Search for low-mass resonances decaying into bottom quark-antiquark pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV

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A search for narrow, low-mass, scalar, and pseudoscalar resonances decaying to bottom quark-antiquark pairs is presented. The search is based on events recorded in $\sqrt{s} = 13$ TeV proton-proton collisions with the CMS detector at the LHC, collected in 2016, and corresponding to an integrated luminosity of $35.9\ \mathrm{fb}^{-1}$. The search selects events in which the resonance would be produced with high transverse momentum because of the presence of initial- or final-state radiation. In such events, the decay products of the resonance would be reconstructed as a single large-radius jet with high mass and two-prong substructure. A potential signal would be identified as a narrow excess in the jet invariant mass spectrum. No evidence for such a resonance is observed within the mass range from 50 to 350 GeV, and upper limits at 95% confidence level are set on the product of the cross section and branching fraction to a bottom quark-antiquark pair. These constitute the first constraints from the LHC on exotic bottom quark-antiquark resonances with masses below 325 GeV.

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I. INTRODUCTION

Many models of physics beyond the standard model (SM) require new particles that couple to quarks and gluons and can be observed as dijet resonances. One example is a model in which dark matter particles (χ) couple to SM particles through a spin-0 scalar (Φ) or pseudoscalar (A) mediator, which decays preferentially to a bottom quark-antiquark ($b\bar{b}$) pair [1–5]. As the mass of such a mediator is an unknown parameter of the model, it is important to search in as broad a mass range as possible.

Because of the overwhelming background of events from jets produced through the strong interaction, referred to as quantum chromodynamics (QCD) multijet events, inclusive searches for dijet resonances at the CERN LHC have historically been limited to dijet invariant masses greater than 1 TeV. Several techniques have been explored to evade this limitation. Trigger-level analyses, also known as "data scouting," increase the number of events collected at lower dijet invariant masses by recording a minimal subset of the total event content. The ATLAS and CMS experiments have used this technique to search for resonances with masses as low as 450 GeV [6–9]. The invariant mass threshold can also be lowered by performing bottom quark tagging at the trigger level, enabling masses as low as 325 GeV to be probed [10,11]. The analysis presented here uses a different technique, requiring that the dijet resonances be produced with significant initial- or final-state radiation. The technique has been employed in searches for low mass resonances decaying to quark-antiquark pairs [12–14], which have provided the best sensitivity to date for resonances with masses between 50 and 300 GeV. This technique has also been used to search for SM Higgs bosons (H) produced through gluon fusion and decaying to $b\bar{b}$ pairs [15], with an observed significance of 1.5 standard deviations.

This paper presents the first LHC search for new particles that decay to $b\bar{b}$ resonances with masses as low as 50 GeV. Spin-0 scalar and pseudoscalar resonances, which may mediate interactions between dark matter particles and SM particles, are considered. Minimal flavor violation is assumed, to ensure consistency with flavor constraints [1–5]. Under this assumption, the Φ or A particles decay only to fermion-antifermion pairs of the same flavor. Further, the SM couplings are assumed to be proportional to the SM Yukawa couplings with a single universal constant of proportionality, $g_{q\Phi}$ or g_{qA}. The two interaction Lagrangians are

$$\mathcal{L}_\Phi = g_{\chi\Phi}\Phi\bar{\chi}\chi + \frac{\Phi}{\sqrt{2}}\sum_f g_{q\Phi} y_f \bar{f} f, \qquad (1)$$

$$\mathcal{L}_A = i g_{\chi A} A\bar{\chi}\gamma_5\chi + \frac{iA}{\sqrt{2}}\sum_f g_{qA} y_f \bar{f}\gamma_5 f, \qquad (2)$$

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where the sum is over all charged SM fermions, $g_{\chi\Phi}$ and $g_{\chi A}$ are the couplings to the dark matter particle, the Yukawa couplings of fermions y_f are normalized to the Higgs vacuum expectation value as $y_f = \sqrt{2}m_f/v$ with $v = 246$ GeV, and m_f the corresponding fermion mass. For resonance masses below twice the dark matter particle mass (m_χ), Φ and A couple preferentially to heavier quarks. Consequently, the resonances are predominantly produced via a loop-induced coupling to gluons, and, for resonance masses below twice the top quark mass (m_t), decay mostly to $b\bar{b}$ pairs. This search is also sensitive to extensions of the SM that include a new gauge boson that couples to the right-handed components of the bottom and charm quarks [16].

This paper reports the results of a search for narrow $b\bar{b}$ resonances with masses between 50 and 350 GeV in events collected in $\sqrt{s} = 13$ TeV proton-proton (pp) collisions with the CMS detector at the LHC. The data sample corresponds to an integrated luminosity of 35.9 fb^{-1}. We search for resonances produced with high transverse momentum p_{T} because of significant initial- or final-state radiation (ISR or FSR). This ISR or FSR ensures the events pass stringent trigger restrictions set by bandwidth limitations, allowing resonance masses as low as 50 GeV to be probed. The resonance decay products are merged into a single wide jet. Two wide-jet algorithms are considered: the anti-k_{T} algorithm [17] with distance parameter $R = 0.8$ (AK8), and the Cambridge-Aachen algorithm [18,19] with distance parameter $R = 1.5$ (CA15). The AK8 algorithm provides better sensitivity at signal masses below 175 GeV, while the CA15 algorithm provides better sensitivity at higher masses because of the increased acceptance of decay products with wider angular separation [20]. Jet substructure [21] techniques and dedicated b tagging [22] algorithms are used to distinguish the signal from the QCD background.

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, and a brass and scintillator hadron calorimeter, each composed of a barrel and two end cap sections, reside within the solenoid. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and end cap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid.

Events of interest are selected using a two-tiered trigger system [23]. 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 time interval of less than 4 μs. 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.

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. [24].

III. SIMULATED SAMPLES

Simulated samples of signal and background events are produced using various Monte Carlo (MC) event generators, with the CMS detector response modeled by GEANT4 [25]. The benchmark Φ and A signal events, produced primarily via gluon fusion, are simulated using the MADGRAPH5_aMC@NLO 2.4.2 generator [26] for various mass hypotheses in the range 50–500 GeV. The events are generated with a parton-level filter requiring total hadronic transverse energy $H_{\mathrm{T}} > 400$ GeV; events failing this requirement fall outside the acceptance of the analysis selection, discussed in the following section. Figure 1 shows representative one-loop Feynman diagrams producing a boosted jet originating from a $b\bar{b}$ pair (double-b jet).

In accordance with the recommendations of the ATLAS-CMS Dark Matter Forum [1] and the LHC Dark Matter Working Group [5], the Φ and A signal samples are normalized to their production cross sections at leading order (LO) accuracy calculated with the MADGRAPH5_aMC@NLO 2.4.2 generator using the DMSIMP package [27]. The total

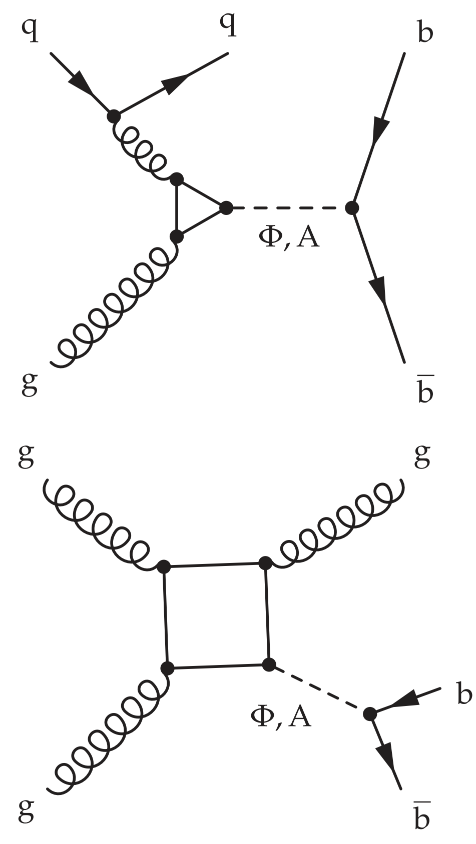

FIG. 1. One-loop Feynman diagrams of processes exchanging a scalar Φ (top) or pseudoscalar A (bottom) mediator, leading to a boosted double-b jet signature.

cross sections, which are compared to the upper limits obtained with this analysis, are calculated using the LO diagram with no additional partons and no cuts applied to the final state kinematics. The production cross section at next-to-leading order (NLO) accuracy including the finite m_t has only been calculated for a scalar with a mass of 125 GeV, where it is approximately a factor of 2 greater [28]. This NLO correction is not used in this analysis; applying it would not affect the sensitivity of the search to the signal production cross section, but it would improve the sensitivity to the couplings $g_{q\Phi}$ or g_{qA} by a factor of approximately $\sqrt{2}$.

The MadGraph5_aMC@NLO 2.3.3 [26] generator is used for the diboson, $W+\text{jets}$, $Z+\text{jets}$, and QCD multijet samples, at LO accuracy with matching [29] between jets from the matrix element calculation and the parton shower description, while POWHEG 2.0 [30–32] at NLO precision is used to model the $t\bar{t}$ and single top processes. The Higgs boson signal samples are produced using the POWHEG+MiNLO [31,33] event generator with $m_H = 125$ GeV. For the gluon fusion production mode, the POWHEG generated sample with up to one extra jet in matrix element calculations is normalized to the inclusive cross section at next-to-next-to-next-to-leading order (N^3LO) accuracy [34–37], with a p_T-dependent correction to account for the effects of the finite m_t and associated higher-order QCD corrections [15].

