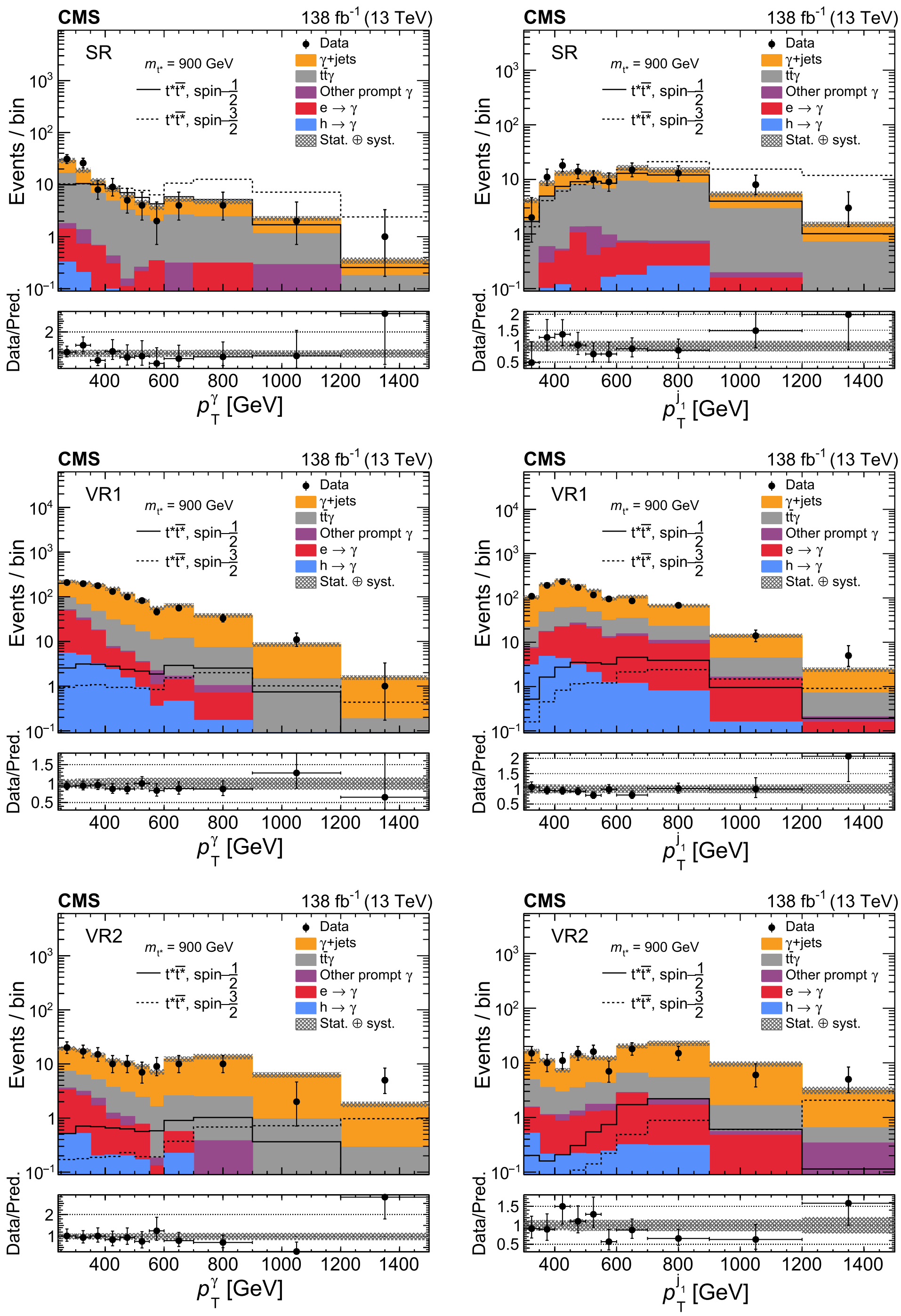

FIG. 3. Photon (left) and j_1 (right) p_T distributions in SR (upper), VR1 (middle), and VR2 (lower) are presented for data and expected backgrounds. Statistical and systematic uncertainties in the expected background yields are depicted by the hatched bands. Additionally, the simulated signal distributions for spin-1/2 and spin-3/2 t^* with a mass of 900 GeV are overlaid for comparison, with both samples normalized to a cross section of 10 fb. The last bins include the overflow. The lower panels show the ratio of the data to the total SM background, with the total uncertainties indicated by the shaded gray band.

the photon passes the medium criteria to the total number of events. The "ABCD" method, a background estimation technique using data that relies on factorizing signal and background contributions in independent control regions (CRs), is used to measure the numerator of f [58]. Since the $\sigma_{i\eta i\eta}$ and I_{chg} variables are almost uncorrelated, three sideband CRs are defined by inverting medium ID requirements on the $\sigma_{i\eta i\eta}$ and I_{chg} variables. The fraction of events with a nonprompt photon candidate in the CRs is larger than 98%. The denominator of f is calculated by adding the number of data events in which the photon fails the medium ID to the numerator of f. The contribution of events with a prompt photon that fails the medium ID is subtracted from data using MC predictions from simulation. The value of f is measured in bins of the reconstructed photon's η. The $\mathrm{h} \to \gamma$ background contributions in the SR, VR1, and VR2 are estimated by reweighting data events that satisfy the same selection criteria, except that the photon is required to fail the medium ID criteria. Each event is assigned a weight of $f/(1-f)$.

The contributions from $\gamma+\mathrm{jet}$ and $\mathrm{h} \to \gamma$ backgrounds are derived from data, and other backgrounds, including $t\bar{t}\gamma$ and $e \to \gamma$, are estimated from simulations. All backgrounds containing a prompt photon alongside a t, W, or Z, except for $t\bar{t}\gamma$, are grouped together and labeled as "other prompt γ." Figure 3 shows the distributions of p_{T} for γ and j_1 in SR, VR1, and VR2. The estimation of the $\gamma+\mathrm{jet}$ background is in good agreement with the observed data in both VR1 and VR2. Additional kinematic distributions in VR1 and VR2 are examined to validate the mistag-rate method and to check for possible residual dependencies on other event variables.

VII. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties, both experimental and theoretical, influence the predicted background yields, distributions, and signal selection efficiency. Uncertainties affecting only event yields are modeled using log-normal distributions, whereas those that impact the shape of distributions are represented with Gaussian distributions. This dual modeling approach effectively corrects for variations in both normalization and kinematic distributions.

The integrated luminosities for the 2016, 2017, and 2018 data-taking periods carry uncertainties of 1.2%–2.5% [59–61], and the combined uncertainty for the entire 2016–2018 period is 1.6%. Pileup modeling uncertainties are evaluated by varying the total inelastic pp cross section by ±4.6% [62], which directly affects the pileup weight applied in simulation.

Trigger SFs are derived from the "tag-and-probe" method [63], using $Z \to ee$ events, to correct the simulated event yields. The associated systematic uncertainties, extracted from the same method, are 1% for photons with $p_{\mathrm{T}} > 240$ GeV.

The systematic uncertainties associated with photon identification SFs are evaluated by varying these SFs within their respective uncertainties. Additional uncertainties in the photon energy scale and resolution are quantified using $Z \to ee$ events, treating the electrons as photonlike by ignoring the track information of the electrons. These events provide a reliable control sample to study discrepancies between measured and simulated photon properties. All photon-related uncertainties, including those for trigger, identification, energy scale, and resolution, are treated as fully correlated across the three data-taking years.

Uncertainties in the jet energy scale and resolution are evaluated by varying the p_{T} of the reconstructed jets in simulated events separately for each of the various uncertainty sources described in Ref. [49]. These uncertainty components are treated based on their origin; some are considered fully correlated across the data-taking eras (e.g., uncertainties from common calibration procedures), whereas others, such as those arising from year-specific detector conditions or from a limited event count, are treated as uncorrelated. For the m_{SD} scale, uncertainties are quantified using the observed shift in the W boson peak mass in a sample enriched with $t\bar{t}$ events in the lepton + jets channel [64]. Efficiency corrections for the t-tagging working point are derived from $t\bar{t}$ events in the leptons + jets channel and applied as a function of AK8 jet p_{T} and $|\eta|$ for AK8 jets originating from top quarks. Systematic uncertainties are assessed by varying the correction factors within their uncertainties. Uncertainties associated with the m_{SD} scale and top quark tagging SF are treated as correlated across the data-taking years.

Theoretical uncertainties due to the renormalization and factorization scales in the matrix element generators are modeled by varying the scales independently by a factor of 0.5 or 2. We exclude the extreme variations (i.e., variations of the two scales in the opposite directions), ensuring that only the relevant variations are included in the uncertainty estimation. The PDF uncertainty is evaluated using a set of replicas of NNPDF3.1 [34]. The final PDF uncertainty is calculated by evaluating distributions for each replica and determining the spread in the predictions. The standard deviation of the results across all replicas quantifies the PDF uncertainty. These theoretical uncertainties are considered for only the signal and $t\bar{t}\gamma$ samples and are implemented by including their modifications to the shapes of kinematic distributions that affect the experimental detection efficiency and signal acceptance. A conservative 30% uncertainty is applied to the normalization of $e \to \gamma$ and other prompt γ backgrounds, which contribute 2% and 3% to the total background in the SR, respectively [65]. All sources of theoretical uncertainties are treated as fully correlated across the data-taking years.

The primary source of uncertainty in the $\gamma+\mathrm{jet}$ background estimate arises from the statistical uncertainty in the transfer function $r(p_{\mathrm{T}}, m_{\mathrm{SD}})$. Each bin of $r(p_{\mathrm{T}}, m_{\mathrm{SD}})$ is treated as an independent source of uncertainty, allowing for a granular assessment. Additionally, a 15% uncertainty on the overall normalization of the $\gamma +$ jet background is included to account for systematic variations. This value is consistent with the level of agreement observed in VR2 between the data and the prediction. The contribution from the $\mathrm{h} \to \gamma$ background to the SR is negligible ($< 1\%$), but a conservative uncertainty of 50% is assigned to this component to account for possible variations. Varying this uncertainty by a factor of two has no noticeable impact on the results.

VIII. RESULTS

The statistical interpretation of the results in this analysis is carried out using the CMS COMBINE framework [66]. A maximum likelihood fit is applied to the $m_{\gamma \mathrm{j}_1}$ distributions in the SR and VR1, with the systematic uncertainties discussed in Sec. VII incorporated as nuisance parameters. To address the finite sizes of the simulated samples, each bin of the simulated signal-plus-background template is varied independently within its statistical uncertainty. This is done following the Barlow-Beeston "lite" approach [67]. While including VR1 in the fit aids in constraining the $\gamma +$ jet background, adding VR2 does not improve the results due to its low statistical significance. Therefore, VR2 is used solely to validate the $\gamma +$ jet background and is not included in the final results.

The background-only fits to the reconstructed m_{t^*} distributions are shown in Fig. 4 for the SR and VR1. The $\gamma +$ jet background describes the data in VR1 within uncertainties. The binning of the $m_{\gamma \mathrm{j}_1}$ distribution is chosen to ensure a sufficient number of data events in the $\gamma +$ jet AR, while preserving sensitivity to a potential signal resonance. No notable excess is observed at low masses in the SR. However, at high masses, the data exhibit a deviation from the background expectation, reaching a maximum local significance of approximately 2.5 standard deviations. After accounting for the look-elsewhere effect over the full mass range probed, the global significance is reduced to approximately 1.8 standard deviations. Variations of the fit configuration, including changes to the treatment of the $\gamma +$ jet background uncertainties, have a negligible impact on the observed significance. In addition, distributions for signal samples with $m_{t^*} = 900$ GeV are shown for both spin-1/2 (solid lines) and spin-3/2 t^* (dotted lines). Both signal samples exhibit distinct peaks at 900 GeV; however, the spin-3/2 signal features a more pronounced tail extending toward higher m_{t^*}, whereas the spin-1/2 signal shows a broader distribution toward lower m_{t^*}.

Upper limits on the $t^*\overline{t^*}$ production cross section times the branching fraction $\mathcal{B}(t^*\overline{t^*} \to t\bar{t}\gamma g)$, are determined for both the spin-1/2 and spin-3/2 hypotheses. These limits are obtained using the distributions of the likelihood ratio, calculated with the asymptotic approximation [68], and the $\mathrm{CL_s}$ criterion [69]. The excluded phase space as a function of m_{t^*} obtained from the expected and observed upper limits at 95% confidence level (CL) is shown in Fig. 5. The three key sources of uncertainty that strongly correlate with the signal strength parameter and are consistent across different t^* masses are the normalization uncertainty of the $\gamma +$ jet process, the renormalization and factorization scale uncertainty in $t\bar{t}\gamma$ simulation, and the uncertainty in the signal PDF. The observed (expected) 95% CL lower limits on the mass of the spin-1/2 and spin-3/2 t^* are 930 (930) GeV and 1330 (1390) GeV, respectively. Although the limits on m_{t^*} depend on the assumed relative branching fractions of $t^* \to t\gamma$ and $t^* \to tg$, we compare our results, assuming $\mathcal{B}(t^* \to t\gamma) = 3\%$ and $\mathcal{B}(t^* \to tg) = 97\%$, with the limits obtained in the $pp \to t^*\overline{t^*} \to t\bar{t}gg$ search by the CMS Collaboration, which assumes $\mathcal{B}(t^* \to tg) = 100\%$ [21], as presented in Table I. These limits could vary due to the dependence of the theoretical prediction on the assumed

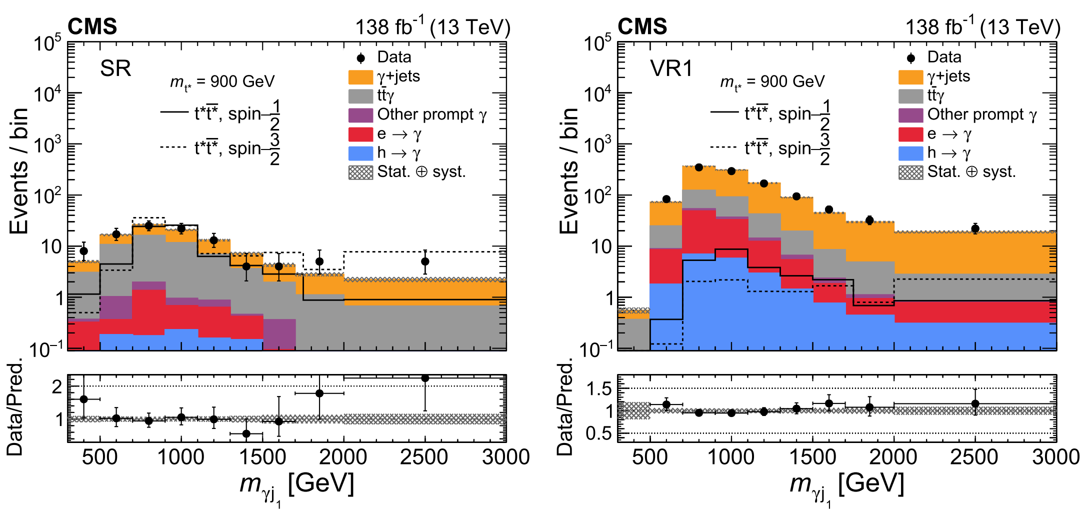

FIG. 4. Background-only postfit $m_{\gamma \mathrm{j}_1}$ distributions for the SR (left) and VR1 (right) are shown. Notations are as in Fig. 3.