For parton showering and hadronization, the POWHEG and MadGraph5_aMC@NLO samples are interfaced with PYTHIA 8.212 [38]. The PYTHIA parameters for the underlying event description are set to the CUETP8M1 tune [39]. The production cross sections for the diboson samples are calculated to next-to-next-to-leading order (NNLO) accuracy with the MCFM 7.0 program [40]. The cross section for top quark pair production is computed with Top++ 2.0 [41] at NNLO including soft-gluon resummation to next-to-next-to-leading-log order. The cross sections for $W+\text{jets}$ and $Z+\text{jets}$ samples include higher-order QCD and electroweak (EW) corrections improving the modeling of high-p_T W and Z bosons events [42–45]. The parton distribution function set NNPDF3.0 [46] is used to produce all simulated samples, with the accuracy (LO or NLO) corresponding to that of the matrix elements used for generation.

IV. EVENT RECONSTRUCTION AND SELECTION

Event reconstruction is based on a particle-flow algorithm [47], which aims to reconstruct and identify each individual particle with an optimized combination of information from the various elements of the CMS detector. The algorithm identifies each reconstructed particle as an electron, a muon, a photon, or a charged or neutral hadron. The missing transverse momentum vector is defined as the negative vector sum of the transverse momenta of all the particles identified in the event, and its magnitude is referred to as p_T^{miss}. Particles are clustered into AK8 [17] or CA15 [18] jets, depending on the signal mass hypothesis. The clustering algorithms are implemented by the FastJet package [48]. To mitigate the effect from the contributions of extraneous pp collisions (pileup), the pileup per particle identification algorithm [49] assigns a weight to each particle prior to jet clustering based on the likelihood of the particle to originate from the hard scattering vertex. Further corrections are applied to the jet energy as a function of jet η and p_T to bring the measured response of jets to that of particle level jets on average [50].

A combination of several event selection criteria is used to trigger on events, all imposing minimum thresholds either on H_T or on the AK8 jet p_T. In addition, a minimum threshold on the trimmed jet mass, where remnants of soft radiation are removed before computing the mass [51], is imposed to reduce the H_T or p_T thresholds and improve the signal acceptance. The trigger selection is greater than 95% efficient at selecting events with at least one AK8 jet with $p_T > 450$ GeV, $|\eta| < 2.5$, and mass greater than 40 GeV or events with at least one CA15 jet with $p_T > 500$ GeV and $|\eta| < 2.5$. We also define six (five) p_T categories from 450 (500) GeV to 1 TeV for AK8 (CA15) jets with variable width from 50 to 200 GeV. To reduce backgrounds from SM EW processes, events containing isolated electrons [52] or muons [53], or hadronically decaying τ leptons with $p_T > 10$, 10, or 18 GeV and $|\eta| < 2.5$, 2.4, or 2.3, respectively, are vetoed. For electrons or muons, the isolation criteria require that the pileup-corrected sum of the p_T of charged hadrons and neutral particles surrounding the lepton divided by the lepton p_T be less than approximately 15% or 25%, respectively, depending on η [52,53]. Events with $p_T^{\text{miss}} > 140$ GeV are vetoed in order to reduce the top quark background contamination. For each event, the leading jet in p_T is assumed to be the $\Phi(b\bar{b})$ or $A(b\bar{b})$ candidate. The soft-drop algorithm [54] with angular exponent $\beta = 0$ is applied to the jet to remove soft and wide-angle radiation with a soft radiation fraction z less than 0.1. The parameter β controls the grooming profile as a function of subjet separation; when $\beta = 0$, the grooming threshold is independent of subjet separation, and the algorithm is equivalent to the modified mass-drop tagger [55]. For background QCD multijet events where large jet masses arise from soft gluon radiation, the soft-drop jet mass m_{SD} is reduced relative to the ungroomed jet mass. On the other hand, for signal events m_{SD} is primarily determined by the $\Phi(b\bar{b})$ decay kinematics, and the distribution peaks at the mass of the $\Phi(b\bar{b})$ signal.

Dedicated m_{SD} corrections are derived from a comparison of simulated and measured samples in a region enriched with merged $W(q\bar{q})$ decays from $t\bar{t}$ events [56]. The m_{SD} corrections remove a residual dependence on the jet p_T, and match the simulated jet mass scale and resolution to those observed in data. A lower m_{SD} bound of 40 GeV is applied in the search with AK8 jets to ensure that the trigger has greater than 95% efficiency, while a lower m_{SD} bound of 82 GeV is applied in the search with

TABLE I. The selection efficiencies in percent for simulated $\Phi(b\bar{b})$ signal events with parton-level $H_T > 400$ GeV, at different stages of the event selection, shown for different mass hypotheses and for AK8 and CA15 jets. The statistical uncertainties due to the simulated sample size are also shown.

AK8 jets							
m_Φ (GeV)	$p_T > 450$ GeV	$m_{SD} > 40$ GeV	Lepton veto	$p_T^{miss} < 140$ GeV	$N_2^{1,DDT} < 0$	$-6 < \rho < 2.1$	double-*b* tag
50	75.0 ± 0.1	37.5 ± 0.2	36.2 ± 0.2	32.9 ± 0.2	14.7 ± 0.1	14.3 ± 0.1	7.3 ± 0.1
100	75.4 ± 0.1	42.2 ± 0.2	40.6 ± 0.2	37.5 ± 0.2	18.0 ± 0.1	17.5 ± 0.1	7.1 ± 0.1
125	75.5 ± 0.2	42.3 ± 0.2	40.6 ± 0.2	37.5 ± 0.2	18.1 ± 0.1	17.5 ± 0.1	6.1 ± 0.1
CA15 jets							
m_Φ (GeV)	$p_T > 500$ GeV	$m_{SD} > 82$ GeV	Lepton veto	$p_T^{miss} < 140$ GeV	$N_2^{1,DDT} < 0$	$-4.7 < \rho < -1.0$	double-*b* tag
200	61.0 ± 0.1	35.6 ± 0.1	33.9 ± 0.1	31.1 ± 0.1	13.9 ± 0.1	13.0 ± 0.1	3.3 ± 0.1
300	63.4 ± 0.1	35.7 ± 0.1	34.0 ± 0.1	31.1 ± 0.1	13.2 ± 0.1	11.1 ± 0.1	1.9 ± 0.1
350	64.3 ± 0.1	35.8 ± 0.1	33.9 ± 0.1	31.1 ± 0.1	13.0 ± 0.1	8.6 ± 0.1	1.1 ± 0.1

CA15 jets to ensure the background model described in Sec. V is robust. The resulting m_{SD} distributions are binned with a bin width of 7 GeV, corresponding to the m_{SD} resolution near the W and Z resonances.

The dimensionless mass scale variable for QCD multijet jets, $\rho = \ln(m_{SD}^2/p_T^2)$ [55,57], is used to characterize the correlation between the jet b tagging discriminator, jet mass, and jet p_T. Its distribution is roughly invariant in different ranges of jet p_T. Only events in the range $-6.0 < \rho < -2.1$ ($-4.7 < \rho < -1.0$) are considered for AK8 (CA15) jets, effectively defining different m_{SD} ranges depending on jet p_T. The upper bound is imposed to avoid instabilities at the edges of the distribution due to finite cone limitations from the jet clustering, while the lower bound avoids the nonperturbative regime of the m_{SD} calculation. This requirement is about 98% efficient for the $\Phi(b\bar{b})$ signal at low masses (50–125 GeV) when reconstructed as an AK8 jet, and 60%–85% efficient at high masses (200–350 GeV) when reconstructed as a CA15 jet.

The N_2^1 variable [21] is used to determine how consistent a jet is with having a two-prong substructure. It is based on a ratio of 2-point (${}_1e_2$) and 3-point (${}_2e_3$) generalized energy correlation functions [58],

$$ {}_1e_2 = \sum_{1\le i<j\le n} z_i z_j \Delta R_{ij}, \tag{3}$$

$$ {}_2e_3 = \sum_{1\le i<j<k\le n} z_i z_j z_k \times \min\{\Delta R_{ij}\Delta R_{ik}, \Delta R_{ij}\Delta R_{jk}, \Delta R_{ik}\Delta R_{jk}\}, \tag{4}$$

where z_i represents the energy fraction of the constituent i in the jet and ΔR_{ij} is the angular separation between constituents i and j. These generalized energy correlation functions ${}_ve_n$ are sensitive to correlations of v pairwise angles among n-jet constituents [21]. For a two-prong structure, signal jets have a stronger 2-point correlation than a 3-point correlation. The discriminant variable N_2^1 is then constructed via the ratio

$$ N_2^1 = \frac{{}_2e_3}{({}_1e_2)^2}. \tag{5}$$

The calculation of N_2^1 is based on the jet constituents after application of the soft-drop grooming algorithm to the jet. It provides excellent discrimination between two-prong signal jets and QCD background jets. However, imposing requirements on N_2^1, or other similar variables, distorts the jet mass distributions differently depending on the p_T of the jet [59]. To minimize this distortion, a transformation is applied to N_2^1 following the designed decorrelated tagger (DDT) technique [57] to reduce its correlation with ρ and p_T in multijet events. The transformed variable is defined as $N_2^{1,DDT} \equiv N_2^1 - X_{(26\%)}$, where $X_{(26\%)}$ is the 26th percentile of the N_2^1 distribution in simulated QCD events as a function of ρ and p_T. The transformation is derived in bins of ρ and p_T, separately for AK8 and CA15 jets. This ensures that the selection $N_2^{1,DDT} < 0$ yields a constant QCD background efficiency across the ρ and p_T range considered in this search. The chosen background efficiency of 26% maximizes the signal sensitivity, independent of the signal mass.