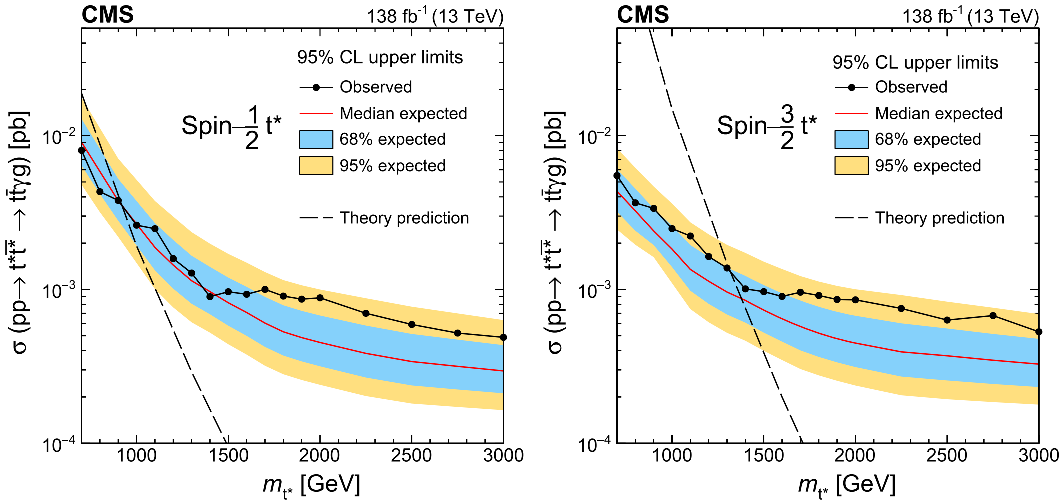

FIG. 5. Expected (red solid lines) and observed (black solid lines) 95% CL upper limits on the cross section of the $pp \to t^*\overline{t^*} \to t\bar{t}\gamma g$ process as functions of the m_{t^*} for a spin-1/2 (left) and spin-3/2 (right) t^*. The blue (inner) and yellow (outer) bands indicate the 68% and 95% coverage of the expected upper limits. The black dashed lines indicate the theoretical expectations [22].

TABLE I. Observed and expected 95% CL lower mass limits for t^* searches comparing this analysis to previous results in the $t\bar{t}gg$ channel [21].

	Observed (GeV)		Expected (GeV)	
Channel	Spin-1/2	Spin-3/2	Spin-1/2	Spin-3/2
$pp \to t^*\overline{t^*} \to t\bar{t}\gamma g$	930	1330	930	1390
$pp \to t^*\overline{t^*} \to t\bar{t}gg$	1050	1700	990	1690

values of $\mathcal{B}(t^* \to t\gamma)$ and $\mathcal{B}(t^* \to tg)$, even though the $pp \to t^*\overline{t^*}$ production cross section is identical in both analyses. Tabulated results are provided in the HEPData record for this analysis [70].

IX. SUMMARY

A search has been presented for spin-1/2 and spin-3/2 heavy particles in a final state with a photon and large-radius jets. The data correspond to an integrated luminosity of 138 fb^{-1} collected between 2016 and 2018 with the CMS detector at the LHC in proton-proton collisions at $\sqrt{s} = 13$ TeV. The pair production of excited top quarks is searched for, considering the decay to (top quark and antiquark, photon and gluon) signature $t^*\overline{t^*} \to t\bar{t}\gamma g$. Lorentz-boosted top quark identification techniques are used to select events containing large-radius jets originating from top quarks and to suppress standard model (SM) backgrounds. A small deviation from the SM expectations with a local significance of 2.5 standard deviations is seen in the data. Upper limits are placed on the product of the $t^*\overline{t^*}$ cross section and $\mathcal{B}(t^*\overline{t^*} \to t\bar{t}\gamma g)$, as a function of the t^* mass. A spin-1/2 (spin-3/2) t^* with a mass below 930 (1330) GeV is excluded at 95% confidence level. These are the first limits obtained from the $t^*\overline{t^*} \to t\bar{t}\gamma g$ channel. They are competitive to the limits obtained from the $t^*\overline{t^*} \to t\bar{t}gg$ channel for a spin-$1/2 t^*$ using complementary techniques.

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DATA AVAILABILITY

Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, reuse, and open access policy [71].