A dedicated double-*b* tagger is used to select jets likely to originate from two b quarks [22]. Events where the selected wide jet is double-*b*-tagged constitute the "passing", or signal, region while events failing the double-*b* tagger form the "failing" region, which is used to estimate the QCD multijet background in the signal region. The multivariate algorithm, based on a boosted decision tree, takes as inputs several observables that characterize the distinct properties of b hadrons and their flight directions in relation to the jet substructure. A wide jet is considered double-*b* tagged if its double-*b* tagger discriminator value exceeds a threshold corresponding to a 1% misidentification rate for QCD jets and a 33% efficiency for $\Phi(b\bar{b})$ candidates with a mass of 125 GeV reconstructed as AK8 jets.

For CA15 jets, because of the larger cone with radius parameter of 1.5, it is often possible to resolve two subjets within the wide jet; hence additional background discrimination can be obtained by incorporating the individual subjet b tagging probabilities. The subjets are constructed using the soft-drop algorithm, and assigned b tagging scores using the combined secondary vertex algorithm (CSVv2) [22] that combines information from displaced tracks and vertices using a multilayer perceptron. The second highest CSVv2 score is then used as an additional input to the boosted decision tree of the double-b tagger. For the chosen discriminator threshold, the double-b tagger algorithm has a misidentification rate of about 4%, and a signal efficiency which decreases with mass, equalling 25 (13)% for a signal mass of 200 GeV (350 GeV).

The efficiency (in percent) of the cumulative selection criteria for the scalar $\Phi(b\bar{b})$ signal benchmark is shown in Table I. The efficiencies for the $A(b\bar{b})$ signal are consistent within the statistical uncertainties.

V. BACKGROUND ESTIMATION

The W, Z, and $H+$jets backgrounds are modeled using MC simulation. Their overall contribution is less than 5% of the total SM background. The normalization and shape of the simulated $W/Z+$jets backgrounds are corrected for NLO QCD and EW effects. Other EW processes, such as diboson, triboson, and $t\bar{t}+W/Z$, are estimated from simulation and found to be negligible.

The contribution of $t\bar{t}$ production to the total SM background, estimated to be less than 3%, is obtained from simulation corrected with scale factors derived from a $t\bar{t}$-enriched control sample in which an isolated muon [53] is required. Scale factors correct the overall $t\bar{t}$ normalization and the double-b mistag efficiency for jets originating from top quark decays. The control sample is included in the global fit used to extract the signal, with the scale factors treated as unconstrained parameters.

The main background in the passing region, QCD multijet production, has a nontrivial jet mass shape that is difficult to model parametrically and depends on jet p_{T}. Therefore, we constrain it using the background-enriched failing region, i.e., events failing the double-b tagger selection. Since the double-b tagger discriminator and the jet mass are largely uncorrelated, the passing and failing regions have similar QCD jet mass distributions, and their ratio, the "pass-fail ratio" $R_{\mathrm{p/f}}$, is expected to be nearly constant as a function of jet mass and p_{T}. To account for the residual difference between the shapes of passing and failing events, $R_{\mathrm{p/f}}$ is parametrized as a Bernstein polynomial in ρ and p_{T},

$$R_{\mathrm{p/f}}(\rho, p_{\mathrm{T}}) = \sum_{k=0}^{n_\rho} \sum_{\ell=0}^{n_{p_{\mathrm{T}}}} a_{k,\ell} b_{k,n_\rho}(\rho) b_{\ell,n_{p_{\mathrm{T}}}}(p_{\mathrm{T}}), \qquad (6)$$

where n_ρ is the degree of the polynomial in ρ, $n_{p_{\mathrm{T}}}$ is the degree of the polynomial in p_{T}, $a_{k,\ell}$ is a Bernstein coefficient, and

$$b_{\nu,n}(x) = \binom{n}{\nu} x^\nu (1-x)^{n-\nu} \qquad (7)$$

is a Bernstein basis polynomial of degree n.

The coefficients $a_{k,\ell}$ have no external constraints, but are determined from a simultaneous binned fit to data in passing and failing regions across the whole jet mass and p_{T} range. The p_{T} binning, varying from 50 to 200 GeV, is chosen to provide enough data points to constrain the shape of $R_{\mathrm{p/f}}$. To determine the degree of polynomial necessary to fit the data, a Fisher F-test [60] is performed. Based on its results, a polynomial of second (fifth) degree in ρ and first degree in p_{T} is selected for the AK8 (CA15) analysis category. The fitted pass-fail ratios $R_{\mathrm{p/f}}$ as functions of ρ and p_{T} under the background-only hypothesis are shown in Fig. 2 for the AK8 and CA15 selections.

Figures 3 and 4 show the m_{SD} distributions in the full data set for the passing and failing regions with fitted SM background for AK8 and CA15 selections, respectively. Note that the different ρ boundaries define different m_{SD} ranges for the AK8 and CA15 selections as well as within each p_{T} category, giving rise to the features at 166, 180,

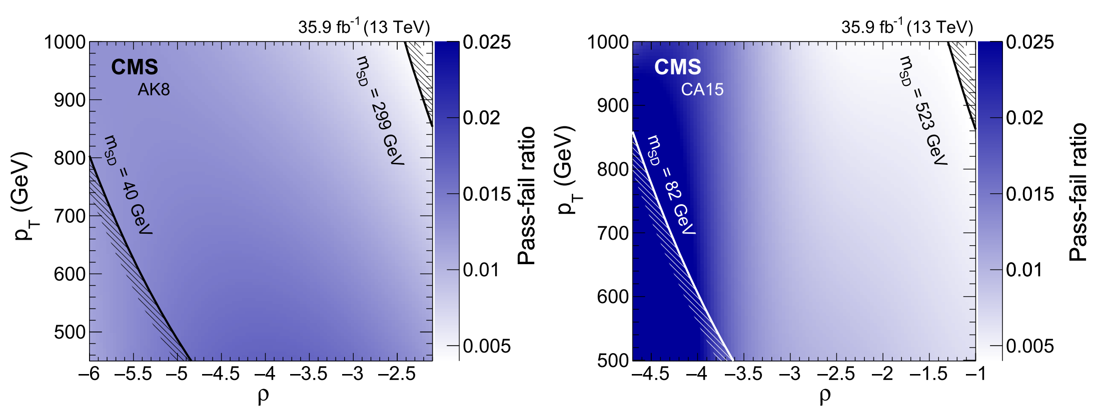

FIG. 2. The fitted pass-fail ratio $R_{\mathrm{p/f}}$ as a function of p_{T} and ρ for the AK8 selection (left) and the CA15 selection (right).

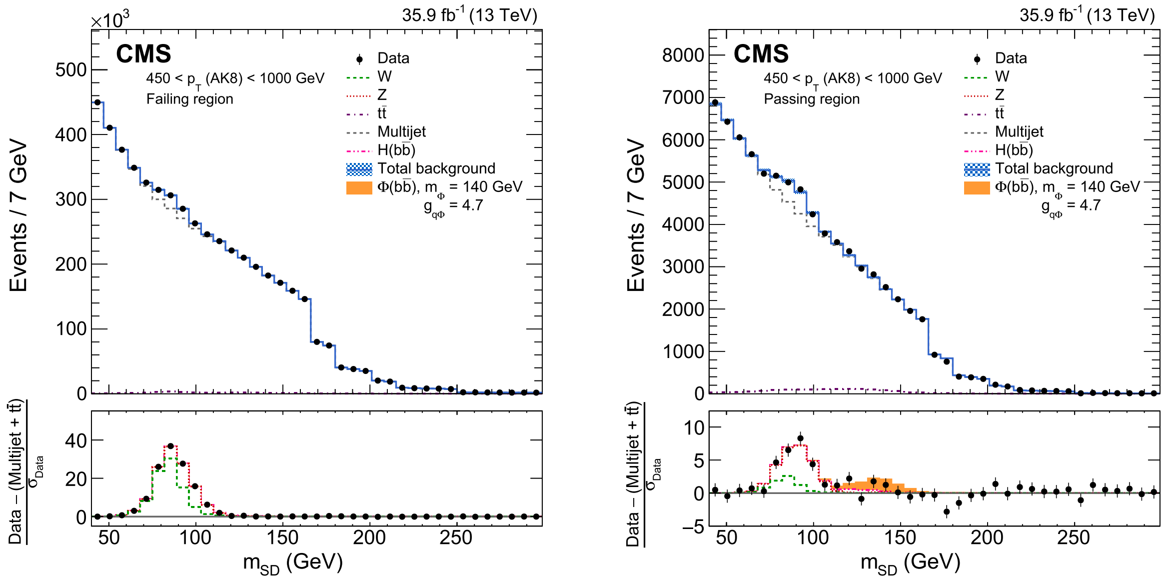

FIG. 3. The observed and fitted background m_{SD} distributions for the AK8 selection for the failing (left) and passing (right) regions, combining all the p_{T} categories. The background fit is performed under the background-only hypothesis. A hypothetical $\Phi(b\bar{b})$ signal at a mass of 140 GeV is also indicated. The features at 166, 180, 201, 215, and 250 GeV in the m_{SD} distribution are due to the ρ boundaries, which define different m_{SD} ranges for each p_{T} category. The shaded blue band shows the systematic uncertainty in the total background prediction. The bottom panel shows the difference between the data and the nonresonant background prediction, divided by the statistical uncertainty in the data.