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Carvalho Antunes De Oliveira,[18] S. Deng,[18] B. Guo,[18] Q. Guo,[18] C. Jiang,[18] A. Levin,[18] C. Li,[18] Q. Li,[18] Y. Mao,[18] S. Qian,[18] S. J. Qian,[18] X. Qin,[18] X. Sun,[18] D. Wang,[18] J. Wang,[18] H. Yang,[18] M. Zhang,[18] Y. Zhao,[18] C. Zhou,[18] S. Yang,[19] Z. You,[20] K. Jaffel,[21] N. Lu,[21] G. Bauer,[22,l,m] B. Li,[22,n] H. Wang,[22] K. Yi,[22,o] J. Zhang,[22] Y. Li,[23] Z. Lin,[24] C. Lu,[24] M. Xiao,[24,p] C. Avila,[25] D. A. Barbosa Trujillo,[25] A. Cabrera,[25] C. Florez,[25] J. Fraga,[25] J. A. Reyes Vega,[25] C. Rendón,[26] M. Rodriguez,[26] A. A. Ruales Barbosa,[26] J. D. Ruiz Alvarez,[26] N. Godinovic,[27] D. Lelas,[27] A. Sculac,[27] M. Kovac,[28] A. Petkovic,[28] T. Sculac,[28] P. Bargassa,[29] V. Brigljevic,[29] B. K. Chitroda,[29] D. Ferencek,[29] K. Jakovcic,[29] A. Starodumov,[29] T. Susa,[29] A. Attikis,[30] K. Christoforou,[30] A. Hadjiagapiou,[30] C. Leonidou,[30] C. Nicolaou,[30] L. Paizanos,[30] F. Ptochos,[30] P. A. Razis,[30] H. Rykaczewski,[30] H. Saka,[30] A. Stepennov,[30] M. Finger,[31,a] M. Finger Jr.,[31] E. Ayala,[32] E. Carrera Jarrin,[33] S. Khalil,[34,q] E. Salama,[34,r,s] M. Abdullah Al-Mashad,[35] A. Hussein,[35] H. Mohammed,[35] K. Ehataht,[36] M. Kadastik,[36] T. Lange,[36] C. Nielsen,[36] J. Pata,[36] M. Raidal,[36] N. Seeba,[36] L. Tani,[36] A. Milieva,[37] K. Osterberg,[37] M. Voutilainen,[37] N. Bin Norjoharuddeen,[38] E. Brücken,[38] F. Garcia,[38] P. Inkaew,[38] K. T. S. Kallonen,[38] R. Kumar Verma,[38] T. Lampén,[38] K. Lassila-Perini,[38] B. Lehtela,[38] S. Lehti,[38] T. Lindén,[38] N. R. Mancilla Xinto,[38] M. Myllymäki,[38] M. m. Rantanen,[38] S. Saariokari,[38] N. T. Toikka,[38] J. Tuominiemi,[38] H. Kirschenmann,[39] P. Luukka,[39] H. Petrow,[39] M. Besancon,[40] F. Couderc,[40] M. Dejardin,[40] D. Denegri,[40] P. Devouge,[40] J. L. Faure,[40] F. Ferri,[40] P. Gaigne,[40] S. Ganjour,[40] P. Gras,[40] G. Hamel de Monchenault,[40] M. Kumar,[40] V. Lohezic,[40] J. Malcles,[40] F. Orlandi,[40] L. Portales,[40] S. Ronchi,[40] M. Ö. Sahin,[40] A. Savoy-Navarro,[40,t] P. Simkina,[40] M. Titov,[40] M. Tornago,[40] F. Beaudette,[41] G. Boldrini,[41] P. Busson,[41] C. Charlot,[41] M. Chiusi,[41] T. D. Cuisset,[41] F. Damas,[41] O. Davignon,[41] A. De Wit,[41] T. Debnath,[41] I. T. Ehle,[41] B. A. Fontana Santos Alves,[41] S. Ghosh,[41] A. Gilbert,[41] R. Granier de Cassagnac,[41] L. Kalipoliti,[41] M. Manoni,[41] M. Nguyen,[41] S. Obraztsov,[41] C. Ochando,[41] R. Salerno,[41] J. B. Sauvan,[41] Y. Sirois,[41] G. Sokmen,[41] L. Urda Gómez,[41] A. Zabi,[41] A. Zghiche,[41] J.-L. Agram,[42,u] J. Andrea,[42] D. Bloch,[42] J.-M. Brom,[42] E. C. Chabert,[42] C. Collard,[42] G. Coulon,[42] S. Falke,[42] U. Goerlach,[42] R. Haeberle,[42] A.-C. Le Bihan,[42] M. Meena,[42] O. Poncet,[42] G. Saha,[42] P. Vaucelle,[42] A. Di Florio,[43] D. Amram,[44] S. Beauceron,[44] B. Blancon,[44] G. Boudoul,[44] N. Chanon,[44] D. Contardo,[44] P. Depasse,[44] C. Dozen,[44,v] H. El Mamouni,[44] J. Fay,[44] S. Gascon,[44] M. Gouzevitch,[44] C. Greenberg,[44] G. Grenier,[44] B. Ille,[44] E. Jourd'huy,[44] I. B. Laktineh,[44] M. Lethuillier,[44] B. Massoteau,[44] L. Mirabito,[44] A. Purohit,[44] M. Vander Donckt,[44] J. Xiao,[44] I. Lomidze,[45] T. Toriashvili,[45,w] Z. Tsamalaidze,[45,x] V. Botta,[46] S. Consuegra Rodríguez,[46] L. Feld,[46] K. Klein,[46] M. Lipinski,[46] D. Meuser,[46] P. Nattland,[46] V. Oppenländer,[46] A. Pauls,[46] D. Pérez Adán,[46] N. Röwert,[46] M. Teroerde,[46] C. Daumann,[47] S. Diekmann,[47] A. Dodonova,[47] N. Eich,[47] D. Eliseev,[47] F. Engelke,[47] J. Erdmann,[47] M. Erdmann,[47] B. Fischer,[47] T. Hebbeker,[47] K. Hoepfner,[47] F. Ivone,[47] A. Jung,[47] N. Kumar,[47] M. y. Lee,[47] F. Mausolf,[47] M. Merschmeyer,[47] A. Meyer,[47] F. Nowotny,[47] A. Pozdnyakov,[47] W. Redjeb,[47] H. Reithler,[47] U. Sarkar,[47] V. Sarkisovi,[47] A. Schmidt,[47] C. Seth,[47] A. Sharma,[47] J. L. Spah,[47] V. Vaulin,[47] S. Zaleski,[47] M. R. Beckers,[48] C. Dziwok,[48] G. Flügge,[48] N. Hoeflich,[48] T. Kress,[48] A. Nowack,[48] O. Pooth,[48] A. Stahl,[48] A. Zotz,[48] H. Aarup Petersen,[49] A. Abel,[49] M. Aldaya Martin,[49] J. Alimena,[49] S. Amoroso,[49] Y. An,[49] I. Andreev,[49] J. Bach,[49] S. Baxter,[49] M. Bayatmakou,[49] H. Becerril Gonzalez,[49] O. Behnke,[49] A. Belvedere,[49] F. Blekman,[49,y] K. Borras,[49,z] A. Campbell,[49] S. Chatterjee,[49] L. X. Coll Saravia,[49] G. Eckerlin,[49] D. Eckstein,[49] E. Gallo,[49,y] A. Geiser,[49] V. Guglielmi,[49] M. Guthoff,[49] A. Hinzmann,[49] L. Jeppe,[49] M. Kasemann,[49] C. Kleinwort,[49] R. Kogler,[49] M. Komm,[49] D. Krücker,[49] W. Lange,[49] D. Leyva Pernia,[49] K.-Y. Lin,[49] K. Lipka,[49,aa] W. Lohmann,[49,bb] J. Malvaso,[49] R. Mankel,[49] I.-A. Melzer-Pellmann,[49] M. Mendizabal Morentin,[49] A. B. Meyer,[49] G. Milella,[49] K. Moral Figueroa,[49]

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Dhingra,[61,kk] A. Kaur,[61] A. Kaur,[61] H. Kaur,[61] M. Kaur,[61] S. Kumar,[61] T. Sheokand,[61] J. B. Singh,[61] A. Singla,[61] A. Bhardwaj,[62] A. Chhetri,[62] B. C. Choudhary,[62] A. Kumar,[62] A. Kumar,[62] M. Naimuddin,[62] S. Phor,[62] K. Ranjan,[62] M. K. Saini,[62] S. Acharya,[63,ll] B. Gomber,[63,ll] B. Sahu,[63,ll] S. Mukherjee,[64] S. Baradia,[65] S. Bhattacharya,[65] S. Das Gupta,[65] S. Dutta,[65] S. Dutta,[65] S. Sarkar,[65] M. M. Ameen,[66] P. K. Behera,[66] S. Chatterjee,[66] G. Dash,[66] A. Dattamunsi,[66] P. Jana,[66] P. Kalbhor,[66] S. Kamble,[66] J. R. Komaragiri,[66,mm] T. Mishra,[66] P. R. Pujahari,[66] A. K. Sikdar,[66] R. K. Singh,[66] P. Verma,[66] S. Verma,[66] A. Vijay,[66] B. K. Sirasva,[67] L. Bhatt,[68] S. Dugad,[68] G. B. Mohanty,[68] M. Shelake,[68] P. Suryadevara,[68] A. Bala,[69] S. Banerjee,[69] S. Barman,[69,nn] R. M. Chatterjee,[69] M. Guchait,[69] Sh. Jain,[69] A. Jaiswal,[69] B. M. Joshi,[69] S. Kumar,[69] M. Maity,[69,nn] G. Majumder,[69] K. Mazumdar,[69] S. Parolia,[69] R. Saxena,[69] A. Thachayath,[69] S. Bahinipati,[70,oo] D. Maity,[70,pp] P. Mal,[70] K. Naskar,[70,pp] A. Nayak,[70,pp] S. Nayak,[70] K. Pal,[70] R. Raturi,[70] P. Sadangi,[70] S. K. Swain,[70] S. Varghese,[70,pp] D. Vats,[70,pp] A. Alpana,[71] S. Dube,[71] P. Hazarika,[71] B. Kansal,[71] A. Laha,[71] R. Sharma,[71] S. Sharma,[71] K. Y. Vaish,[71] S. Ghosh,[72] H. Bakhshiansohi,[73,qq] A. Jafari,[73,rr] V. Sedighzadeh Dalavi,[73] M. Zeinali,[73,ss] S. Bashiri,[74] S. Chenarani,[74,tt] S. M. Etesami,[74] Y. Hosseini,[74] M. Khakzad,[74] E. Khazaie,[74] M. Mohammadi Najafabadi,[74] S. Tizchang,[74,uu] M. Felcini,[75] M. Grunewald,[75] M. Abbrescia,[76a,76b] M. Barbieri,[76a,76b] M. Buonsante,[76a,76b] A. Colaleo,[76a,76b] D. Creanza,[76a,76c] B. D'Anzi,[76a,76b] N. De Filippis,[76a,76c] M. De Palma,[76a,76b] W. Elmetenawee,[76a,76b,vv] N. Ferrara,[76a,76c] L. Fiore,[76a] L. Longo,[76a] M. Louka,[76a,76b] G. Maggi,[76a,76c] M. Maggi,[76a] I. 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S. Costa,[78a,78b,xx] A. Di Mattia,[78a] A. Lapertosa,[78a] R. Potenza,[78a,78b] A. Tricomi,[78a,78b,xx] J. Altork,[79a,79b] P. Assiouras,[79a] G. Barbagli,[79a] G. Bardelli,[79a] M. Bartolini,[79a,79b] A. Calandri,[79a,79b] B. Camaiani,[79a,79b] A. Cassese,[79a] R. Ceccarelli,[79a] V. Ciulli,[79a,79b] C. Civinini,[79a] R. D'Alessandro,[79a,79b] L. Damenti,[79a,79b] E. Focardi,[79a,79b] T. Kello,[79a] G. Latino,[79a,79b] P. Lenzi,[79a,79b] M. Lizzo,[79a] M. Meschini,[79a] S. Paoletti,[79a] A. Papanastassiou,[79a,79b] G. Sguazzoni,[79a] L. Viliani,[79a] L. Benussi,[80] S. Colafranceschi,[80,yy] S. Meola,[80,zz] D. Piccolo,[80] M. Alves Gallo Pereira,[81a] F. Ferro,[81a] E. Robutti,[81a] S. Tosi,[81a,81b] A. Benaglia,[82a] F. Brivio,[82a] V. Camagni,[82a,82b] F. Cetorelli,[82a,82b] F. De Guio,[82a,82b] M. E. Dinardo,[82a,82b] P. Dini,[82a] S. Gennai,[82a] R. Gerosa,[82a,82b] A. Ghezzi,[82a,82b] P. Govoni,[82a,82b] L. Guzzi,[82a] M. R. Kim,[82a] G. Lavizzari,[82a,82b] M. T. Lucchini,[82a,82b] M. Malberti,[82a] S. Malvezzi,[82a] A. Massironi,[82a] D. Menasce,[82a] L. Moroni,[82a] M. Paganoni,[82a,82b] S. Palluotto,[82a,82b] D. Pedrini,[82a] A. Perego,[82a,82b] G. Pizzati,[82a,82b] S. Ragazzi,[82a,82b] T. Tabarelli de Fatis,[82a,82b] S. Buontempo,[83a] C. Di Fraia,[83a,83b] F. Fabozzi,[83a,83c] L. Favilla,[83a,83d] A. O. M. Iorio,[83a,83b] L. Lista,[83a,83b,aaa] P. Paolucci,[83a,dd] B. Rossi,[83a] P. Azzi,[84a] N. Bacchetta,[84a,bbb] D. Bisello,[84a,84b] P. Bortignon,[84a,84c] G. Bortolato,[84a,84b] A. C. M. Bulla,[84a,84c] R. Carlin,[84a,84b] P. Checchia,[84a] T. Dorigo,[84a,ccc] F. Fanzago,[84a] U. Gasparini,[84a,84b] S. Giorgetti,[84a] E. Lusiani,[84a] M. Margoni,[84a,84b] A. T. Meneguzzo,[84a,84b] J. Pazzini,[84a,84b] P. Ronchese,[84a,84b] R. Rossin,[84a,84b] F. Simonetto,[84a,84b] M. Tosi,[84a,84b] A. Triossi,[84a,84b] M. Zanetti,[84a,84b] P. Zotto,[84a,84b] A. Zucchetta,[84a,84b] G. Zumerle,[84a,84b] A. Braghieri,[85a] S. Calzaferri,[85a] P. Montagna,[85a,85b] M. Pelliccioni,[85a] V. Re,[85a] C. Riccardi,[85a,85b] P. Salvini,[85a] I. Vai,[85a,85b] P. Vitulo,[85a,85b] S. Ajmal,[86a,86b] M. E. Ascioti,[86a,86b] G. M. Bilei,[86a] C. Carrivale,[86a,86b] D. Ciangottini,[86a,86b] L. Della