201, 215, and 250 GeV in Fig. 3 and at 285, 313, 341, 376, and 432 GeV in Fig. 4. The bottom panels of Figs. 3–6 show the difference between the data and the prediction from the nonresonant background, composed of the QCD multijet and $t\bar{t}$ processes, divided by the statistical uncertainty in the data. These highlight the agreement between the data and the contributions from W and Z boson production, which are clearly visible in the failing and passing regions, respectively. The remaining W boson contribution in the passing region is due to the

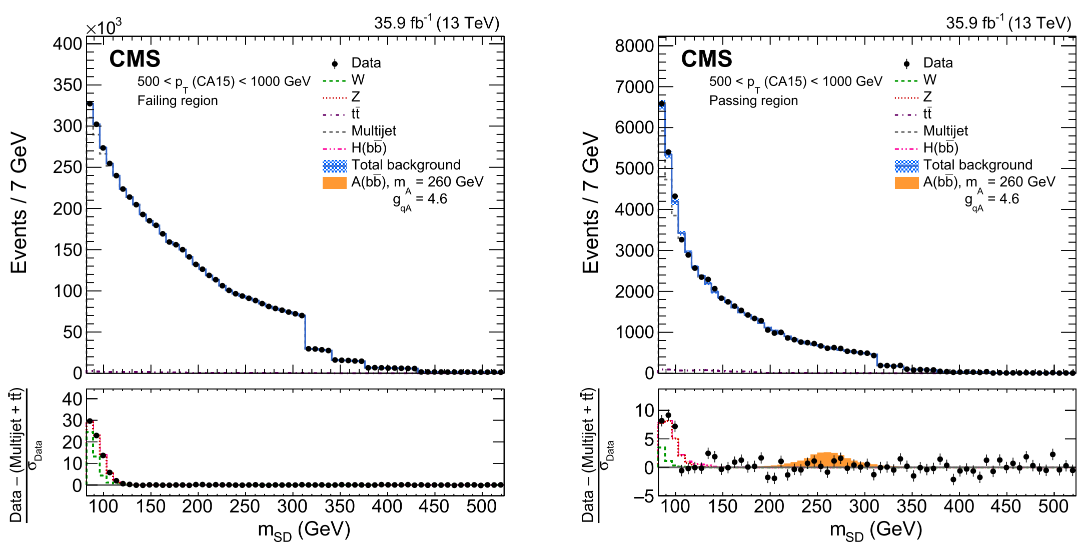

FIG. 4. The observed and fitted background m_{SD} distributions for the CA15 selection for the failing (top) and passing (bottom) regions, combining all the p_{T} categories. The background fit is performed under the background-only hypothesis. A hypothetical $A(b\bar{b})$ signal at a mass of 260 GeV is also indicated. The features at 285, 313, 341, 376, and 432 GeV in the m_{SD} distribution are due to the ρ boundaries, which define different m_{SD} ranges for each p_{T} category. The shaded blue band shows the systematic uncertainty in the total background prediction. The bottom panel shows the difference between the data and the nonresonant background prediction, divided by the statistical uncertainty in the data.

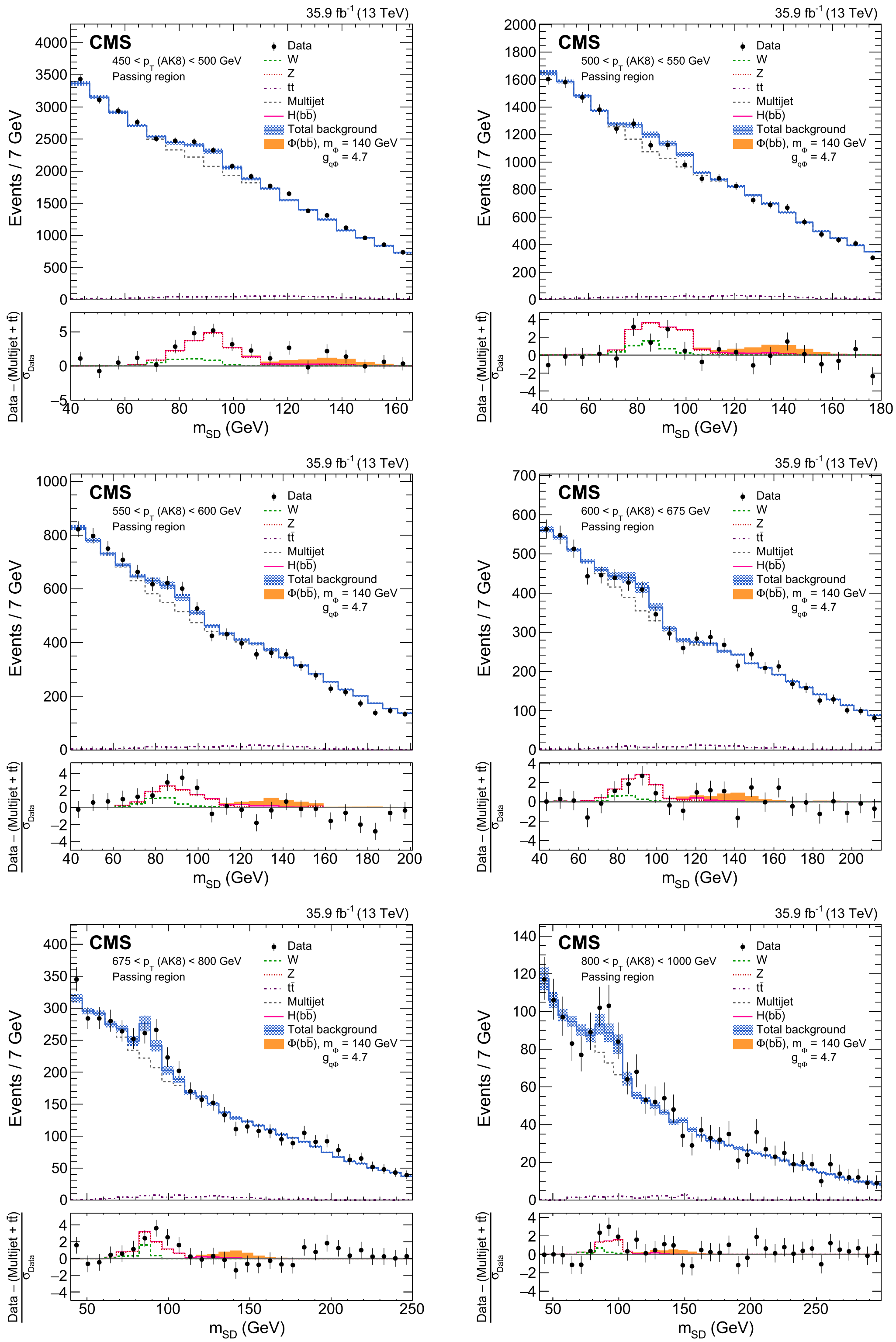

FIG. 5. The observed and fitted background m_{SD} distributions in each p_T category for the AK8 selection in the passing regions. The fit is performed under the background-only hypothesis. A hypothetical $\Phi(b\bar{b})$ signal at a mass of 140 GeV is also indicated. The shaded blue band shows the systematic uncertainty in the total background prediction. The bottom panel shows the difference between the data and the nonresonant background prediction, divided by the statistical uncertainty in the data.

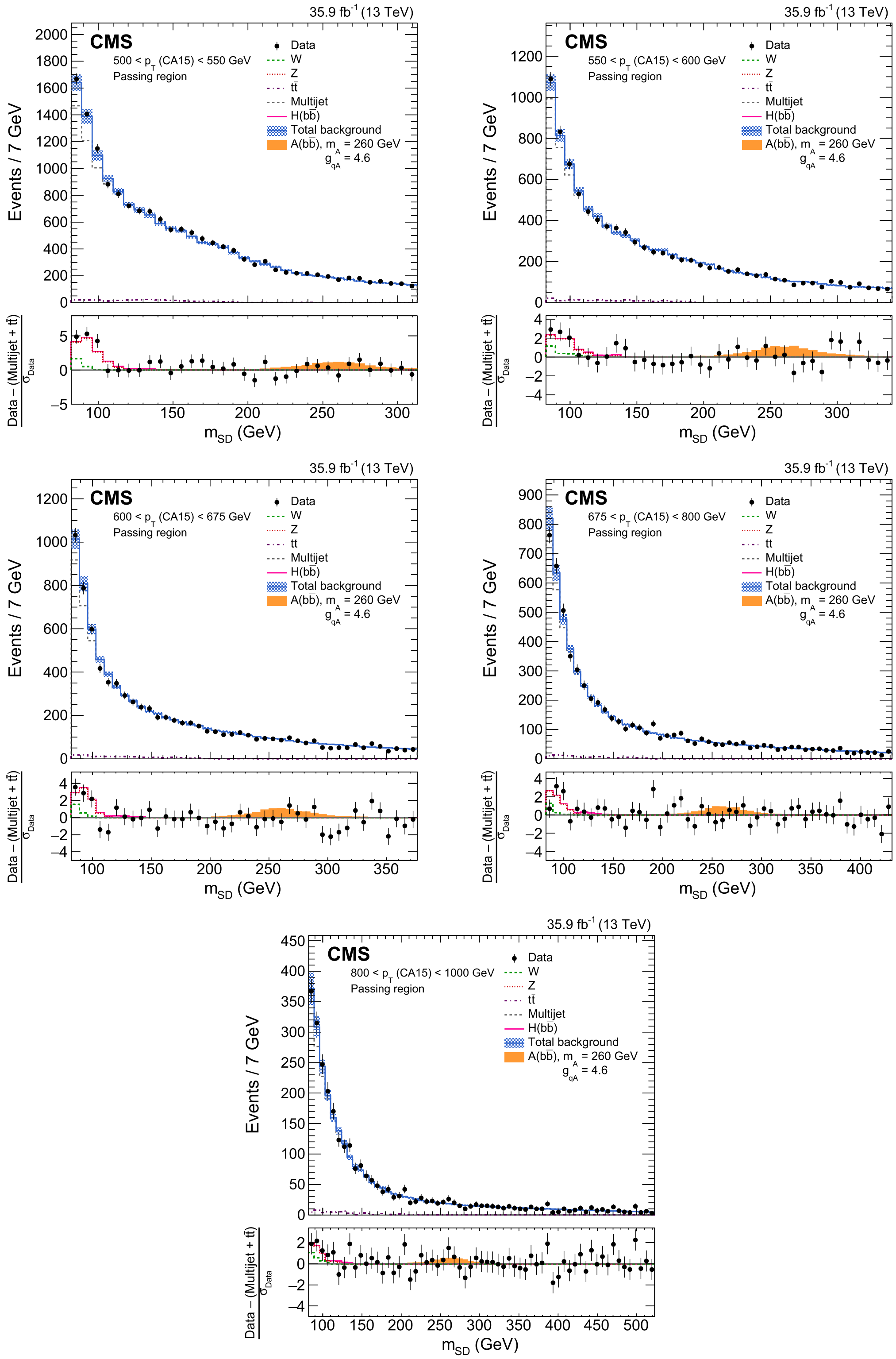

FIG. 6. The observed and fitted background m_{SD} distributions in each p_{T} category for the CA15 selection in the passing regions. The fit is performed under the background-only hypothesis. A hypothetical $A(b\bar{b})$ signal at a mass of 260 GeV is also indicated. The shaded blue band shows the systematic uncertainty in the total background prediction. The bottom panel shows the difference between the data and the nonresonant background prediction, divided by the statistical uncertainty in the data.

misidentification of $W(q\bar{q})$ decays. No significant deviations from the background-only expectations are observed. In Figs. 5 and 6, the m_{SD} distributions are reported for each p_{T} category for AK8 and CA15 jets, respectively.

In order to validate the background estimation method and associated systematic uncertainties, bias studies are performed on simulated samples and on the background-only fits. Pseudoexperiment data sets are generated, with and without the injection of signal events, and then fit with the signal plus background model. No significant bias in the fitted signal strength is observed; specifically, the means of the differences between the fitted and injected signal strengths divided by the fitted uncertainty are found to be less than 15%.

In addition, to validate the corrections and uncertainties related to the $W(q\bar{q})$ and $Z(q\bar{q})$ resonances, we perform a consistency check by directly measuring a combined signal strength for those contributions assuming the SM background-only hypothesis. We find agreement with the SM expectation within the measured uncertainties.

VI. SYSTEMATIC UNCERTAINTIES

The systematic uncertainties associated with the jet mass scale, the jet mass resolution, and the $\mathrm{N}_2^{1,\mathrm{DDT}}$ selection efficiency are correlated among the W, Z, $H(b\bar{b})$, and $\Phi(b\bar{b})$ or $A(b\bar{b})$ processes. These uncertainties are estimated using an independent sample of merged W jets in semileptonic $t\bar{t}$ events in data.

To select a sample of merged W jets from semileptonic $t\bar{t}$ production, events are required to have an energetic muon with $p_{\mathrm{T}} > 100$ GeV, $p_{\mathrm{T}}^{\mathrm{miss}} > 80$ GeV, a high-p_{T} AK8 or CA15 jet with $p_{\mathrm{T}} > 200$ GeV, and an additional jet separated from the AK8 (CA15) jet by $\Delta R > 0.8\,(1.5)$. Using the same $\mathrm{N}_2^{1,\mathrm{DDT}}$ requirements that define the signal regions, we define samples with events that pass and fail the selection for merged W boson jets in data and simulation. A simultaneous fit to the two samples is performed in order to extract the selection efficiency of a merged W jet in simulation and in data. This is performed separately for AK8 and CA15 selections. We measure the data-to-simulation scale factor for the $\mathrm{N}_2^{1,\mathrm{DDT}}$ selection to be 0.99 ± 0.04 for AK8 jets and 0.97 ± 0.06 for CA15 jets. The jet mass scales in data and simulation are found to be consistent within 1%. The jet mass resolution data-to-simulation scale factor is 1.08 ± 0.09 for AK8 jets and 0.99 ± 0.08 for CA15 jets. As the semileptonic $t\bar{t}$ sample does not contain a large population of jets with very high p_{T}, an additional systematic uncertainty is included to account for the extrapolation to very high p_{T} jets. The jet mass scale uncertainty is allowed to vary in the signal extraction differently depending on the jet p_{T}, and ranges from 2% at 450 GeV to 4% at 1 TeV.

The efficiency of the double-b tagger is measured in data and simulation in a sample enriched in $b\bar{b}$ pairs from gluon splitting [22]. Scale factors relating data and simulation are then computed and applied to the simulation. The measured double-b tagger efficiency scale factor is found to be 0.86 ± 0.07 for CA15 jets and 0.91 ± 0.04 for AK8 jets, where the uncertainty accounts for various systematic effects including the calibration of the jet probability tagger algorithm used in the method, the modeling of the track reconstruction efficiency, the modeling of b quark fragmentation, and others [22].

The scale factors described above determine the initial distributions of the jet mass for the $W(q\bar{q})$, $Z(q\bar{q})$, $H(b\bar{b})$, and $\Phi(b\bar{b})$ or $A(b\bar{b})$ processes and are further constrained in the fit to data by the presence of the W and Z resonances in the jet mass distribution.

TABLE II. Summary of the systematic uncertainties affecting the signal, W and $Z+$ jets processes. Instances where the uncertainty does not apply are indicated by a dash. The reported percentages reflect a one standard deviation effect on the product of acceptance and efficiency of each process. For the uncertainties related to the jet mass scale and resolution, which affect the mass distribution shapes, the reported percentages reflect a one standard deviation effect on the nominal jet mass.

Uncertainty source	Process			
	W or Z (AK8)	W or Z (CA15)	Φ or A (AK8)	Φ or A (CA15)
Integrated luminosity	2.5%	2.5%	2.5%	2.5%
Trigger efficiency	2%	2%	2%	2%
Pileup	<1%	<1%	<1%	<1%
$\mathrm{N}_2^{1,\mathrm{DDT}}$ selection efficiency	4.3%	6%	4.3%	6%
Double-b tag	4% (Z)	8% (Z)	4%	8%
Jet energy scale/resolution	5%–15%	5%–15%	5%–15%	5%–15%
Jet mass resolution	8%	8%	8%	8%
Jet mass scale $(\%/(p_{\mathrm{T}}[\mathrm{GeV}]/100))$	0.4%	1%	0.4%	1%
Simulation sample size	2%–25%	2%–25%	4%–20%	4%–20%
NLO QCD corrections	10%	10%	⋯	⋯
NLO EW corrections	15%–35%	15%–35%	⋯	⋯
NLO EW W/Z decorrelation	5%–15%	5%–15%	⋯	⋯

To account for potential p_T-dependent deviations due to missing higher-order corrections, uncertainties are applied to the $W(q\bar{q})$ and $Z(q\bar{q})$ yields that are p_T dependent and correlated per p_T bin [42,43,61–65]. An additional systematic uncertainty is included to account for potential differences between the W and Z higher-order corrections (EW W/Z decorrelation) [61].

Finally, additional systematic uncertainties are applied to the $W(q\bar{q})$, $Z(q\bar{q})$, $t\bar{t}$, $H(b\bar{b})$, and $\Phi(b\bar{b})$ or $A(b\bar{b})$ yields to account for the uncertainties due to the jet energy scale and resolution [66], variations in the amount of pileup, the integrated luminosity determination [67], and the limited simulation sample sizes. A quantitative summary of the systematic effects considered is shown in Table II.

VII. RESULTS

The search results are interpreted in the context of the scalar and pseudoscalar signal models described in Sec. I. The signals are modeled using MC simulation. For the search with AK8 (CA15) jets, a binned maximum likelihood fit to the observed m_{SD} distributions in the range 40 to 201 (82 to 399) GeV with a 7 GeV bin width is performed using the sum of the signal, $H(b\bar{b})$, W, Z, $t\bar{t}$, and QCD multijet contributions. The fit is performed simultaneously in the passing and failing regions of the six (five) p_T categories within $450(500) < p_T < 1000$ GeV for AK8 (CA15) jets, as well as in the passing and failing components of the $t\bar{t}$-enriched control region.

The chosen test statistic, used to determine how signal- or background-like the data are, is based on the profile likelihood ratio [68] using the CL_s criterion [69,70]. Systematic uncertainties are incorporated into the analysis via nuisance parameters and treated according to the frequentist paradigm. Upper limits at 95% confidence level (CL) are obtained using asymptotic formulae [68,71,72].

The 95% CL upper limits on the $\Phi(b\bar{b})$ and $A(b\bar{b})$ production as a function of resonance mass are shown

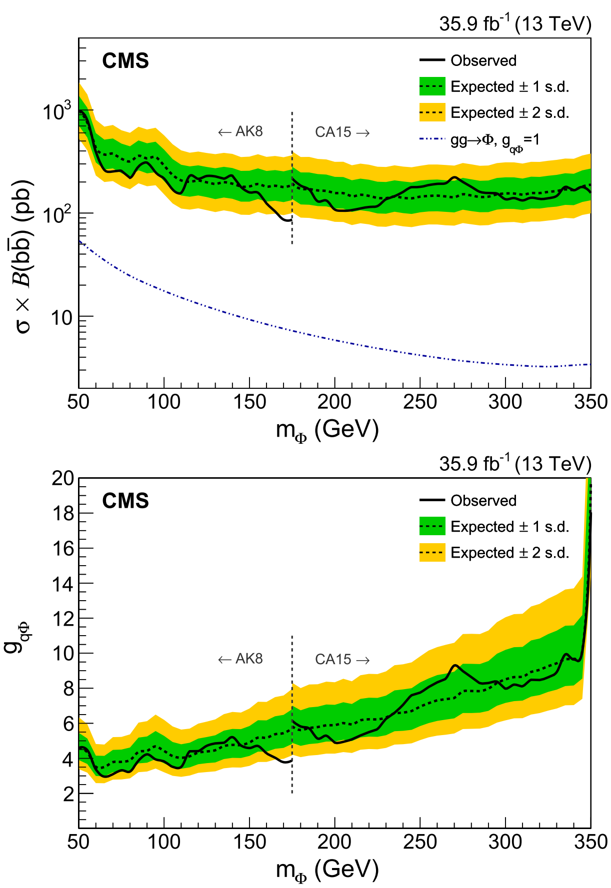

FIG. 7. Upper limits at 95% CL on the product of the Φ production cross section and the branching fraction to $b\bar{b}$ (top) and on $g_{q\Phi}$ (bottom), as a function of the resonance mass m_Φ. The blue dash-dotted line indicates the theoretical scalar production cross section assuming $g_{q\Phi} = 1$ as a chosen benchmark [5]. The vertical line at 175 GeV corresponds to the transition between the AK8 and CA15 jet selections.