Penna,[86a,86b] L. Fanò,[86a,86b] V. Mariani,[86a,86b] M. Menichelli,[86a] F. Moscatelli,[86a,ddd] A. Rossi,[86a,86b] A. Santocchia,[86a,86b] D. Spiga,[86a] T. Tedeschi,[86a,86b] C. Aimè,[87a,87b] C. A. Alexe,[87a,87c] P. Asenov,[87a,87b] P. Azzurri,[87a] G. Bagliesi,[87a] R. Bhattacharya,[87a] L. Bianchini,[87a,87b] T. Boccali,[87a] E. Bossini,[87a] D. Bruschini,[87a,87c] L. Calligaris,[87a,87b] R. Castaldi,[87a] F. Cattafesta,[87a,87c] M. A. Ciocci,[87a,87d] M. Cipriani,[87a,87b] R. Dell'Orso,[87a] S. Donato,[87a,87b] R. Forti,[87a,87b] A. Giassi,[87a] F. Ligabue,[87a,87c] A. C. Marini,[87a,87b] D. Matos Figueiredo,[87a] A. Messineo,[87a,87b] S. Mishra,[87a] V. K. Muraleedharan Nair Bindhu,[87a,87b] S. Nandan,[87a] F. Palla,[87a] M. Riggirello,[87a,87c] A. Rizzi,[87a,87b] G. Rolandi,[87a,87c] S. Roy Chowdhury,[87a,eee] T. Sarkar,[87a] A. Scribano,[87a] P. Solanki,[87a,87b] P. Spagnolo,[87a] F. Tenchini,[87a,87b] R. Tenchini,[87a] G. Tonelli,[87a,87b] N. Turini,[87a,87d] F. Vaselli,[87a,87c] A. Venturi,[87a] P. G. Verdini,[87a] P. Akrap,[88a,88b] C. Basile,[88a,88b] S. C. Behera,[88a] F. Cavallari,[88a] L. Cunqueiro Mendez,[88a,88b] F. De Riggi,[88a,88b] D. Del Re,[88a,88b] E. Di Marco,[88a] M. Diemoz,[88a] F. Errico,[88a] L. Frosina,[88a,88b] R. Gargiulo,[88a,88b] B. Harikrishnan,[88a,88b] F. Lombardi,[88a,88b] E. Longo,[88a,88b] L. Martikainen,[88a,88b] J. Mijuskovic,[88a,88b] G. Organtini,[88a,88b] N. Palmeri,[88a,88b] R. Paramatti,[88a,88b] C. Quaranta,[88a,88b] S. Rahatlou,[88a,88b] C. Rovelli,[88a] F. Santanastasio,[88a,88b] L. Soffi,[88a] V. Vladimirov,[88a,88b] N. Amapane,[89a,89b] R. Arcidiacono,[89a,89c] S. Argiro,[89a,89b] M. Arneodo,[89a,89c] N. Bartosik,[89a,89c] R. Bellan,[89a,89b] A. Bellora,[89a,89b] C. Biino,[89a] C. Borca,[89a,89b] N. Cartiglia,[89a] M. Costa,[89a,89b] R. Covarelli,[89a,89b] N. Demaria,[89a] L. Finco,[89a] M. Grippo,[89a,89b] B. Kiani,[89a,89b] L. Lanteri,[89a,89b] F. Legger,[89a] F. Luongo,[89a,89b] C. Mariotti,[89a] S. Maselli,[89a] A. Mecca,[89a,89b] L. Menzio,[89a,89b] P. Meridiani,[89a] E. Migliore,[89a,89b] M. Monteno,[89a] M. M. Obertino,[89a,89b] G. Ortona,[89a] L. Pacher,[89a,89b] N. Pastrone,[89a] M. Ruspa,[89a,89c] F. Siviero,[89a,89b] V. Sola,[89a,89b] A. Solano,[89a,89b] A. Staiano,[89a] C. Tarricone,[89a,89b] D. Trocino,[89a] G. Umoret,[89a,89b] E. Vlasov,[89a,89b] R. White,[89a,89b] J. Babbar,[90a,90b] S. Belforte,[90a] V. Candelise,[90a,90b] M. Casarsa,[90a] F. Cossutti,[90a] K. De Leo,[90a] G. Della Ricca,[90a,90b] R. Delli Gatti,[90a,90b] S. Dogra,[91] J. Hong,[91] J. Kim,[91] T. Kim,[91] D. Lee,[91] H. Lee,[91] J. Lee,[91] S. W. Lee,[91] C. S. Moon,[91] Y. D. Oh,[91] S. Sekmen,[91] B. Tae,[91] Y. C. Yang,[91] M. S. Kim,[92] G. Bak,[93] P. Gwak,[93] H. Kim,[93] D. H. Moon,[93] J. Seo,[93] E. Asilar,[94] F. Carnevali,[94] J. Choi,[94,fff] T. J. Kim,[94] Y. Ryou,[94] S. Ha,[95] S. Han,[95] B. Hong,[95] J. Kim,[95] K. Lee,[95] K. S. Lee,[95] S. Lee,[95] J. Yoo,[95] J. Goh,[96] J. Shin,[96] S. Yang,[96] Y. Kang,[97] H. S. Kim,[97] Y. Kim,[97] S. Lee,[97] J. Almond,[98] J. H. Bhyun,[98] J. Choi,[98] J. Choi,[98] W. Jun,[98] H. Kim,[98] J. Kim,[98] T. Kim,[98] Y. Kim,[98] Y. W. Kim,[98] S. Ko,[98] H. Lee,[98] J. Lee,[98] J. Lee,[98] B. H. Oh,[98] S. B. Oh,[98] J. Shin,[98] U. K. Yang,[98] I. Yoon,[98] W. Jang,[99] D. Y. Kang,[99] D. Kim,[99] S. Kim,[99] B. Ko,[99] J. S. H. Lee,[99] Y. Lee,[99] I. C. Park,[99] Y. Roh,[99] I. J. Watson,[99] G. Cho,[100] K. Hwang,[100] B. Kim,[100] S. Kim,[100] K. Lee,[100] H. D. Yoo,[100] M. Choi,[101] Y. Lee,[101] I. Yu,[101] T. Beyrouthy,[102] Y. Gharbia,[102] F. Alazemi,[103] K. Dreimanis,[104] O. M. Eberlins,[104] A. Gaile,[104] C. Munoz Diaz,[104] D. Osite,[104] G. Pikurs,[104] R. Plese,[104] A. Potrebko,[104] M. Seidel,[104] D. Sidiropoulos Kontos,[104] N. R. Strautnieks,[105] M. Ambrozas,[106]