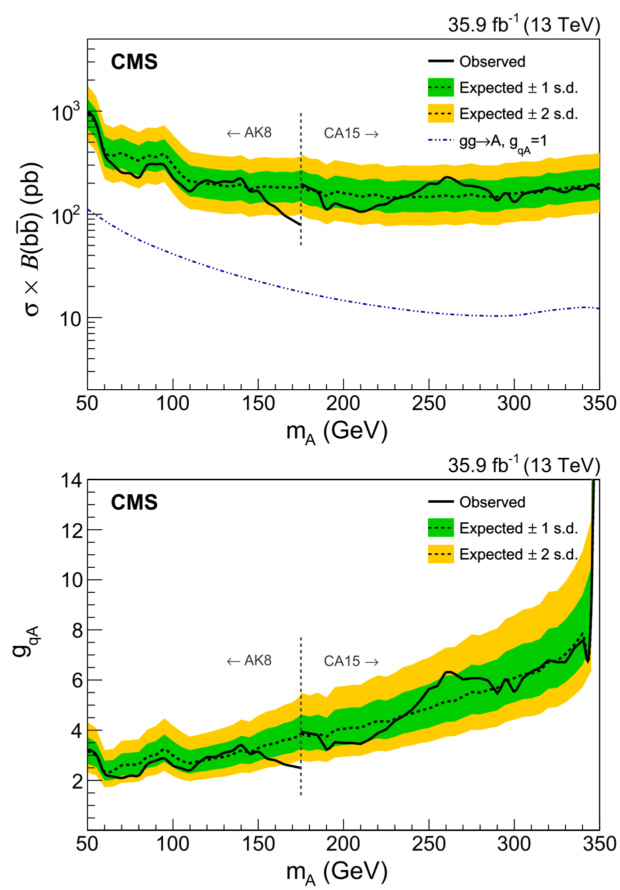

FIG. 8. Upper limits at 95% CL on the product of the A production cross section and the branching fraction to $b\bar{b}$ (top) and on g_{qA} (bottom), as a function of the resonance mass m_A. The blue dash-dotted line indicates the theoretical pseudoscalar production cross section assuming $g_{qA} = 1$ as a chosen benchmark [5]. The vertical line at 175 GeV corresponds to the transition between the AK8 and CA15 jet selections.

in Figs. 7 and 8, respectively. Based on the expected sensitivity, the AK8 jet selection is used for signal masses below 175 GeV, and the CA15 jet selection is used above. We exclude Φ or A production with a product of the cross section and branching fraction [$\sigma\mathcal{B}(b\bar{b})$] as low as 79 or 86 pb, respectively, at a resonance mass of 175 GeV. The exclusions are converted to upper limits on the coupling $g_{q\Phi}$ for the scalar model and the coupling g_{qA} for the pseudoscalar model. The abrupt loss in sensitivity to the coupling constants for resonance masses greater than $2m_t$ is because the branching fraction to $b\bar{b}$ falls steeply as the decay to $t\bar{t}$ becomes kinematically allowed. For a resonance mass of 175 GeV, the exclusion corresponds to an upper limit on $g_{q\Phi}$ or g_{qA} of 3.9 or 2.5, respectively.

For the search with AK8 jets, the maximum local significance [73] corresponds to 0.5 standard deviations from the background-only expectation at a $\Phi(b\bar{b})$ mass of 140 GeV. The hypothetical $\Phi(b\bar{b})$ signal is indicated in Figs. 3 and 5 with $g_{q\Phi} = 4.7$, which is equivalent to the 95% CL upper limit. Similarly, for the CA15 search, the maximum local significance is 1.2 standard deviations at an $A(b\bar{b})$ mass of 260 GeV. The hypothetical $A(b\bar{b})$ signal is indicated in Figs. 4 and 6 with $g_{qA} = 4.6$, which is equivalent to the 95% CL upper limit. The largest downward fluctuation in the limits occurs at an $A(b\bar{b})$ mass of 175 GeV in the AK8 search, corresponding to a local significance of -2.9 standard deviations and a global significance [73], calculated over the probed mass range (50–350 GeV), of approximately -1.7 standard deviations. A corresponding deficit is not seen in CA15 search, as the events used in the AK8 and CA15 searches are largely independent; approximately 20 (37)% of events in the CA15 search are selected in the AK8 search, while conversely, approximately 37% of events in the AK8 search are selected in the CA15 search.

VIII. SUMMARY

A search for a low-mass resonance decaying into a bottom quark-antiquark pair and reconstructed as a single wide jet has been presented, using a data set of proton-proton collisions at $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of 35.9 fb^{-1}. Dedicated substructure and double-b tagging techniques were employed to identify jets containing a resonance candidate over a smoothly falling soft-drop jet mass distribution in data. No significant excess above the standard model prediction was observed for signal masses between 50–350 GeV. Upper limits at 95% confidence level are set on the product of the resonance production cross section and the branching fraction to bottom quark-antiquark pairs, as well as on the coupling $g_{q\Phi}$ (g_{qA}) of a scalar (pseudoscalar) boson decaying to quarks. The search excludes the production through gluon fusion of a scalar (pseudoscalar) decaying to $b\bar{b}$ with a product of the cross section and branching fraction as low as 79 (86) pb at a resonance mass of 175 GeV, corresponding to an upper limit on $g_{q\Phi}$ (g_{qA}) of 3.9 (2.5). This constitutes the first LHC constraint on exotic bottom quark-antiquark resonances below 325 GeV.