A. Juodagalvis,[106] S. Nargelas,[106] A. Rinkevicius,[106] G. Tamulaitis,[106] I. Yusuff,[107,ggg] Z. Zolkapli,[107] J. F. Benitez,[108] A. Castaneda Hernandez,[108] A. Cota Rodriguez,[108] L. E. Cuevas Picos,[108] H. A. Encinas Acosta,[108] L. G. Gallegos Maríñez,[108] J. A. Murillo Quijada,[108] L. Valencia Palomo,[108] G. Ayala,[109] H. Castilla-Valdez,[109] H. Crotte Ledesma,[109] R. Lopez-Fernandez,[109] J. Mejia Guisao,[109] R. Reyes-Almanza,[109] A. Sánchez Hernández,[109] C. Oropeza Barrera,[110] D. L. Ramirez Guadarrama,[110] M. Ramírez García,[110] I. Bautista,[111] F. E. Neri Huerta,[111] I. Pedraza,[111] H. A. Salazar Ibarguen,[111] C. Uribe Estrada,[111] I. Bubanja,[112] N. Raicevic,[112] P. H. Butler,[113] A. Ahmad,[114] M. I. Asghar,[114] A. Awais,[114] M. I. M. Awan,[114] W. A. Khan,[114] V. Avati,[115] L. Forthomme,[115] L. Grzanka,[115] M. Malawski,[115] K. Piotrzkowski,[115] M. Bluj,[116] M. Górski,[116] M. Kazana,[116] M. Szleper,[116] P. Zalewski,[116] K. Bunkowski,[117] K. Doroba,[117] A. Kalinowski,[117] M. Konecki,[117] J. Krolikowski,[117] A. Muhammad,[117] P. Fokow,[118] K. Pozniak,[118] W. Zabolotny,[118] M. Araujo,[119] D. Bastos,[119] C. Beirão Da Cruz E Silva,[119] A. Boletti,[119] M. Bozzo,[119] T. Camporesi,[119] G. Da Molin,[119] M. Gallinaro,[119] J. Hollar,[119] N. Leonardo,[119] G. B. Marozzo,[119] A. Petrilli,[119] M. Pisano,[119] J. Seixas,[119] J. Varela,[119] J. W. Wulff,[119] P. Adzic,[120] L. Markovic,[120] P. Milenovic,[120] V. Milosevic,[120] D. Devetak,[121] M. Dordevic,[121] J. Milosevic,[121] L. Nadderd,[121] V. Rekovic,[121] M. Stojanovic,[121] M. Alcalde Martinez,[122] J. Alcaraz Maestre,[122] Cristina F. Bedoya,[122] J. A. Brochero Cifuentes,[122] Oliver M. Carretero,[122] M. Cepeda,[122] M. Cerrada,[122] N. Colino,[122] J. Cuchillo Ortega,[122] B. De La Cruz,[122] A. Delgado Peris,[122] A. Escalante Del Valle,[122] D. Fernández Del Val,[122] J. P. Fernández Ramos,[122] J. Flix,[122] M. C. Fouz,[122] M. Gonzalez Hernandez,[122] O. Gonzalez Lopez,[122] S. Goy Lopez,[122] J. M. Hernandez,[122] M. I. Josa,[122] J. Llorente Merino,[122] C. Martin Perez,[122] E. Martin Viscasillas,[122] D. Moran,[122] C. M. Morcillo Perez,[122] R. Paz Herrera,[122] C. Perez Dengra,[122] A. Pérez-Calero Yzquierdo,[122] J. Puerta Pelayo,[122] I. Redondo,[122] J. Vazquez Escobar,[122] J. F. de Trocóniz,[123] B. Alvarez Gonzalez,[124] J. Ayllon Torresano,[124] A. Cardini,[124] J. Cuevas,[124] J. Del Riego Badas,[124] D. Estrada Acevedo,[124] J. Fernandez Menendez,[124] S. Folgueras,[124] I. Gonzalez Caballero,[124] P. Leguina,[124] M. Obeso Menendez,[124] E. Palencia Cortezon,[124] J. Prado Pico,[124] A. Soto Rodríguez,[124] C. Vico Villalba,[124] P. Vischia,[124] S. Blanco Fernández,[125] I. J. Cabrillo,[125] A. Calderon,[125] J. Duarte Campderros,[125] M. Fernandez,[125] G. Gomez,[125] C. Lasaosa García,[125] R. Lopez Ruiz,[125] C. Martinez Rivero,[125] P. Martinez Ruiz del Arbol,[125] F. Matorras,[125] P. Matorras Cuevas,[125] E. Navarrete Ramos,[125] J. Piedra Gomez,[125] C. Quintana San Emeterio,[125] L. Scodellaro,[125] I. Vila,[125] R. Vilar Cortabitarte,[125] J. M. Vizan Garcia,[125] B. Kailasapathy,[126,hhh] D. D. C. Wickramarathna,[126] W. G. D. Dharmaratna,[127,iii] K. Liyanage,[127] N. Perera,[127] D. Abbaneo,[128] C. Amendola,[128] R. Ardino,[128] E. Auffray,[128] J. Baechler,[128] D. Barney,[128] M. Bianco,[128] A. Bocci,[128] L. Borgonovi,[128] C. Botta,[128] A. Bragagnolo,[128] C. E. Brown,[128] C. Caillol,[128] G. Cerminara,[128] P. Connor,[128] D. d'Enterria,[128] A. Dabrowski,[128] A. David,[128] A. De Roeck,[128] M. M. Defranchis,[128] M. Deile,[128] M. Dobson,[128] P. J. Fernández Manteca,[128] W. Funk,[128] A. Gaddi,[128] S. Giani,[128] D. Gigi,[128] K. Gill,[128] F. Glege,[128] M. Glowacki,[128] A. Gruber,[128] J. Hegeman,[128] J. K. Heikkilä,[128] B. Huber,[128] V. Innocente,[128] T. James,[128] P. Janot,[128] O. Kaluzinska,[128] O. Karacheban,[128,bb] G. Karathanasis,[128] S. Laurila,[128] P. Lecoq,[128] C. Lourenço,[128] A.-M. Lyon,[128] M. Magherini,[128] L. Malgeri,[128] M. Mannelli,[128] A. Mehta,[128] F. Meijers,[128] J. A. Merlin,[128] S. Mersi,[128] E. Meschi,[128] M. Migliorini,[128] F. Monti,[128] F. Moortgat,[128] M. Mulders,[128] M. Musich,[128] I. Neutelings,[128] S. Orfanelli,[128] F. Pantaleo,[128] M. Pari,[128] G. Petrucciani,[128] A. Pfeiffer,[128] M. Pierini,[128] M. Pitt,[128] H. Qu,[128] D. Rabady,[128] A. Reimers,[128] B. Ribeiro Lopes,[128] F. Riti,[128] P. Rosado,[128] M. Rovere,[128] H. Sakulin,[128] R. Salvatico,[128] S. Sanchez Cruz,[128] S. Scarfi,[128] M. Selvaggi,[128] A. Sharma,[128] K. Shchelina,[128] P. Silva,[128] P. Sphicas,[128,jjj] A. G. Stahl Leiton,[128] A. Steen,[128] S. Summers,[128] D. Treille,[128] P. Tropea,[128] E. Vernazza,[128] J. Wanczyk,[128,kkk] J. Wang,[128] S. Wuchterl,[128] M. Zarucki,[128] P. Zehetner,[128] P. Zejdl,[128] G. Zevi Della Porta,[128] T. Bevilacqua,[129,lll] L. Caminada,[129,lll] W. Erdmann,[129] R. Horisberger,[129] Q. Ingram,[129] H. C. Kaestli,[129] D. Kotlinski,[129] C. Lange,[129] U. Langenegger,[129] L. Noehte,[129,lll] T. Rohe,[129] A. Samalan,[129] T. K. Aarrestad,[130] M. Backhaus,[130] G. Bonomelli,[130] C. Cazzaniga,[130] K. Datta,[130] P. De Bryas Dexmiers D'archiacchiac,[130,kkk] A. De Cosa,[130] G. Dissertori,[130] M. Dittmar,[130] M. Donegà,[130] F. Eble,[130] K. Gedia,[130] F. Glessgen,[130] C. Grab,[130] N. Härringer,[130] T. G. Harte,[130] W. Lustermann,[130] M. Malucchi,[130] R. A. Manzoni,[130] M. Marchegiani,[130] L. Marchese,[130] A. Mascellani,[130,kkk] F. Nessi-Tedaldi,[130] F. Pauss,[130] V. Perovic,[130] B. Ristic,[130] R. Seidita,[130] J. Steggemann,[130,kkk] A. Tarabini,[130] D. Valsecchi,[130]