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Z. Antunovic,[20] M. Kovac,[20] V. Brigljevic,[21] D. Ferencek,[21] K. Kadija,[21] B. Mesic,[21] A. Starodumov,[21,h] T. Susa,[21] M. W. Ather,[22] A. Attikis,[22] M. Kolosova,[22] G. Mavromanolakis,[22] J. Mousa,[22] C. Nicolaou,[22] F. Ptochos,[22] P. A. Razis,[22] H. Rykaczewski,[22] M. Finger,[23,i] M. Finger Jr.,[23,i] E. Ayala,[24] E. Carrera Jarrin,[25] Y. Assran,[26,j,k] S. Elgammal,[26,j] A. Ellithi Kamel,[26,l] S. Bhowmik,[27] A. Carvalho Antunes De Oliveira,[27] R. K. Dewanjee,[27] K. Ehataht,[27] M. Kadastik,[27] M. Raidal,[27] C. Veelken,[27] P. Eerola,[28] H. Kirschenmann,[28] J. Pekkanen,[28] M. Voutilainen,[28] J. Havukainen,[29] J. K. Heikkilä,[29] T. Järvinen,[29] V. Karimäki,[29] R. Kinnunen,[29] T. Lampén,[29] K. Lassila-Perini,[29] S. Laurila,[29] S. Lehti,[29] T. Lindén,[29] P. Luukka,[29] T. Mäenpää,[29] H. Siikonen,[29] E. Tuominen,[29] J. Tuominiemi,[29] T. Tuuva,[30] M. Besancon,[31] F. Couderc,[31] M. Dejardin,[31] D. Denegri,[31] J. L. Faure,[31] F. Ferri,[31] S. Ganjour,[31] A. Givernaud,[31] P. Gras,[31] G. Hamel de Monchenault,[31] P. Jarry,[31] C. Leloup,[31] E. Locci,[31] J. Malcles,[31] G. Negro,[31] J. Rander,[31] A. Rosowsky,[31] M. Ö. Sahin,[31] M. Titov,[31] A. Abdulsalam,[32,m] C. Amendola,[32] I. Antropov,[32] F. Beaudette,[32] P. Busson,[32] C. Charlot,[32] R. Granier de Cassagnac,[32] I. Kucher,[32] A. Lobanov,[32] J. Martin Blanco,[32] C. Martin Perez,[32] M. Nguyen,[32] C. Ochando,[32] G. Ortona,[32] P. Paganini,[32] P. Pigard,[32] J. Rembser,[32] R. Salerno,[32] J. B. Sauvan,[32] Y. Sirois,[32] A. G. Stahl Leiton,[32] A. Zabi,[32] A. Zghiche,[32] J.-L. Agram,[33,n] J. Andrea,[33] D. Bloch,[33] J.-M. Brom,[33] E. C. Chabert,[33] V. Cherepanov,[33] C. Collard,[33] E. Conte,[33,n] J.-C. Fontaine,[33,n] D. Gelé,[33] U. Goerlach,[33] M. Jansová,[33] A.-C. Le Bihan,[33] N. Tonon,[33] P. Van Hove,[33] S. Gadrat,[34] S. Beauceron,[35] C. Bernet,[35] G. Boudoul,[35] N. Chanon,[35] R. Chierici,[35] D. Contardo,[35] P. Depasse,[35] H. El Mamouni,[35] J. Fay,[35] L. Finco,[35] S. Gascon,[35] M. Gouzevitch,[35] G. Grenier,[35] B. Ille,[35] F. Lagarde,[35] I. B. Laktineh,[35] H. Lattaud,[35] M. Lethuillier,[35] L. Mirabito,[35] S. Perries,[35] A. Popov,[35,o] V. Sordini,[35] G. Touquet,[35] M. Vander Donckt,[35] S. Viret,[35] T. Toriashvili,[36,p] I. Bagaturia,[37,q] C. Autermann,[38] L. Feld,[38] M. K. Kiesel,[38] K. Klein,[38] M. Lipinski,[38] M. Preuten,[38] M. P. Rauch,[38] C. Schomakers,[38] J. Schulz,[38] M. Teroerde,[38] B. Wittmer,[38] A. Albert,[39] D. Duchardt,[39] M. Erdmann,[39] S. Erdweg,[39] T. Esch,[39] R. Fischer,[39] S. Ghosh,[39] A. Güth,[39] T. Hebbeker,[39] C. Heidemann,[39] K. Hoepfner,[39] H. Keller,[39] L. Mastrolorenzo,[39] M. Merschmeyer,[39] A. Meyer,[39] P. Millet,[39] S. Mukherjee,[39] T. Pook,[39] M. Radziej,[39] H. Reithler,[39] M. Rieger,[39] A. Schmidt,[39] D. Teyssier,[39] S. Thüer,[39] G. Flügge,[40] O. Hlushchenko,[40] T. Kress,[40] T. Müller,[40] A. Nehrkorn,[40] A. Nowack,[40] C. Pistone,[40] O. Pooth,[40] D. Roy,[40] H. Sert,[40] A. Stahl,[40,r] M. Aldaya Martin,[41] T. Arndt,[41] C. Asawatangtrakuldee,[41] I. Babounikau,[41] K. Beernaert,[41] O. Behnke,[41] U. Behrens,[41] A. Bermúdez Martínez,[41] D. Bertsche,[41] A. A. Bin Anuar,[41] K. Borras,[41,s] V. Botta,[41] A. Campbell,[41] P. Connor,[41] C. Contreras-Campana,[41] V. Danilov,[41] A. De Wit,[41] M. M. Defranchis,[41] C. Diez Pardos,[41] D. Domínguez Damiani,[41] G. Eckerlin,[41] T. Eichhorn,[41] A. Elwood,[41] E. Eren,[41] E. Gallo,[41,t] A. Geiser,[41] J. M. Grados Luyando,[41] A. Grohsjean,[41] M. Guthoff,[41] M. Haranko,[41] A. Harb,[41] J. Hauk,[41] H. Jung,[41] M. Kasemann,[41] J. Keaveney,[41] C. Kleinwort,[41] J. Knolle,[41] D. Krücker,[41] W. Lange,[41] A. Lelek,[41] T. Lenz,[41] J. Leonard,[41] K. Lipka,[41] W. Lohmann,[41,u] R. Mankel,[41] I.-A. Melzer-Pellmann,[41] A. B. Meyer,[41] M. Meyer,[41] M. Missiroli,[41] G. Mittag,[41] J. Mnich,[41] V. Myronenko,[41] S. K. Pflitsch,[41] D. Pitzl,[41] A. Raspereza,[41] M. Savitskyi,[41] P. Saxena,[41] P. Schütze,[41] C. Schwanenberger,[41] R. Shevchenko,[41] A. Singh,[41] H. Tholen,[41] O. Turkot,[41] A. Vagnerini,[41] G. P. Van Onsem,[41] R. Walsh,[41] Y. Wen,[41] K. Wichmann,[41] C. Wissing,[41] O. Zenaiev,[41] R. Aggleton,[42] S. Bein,[42] L. Benato,[42] A. Benecke,[42] V. Blobel,[42] T. Dreyer,[42] A. Ebrahimi,[42] E. Garutti,[42] D. Gonzalez,[42] P. Gunnellini,[42] J. Haller,[42] A. Hinzmann,[42] A. Karavdina,[42] G. Kasieczka,[42] R. Klanner,[42] R. Kogler,[42] N. Kovalchuk,[42] S. Kurz,[42] V. Kutzner,[42] J. Lange,[42] D. Marconi,[42] J. Multhaup,[42] M. Niedziela,[42] C. E. N. Niemeyer,[42] D. Nowatschin,[42] A. Perieanu,[42] A. Reimers,[42] O. Rieger,[42] C. Scharf,[42] P. Schleper,[42] S. Schumann,[42] J. Schwandt,[42] J. Sonneveld,[42] H. Stadie,[42] G. Steinbrück,[42] F. M. Stober,[42] M. Stöver,[42] A. Vanhoefer,[42] B. Vormwald,[42] I. Zoi,[42] M. Akbiyik,[43] C. Barth,[43] M. Baselga,[43] S. Baur,[43] E. Butz,[43] R. Caspart,[43] T. Chwalek,[43] F. Colombo,[43] W. De Boer,[43] A. Dierlamm,[43] K. El Morabit,[43] N. Faltermann,[43] B. Freund,[43] M. Giffels,[43] M. A. Harrendorf,[43] F. Hartmann,[43,r] S. M. Heindl,[43] U. Husemann,[43] I. Katkov,[43,o] S. Kudella,[43] S. Mitra,[43] M. U. Mozer,[43] Th. Müller,[43] M. Musich,[43] M. Plagge,[43] G. Quast,[43] K. Rabbertz,[43] M. Schröder,[43] I. Shvetsov,[43] H. J. Simonis,[43] R. Ulrich,[43] S. Wayand,[43] M. Weber,[43] T. Weiler,[43] C. Wöhrmann,[43] R. Wolf,[43] G. Anagnostou,[44] G. Daskalakis,[44] T. Geralis,[44] A. Kyriakis,[44] D. Loukas,[44] G. Paspalaki,[44] G. Karathanasis,[45] P. Kontaxakis,[45] A. Panagiotou,[45] I. Papavergou,[45] N. Saoulidou,[45] E. Tziaferi,[45] K. Vellidis,[45] K. Kousouris,[46] I. Papakrivopoulos,[46] G. Tsipolitis,[46] I. Evangelou,[47] C. Foudas,[47] P. Gianneios,[47] P. Katsoulis,[47] P. Kokkas,[47] S. Mallios,[47] N. Manthos,[47] I. Papadopoulos,[47] E. Paradas,[47] J. Strologas,[47] F. A. Triantis,[47] D. Tsitsonis,[47] M. Bartók,[48,v] M. Csanad,[48] N. Filipovic,[48] P. Major,[48] M. I. Nagy,[48] G. Pasztor,[48] O. Surányi,[48] G. I. Veres,[48] G. Bencze,[49] C. Hajdu,[49] D. Horvath,[49,w] Á. Hunyadi,[49] F. Sikler,[49] T. Á. Vámi,[49] V. Veszpremi,[49] G. Vesztergombi,[49,a,x] N. Beni,[50] S. Czellar,[50] J. Karancsi,[50,v] A. Makovec,[50] J. Molnar,[50] Z. Szillasi,[50] P. Raics,[51] Z. L. Trocsanyi,[51] B. Ujvari,[51] S. Choudhury,[52] J. R. Komaragiri,[52] P. C. Tiwari,[52] S. Bahinipati,[53,y] C. Kar,[53] P. Mal,[53] K. Mandal,[53] A. Nayak,[53,z]