R. Wallny,[130] C. Amsler,[131,mmm] P. Bärtschi,[131] F. Bilandzija,[131] M. F. Canelli,[131] G. Celotto,[131] K. Cormier,[131] M. Huwiler,[131] W. Jin,[131] A. Jofrehei,[131] B. Kilminster,[131] T. H. Kwok,[131] S. Leontsinis,[131] V. Lukashenko,[131] A. Macchiolo,[131] F. Meng,[131] M. Missiroli,[131] J. Motta,[131] P. Robmann,[131] M. Senger,[131] E. Shokr,[131] F. Stäger,[131] R. Tramontano,[131] P. Viscone,[131] D. Bhowmik,[132] C. M. Kuo,[132] P. K. Rout,[132] S. Taj,[132] P. C. Tiwari,[132,mm] L. Ceard,[133] K. F. Chen,[133] Z. g. Chen,[133] A. De Iorio,[133] W.-S. Hou,[133] T. h. Hsu,[133] Y. w. Kao,[133] S. Karmakar,[133] G. Kole,[133] Y. y. Li,[133] R.-S. Lu,[133] E. Paganis,[133] X. f. Su,[133] J. Thomas-Wilsker,[133] L. s. Tsai,[133] D. Tsionou,[133] H. y. Wu,[133] E. Yazgan,[133] C. Asawatangtrakuldee,[134] N. Srimanobhas,[134] Y. Maghrbi,[135] D. Agyel,[136] F. Dolek,[136] I. Dumanoglu,[136,nnn] Y. Guler,[136,ooo] E. Gurpinar Guler,[136,ooo] C. Isik,[136] O. Kara,[136] A. Kayis Topaksu,[136] Y. Komurcu,[136] G. Onengut,[136] K. Ozdemir,[136,ppp] B. Tali,[136,qqq] U. G. Tok,[136] E. Uslan,[136] I. S. Zorbakir,[136] M. Yalvac,[137,rrr] B. Akgun,[138] I. O. Atakisi,[138,sss] E. Gülmez,[138] M. Kaya,[138,ttt] O. Kaya,[138,uuu] M. A. Sarkisla,[138,vvv] S. Tekten,[138,www] A. Cakir,[139] K. Cankocak,[139,nnn,xxx] S. Sen,[139,yyy] O. Aydilek,[140,zzz] B. Hacisahinoglu,[140] I. Hos,[140,aaaa] B. Kaynak,[140] S. Ozkorucuklu,[140] O. Potok,[140] H. Sert,[140] C. Simsek,[140] C. Zorbilmez,[140] S. Cerci,[141] B. Isildak,[141,bbbb] E. Simsek,[141] D. Sunar Cerci,[141] T. Yetkin,[141,v] A. Boyaryntsev,[142] O. Dadazhanova,[142] B. Grynyov,[142] L. Levchuk,[143] J. J. Brooke,[144] A. Bundock,[144] F. Bury,[144] E. Clement,[144] D. Cussans,[144] D. Dharmender,[144] H. Flacher,[144] J. Goldstein,[144] H. F. Heath,[144] M.-L. Holmberg,[144] L. Kreczko,[144] S. Paramesvaran,[144] L. Robertshaw,[144] M. S. Sanjrani,[144,qq] J. Segal,[144] V. J. Smith,[144] A. H. Ball,[145] K. W. Bell,[145] A. Belyaev,[145,cccc] C. Brew,[145] R. M. Brown,[145] D. J. A. Cockerill,[145] A. Elliot,[145] K. V. Ellis,[145] J. Gajownik,[145] K. Harder,[145] S. Harper,[145] J. Linacre,[145] K. Manolopoulos,[145] M. Moallemi,[145] D. M. Newbold,[145] E. Olaiya,[145] D. Petyt,[145] T. Reis,[145] A. R. Sahasransu,[145] G. Salvi,[145] T. Schuh,[145] C. H. Shepherd-Themistocleous,[145] I. R. Tomalin,[145] K. C. Whalen,[145] T. Williams,[145] I. Andreou,[146] R. Bainbridge,[146] P. Bloch,[146] O. Buchmuller,[146] C. A. Carrillo Montoya,[146] D. Colling,[146] J. S. Dancu,[146] I. Das,[146] P. Dauncey,[146] G. Davies,[146] M. Della Negra,[146] S. Fayer,[146] G. Fedi,[146] G. Hall,[146] H. R. Hoorani,[146] A. Howard,[146] G. Iles,[146] C. R. Knight,[146] P. Krueper,[146] J. Langford,[146] K. H. Law,[146] J. León Holgado,[146] E. Leutgeb,[146] L. Lyons,[146] A.-M. Magnan,[146] B. Maier,[146] S. Mallios,[146] A. Mastronikolis,[146] M. Mieskolainen,[146] J. Nash,[146,dddd] M. Pesaresi,[146] P. B. Pradeep,[146] B. C. Radburn-Smith,[146] A. Richards,[146] A. Rose,[146] L. Russell,[146] K. Savva,[146] C. Seez,[146] R. Shukla,[146] A. Tapper,[146] K. Uchida,[146] G. P. Uttley,[146] T. Virdee,[146,dd] M. Vojinovic,[146] N. Wardle,[146] D. Winterbottom,[146] J. E. Cole,[147] A. Khan,[147] P. Kyberd,[147] I. D. Reid,[147] S. Abdullin,[148] A. Brinkerhoff,[148] E. Collins,[148] M. R. Darwish,[148] J. Dittmann,[148] K. Hatakeyama,[148] V. Hegde,[148] J. Hiltbrand,[148] B. McMaster,[148] J. Samudio,[148] S. Sawant,[148] C. Sutantawibul,[148] J. Wilson,[148] J. M. Hogan,[149,eeee] R. Bartek,[150] A. Dominguez,[150] S. Raj,[150] A. E. Simsek,[150] S. S. Yu,[150] B. Bam,[151] A. Buchot Perraguin,[151] S. Campbell,[151] R. Chudasama,[151] S. I. Cooper,[151] C. Crovella,[151] G. Fidalgo,[151] S. V. Gleyzer,[151] A. Khukhunaishvili,[151] K. Matchev,[151] E. Pearson,[151] C. U. Perez,[151] P. Rumerio,[151,ffff] E. Usai,[151] R. Yi,[151] S. Cholak,[152] G. De Castro,[152] Z. Demiragli,[152] C. Erice,[152] C. Fangmeier,[152] C. Fernandez Madrazo,[152] E. Fontanesi,[152] J. Fulcher,[152] F. Golf,[152] S. Jeon,[152] J. O'Cain,[152] I. Reed,[152] J. Rohlf,[152] K. Salyer,[152] D. Sperka,[152] D. Spitzbart,[152] I. Suarez,[152] A. Tsatsos,[152] E. Wurtz,[152] A. G. Zecchinelli,[152] G. Barone,[153] G. Benelli,[153] D. Cutts,[153] S. Ellis,[153] L. Gouskos,[153] M. Hadley,[153] U. Heintz,[153] K. W. Ho,[153] T. Kwon,[153] G. Landsberg,[153] K. T. Lau,[153] J. Luo,[153] S. Mondal,[153] J. Roloff,[153] T. Russell,[153] S. Sagir,[153,gggg] X. Shen,[153] M. Stamenkovic,[153] N. Venkatasubramanian,[153] S. Abbott,[154] B. Barton,[154] R. Breedon,[154] H. Cai,[154] M. Calderon De La Barca Sanchez,[154] M. Chertok,[154] M. Citron,[154] J. Conway,[154] P. T. Cox,[154] R. Erbacher,[154] O. Kukral,[154] G. Mocellin,[154] S. Ostrom,[154] I. Salazar Segovia,[154] W. Wei,[154] S. Yoo,[154] K. Adamidis,[155] M. Bachtis,[155] D. 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