D. K. Sahoo,[53,y] S. K. Swain,[53] S. Bansal,[54] S. B. Beri,[54] V. Bhatnagar,[54] S. Chauhan,[54] R. Chawla,[54] N. Dhingra,[54] R. Gupta,[54] A. Kaur,[54] M. Kaur,[54] S. Kaur,[54] P. Kumari,[54] M. Lohan,[54] A. Mehta,[54] K. Sandeep,[54] S. Sharma,[54] J. B. Singh,[54] A. K. Virdi,[54] G. Walia,[54] A. Bhardwaj,[55] B. C. Choudhary,[55] R. B. Garg,[55] M. Gola,[55] S. Keshri,[55] Ashok Kumar,[55] S. Malhotra,[55] M. Naimuddin,[55] P. Priyanka,[55] K. Ranjan,[55] Aashaq Shah,[55] R. Sharma,[55] R. Bhardwaj,[56,aa] M. Bharti,[56,aa] R. Bhattacharya,[56] S. Bhattacharya,[56] U. Bhawandeep,[56,aa] D. Bhowmik,[56] S. Dey,[56] S. Dutt,[56,aa] S. Dutta,[56] S. Ghosh,[56] K. Mondal,[56] S. Nandan,[56] A. Purohit,[56] P. K. Rout,[56] A. Roy,[56] S. Roy Chowdhury,[56] G. Saha,[56] S. Sarkar,[56] M. Sharan,[56] B. Singh,[56,aa] S. Thakur,[56,aa] P. K. Behera,[57] R. Chudasama,[58] D. Dutta,[58] V. Jha,[58] V. Kumar,[58] P. K. Netrakanti,[58] L. M. Pant,[58] P. Shukla,[58] T. Aziz,[59] M. A. Bhat,[59] S. Dugad,[59] G. B. Mohanty,[59] N. Sur,[59] B. Sutar,[59] Ravindra Kumar Verma,[59] S. Banerjee,[60] S. Bhattacharya,[60] S. Chatterjee,[60] P. Das,[60] M. Guchait,[60] Sa. Jain,[60] S. Karmakar,[60] S. Kumar,[60] M. Maity,[60,bb] G. Majumder,[60] K. Mazumdar,[60] N. Sahoo,[60] T. Sarkar,[60,bb] S. Chauhan,[61] S. Dube,[61] V. Hegde,[61] A. Kapoor,[61] K. Kothekar,[61] S. Pandey,[61] A. Rane,[61] A. Rastogi,[61] S. Sharma,[61] S. Chenarani,[62,cc] E. Eskandari Tadavani,[62] S. M. Etesami,[62,cc] M. Khakzad,[62] M. Mohammadi Najafabadi,[62] M. Naseri,[62] F. Rezaei Hosseinabadi,[62] B. Safarzadeh,[62,dd] M. Zeinali,[62] M. Felcini,[63] M. Grunewald,[63] M. Abbrescia,[64a,64b] C. Calabria,[64a,64b] A. Colaleo,[64a] D. Creanza,[64a,64c] L. Cristella,[64a,64b] N. De Filippis,[64a,64c] M. De Palma,[64a,64b] A. Di Florio,[64a,64b] F. Errico,[64a,64b] L. Fiore,[64a] A. Gelmi,[64a,64b] G. Iaselli,[64a,64c] M. Ince,[64a,64b] S. Lezki,[64a,64b] G. Maggi,[64a,64c] M. Maggi,[64a] G. Miniello,[64a,64b] S. My,[64a,64b] S. Nuzzo,[64a,64b] A. Pompili,[64a,64b] G. Pugliese,[64a,64c] R. Radogna,[64a] A. Ranieri,[64a] G. Selvaggi,[64a,64b] A. Sharma,[64a] L. Silvestris,[64a] R. Venditti,[64a] P. Verwilligen,[64a] G. Zito,[64a] G. Abbiendi,[65a] C. Battilana,[65a,65b] D. Bonacorsi,[65a,65b] L. Borgonovi,[65a,65b] S. Braibant-Giacomelli,[65a,65b] R. Campanini,[65a,65b] P. Capiluppi,[65a,65b] A. Castro,[65a,65b] F. R. Cavallo,[65a] S. S. Chhibra,[65a,65b] C. Ciocca,[65a] G. Codispoti,[65a,65b] M. Cuffiani,[65a,65b] G. M. Dallavalle,[65a] F. Fabbri,[65a] A. Fanfani,[65a,65b] E. Fontanesi,[65a] P. Giacomelli,[65a] C. Grandi,[65a] L. Guiducci,[65a,65b] F. Iemmi,[65a,65b] S. Lo Meo,[65a] S. Marcellini,[65a] G. Masetti,[65a] A. Montanari,[65a] F. L. Navarria,[65a,65b] A. Perrotta,[65a] F. Primavera,[65a,65b,r] T. Rovelli,[65a,65b] G. P. Siroli,[65a,65b] N. Tosi,[65a] S. Albergo,[66a,66b] A. Di Mattia,[66a] R. Potenza,[66a,66b] A. Tricomi,[66a,66b] C. Tuve,[66a,66b] G. Barbagli,[67a] K. Chatterjee,[67a,67b] V. Ciulli,[67a,67b] C. Civinini,[67a] R. D'Alessandro,[67a,67b] E. Focardi,[67a,67b] G. Latino,[67a] P. Lenzi,[67a,67b] M. Meschini,[67a] S. Paoletti,[67a] L. Russo,[67a,ee] G. Sguazzoni,[67a] D. Strom,[67a] L. Viliani,[67a] L. Benussi,[68] S. Bianco,[68] F. Fabbri,[68] D. Piccolo,[68] F. Ferro,[69a] R. Mulargia,[69a,69b] F. Ravera,[69a,69b] E. Robutti,[69a] S. Tosi,[69a,69b] A. Benaglia,[70a] A. Beschi,[70a,70b] F. Brivio,[70a,70b] V. Ciriolo,[70a,70b,r] S. Di Guida,[70a,70b,r] M. E. Dinardo,[70a,70b] S. Fiorendi,[70a,70b] S. Gennai,[70a] A. Ghezzi,[70a,70b] P. Govoni,[70a,70b] M. Malberti,[70a,70b] S. Malvezzi,[70a] D. Menasce,[70a] F. Monti,[70a] L. Moroni,[70a] M. Paganoni,[70a,70b] D. Pedrini,[70a] S. Ragazzi,[70a,70b] T. Tabarelli de Fatis,[70a,70b] D. Zuolo,[70a,70b] S. Buontempo,[71a] N. Cavallo,[71a,71c] A. De Iorio,[71a,71b] A. Di Crescenzo,[71a,71b] F. Fabozzi,[71a,71c] F. Fienga,[71a] G. Galati,[71a] A. O. M. Iorio,[71a,71b] W. A. Khan,[71a] L. Lista,[71a] S. Meola,[71a,71d,r] P. Paolucci,[71a,r] C. Sciacca,[71a,71b] E. Voevodina,[71a,71b] P. Azzi,[72a] N. Bacchetta,[72a] D. Bisello,[72a,72b] A. Boletti,[72a,72b] A. Bragagnolo,[72a] R. Carlin,[72a,72b] P. Checchia,[72a] M. Dall'Osso,[72a,72b] P. De Castro Manzano,[72a] T. Dorigo,[72a] U. Dosselli,[72a] F. Gasparini,[72a,72b] U. Gasparini,[72a,72b] A. Gozzelino,[72a] S. Y. Hoh,[72a] S. Lacaprara,[72a] P. Lujan,[72a] M. Margoni,[72a,72b] A. T. Meneguzzo,[72a,72b] J. Pazzini,[72a,72b] P. Ronchese,[72a,72b] R. Rossin,[72a,72b] F. Simonetto,[72a,72b] A. Tiko,[72a] E. Torassa,[72a] M. Tosi,[72a,72b] M. Zanetti,[72a,72b] P. Zotto,[72a,72b] G. Zumerle,[72a,72b] A. Braghieri,[73a] A. Magnani,[73a] P. Montagna,[73a,73b] S. P. Ratti,[73a,73b] V. Re,[73a] M. Ressegotti,[73a,73b] C. Riccardi,[73a,73b] P. Salvini,[73a] I. Vai,[73a,73b] P. Vitulo,[73a,73b] M. Biasini,[74a,74b] G. M. Bilei,[74a] C. Cecchi,[74a,74b] D. Ciangottini,[74a,74b] L. Fanò,[74a,74b] P. Lariccia,[74a,74b] R. Leonardi,[74a,74b] E. Manoni,[74a] G. Mantovani,[74a,74b] V. Mariani,[74a,74b] M. Menichelli,[74a] A. Rossi,[74a,74b] A. Santocchia,[74a,74b] D. Spiga,[74a] K. Androsov,[75a] P. Azzurri,[75a] G. Bagliesi,[75a] L. Bianchini,[75a] T. Boccali,[75a] L. Borrello,[75a] R. Castaldi,[75a] M. A. Ciocci,[75a,75b] R. Dell'Orso,[75a] G. Fedi,[75a] F. Fiori,[75a,75c] L. Giannini,[75a,75c] A. Giassi,[75a] M. T. Grippo,[75a] F. Ligabue,[75a,75c] E. Manca,[75a,75c] G. Mandorli,[75a,75c] A. Messineo,[75a,75b] F. Palla,[75a] A. Rizzi,[75a,75b] G. Rolandi,[75a,ff] P. Spagnolo,[75a] R. Tenchini,[75a] G. Tonelli,[75a,75b] A. Venturi,[75a] P. G. Verdini,[75a] L. Barone,[76a,76b] F. Cavallari,[76a] M. Cipriani,[76a,76b] D. Del Re,[76a,76b] E. Di Marco,[76a,76b] M. Diemoz,[76a] S. Gelli,[76a,76b] E. Longo,[76a,76b] B. Marzocchi,[76a,76b] P. Meridiani,[76a] G. Organtini,[76a,76b] F. Pandolfi,[76a] R. Paramatti,[76a,76b] F. Preiato,[76a,76b] S. Rahatlou,[76a,76b] C. Rovelli,[76a] F. Santanastasio,[76a,76b] N. Amapane,[77a,77b] R. Arcidiacono,[77a,77c] S. Argiro,[77a,77b] M. Arneodo,[77a,77c] N. Bartosik,[77a] R. Bellan,[77a,77b] C. Biino,[77a] A. Cappati,[77a,77b] N. Cartiglia,[77a] F. Cenna,[77a,77b] S. Cometti,[77a] M. Costa,[77a,77b] R. Covarelli,[77a,77b] N. Demaria,[77a] B. Kiani,[77a,77b] C. Mariotti,[77a] S. Maselli,[77a] E. Migliore,[77a,77b] V. Monaco,[77a,77b] E. Monteil,[77a,77b] M. Monteno,[77a] M. M. Obertino,[77a,77b] L. Pacher,[77a,77b] N. Pastrone,[77a] M. Pelliccioni,[77a] G. L. Pinna Angioni,[77a,77b] A. Romero,[77a,77b] M. Ruspa,[77a,77c] R. Sacchi,[77a,77b] R. Salvatico,[77a,77b] K. Shchelina,[77a,77b] V. Sola,[77a] A. Solano,[77a,77b] D. Soldi,[77a,77b] A. Staiano,[77a] S. Belforte,[78a] V. Candelise,[78a,78b]

M. Casarsa,[78a] F. Cossutti,[78a] A. Da Rold,[78a,78b] G. Della Ricca,[78a,78b] F. Vazzoler,[78a,78b] A. Zanetti,[78a] D. H. Kim,[79] G. N. Kim,[79] M. S. Kim,[79] J. Lee,[79] S. Lee,[79] S. W. Lee,[79] C. S. Moon,[79] Y. D. Oh,[79] S. I. Pak,[79] S. Sekmen,[79] D. C. Son,[79] Y. C. Yang,[79] H. Kim,[80] D. H. Moon,[80] G. Oh,[80] B. Francois,[81] J. Goh,[81,gg] T. J. Kim,[81] S. Cho,[82] S. Choi,[82] Y. Go,[82] D. Gyun,[82] S. Ha,[82] B. Hong,[82] Y. Jo,[82] K. Lee,[82] K. S. Lee,[82] S. Lee,[82] J. Lim,[82] S. K. Park,[82] Y. Roh,[82] H. S. Kim,[83] J. Almond,[84] J. Kim,[84] J. S. Kim,[84] H. Lee,[84] K. Lee,[84] K. Nam,[84] S. B. Oh,[84] B. C. Radburn-Smith,[84] S. h. Seo,[84] U. K. Yang,[84] H. D. Yoo,[84] G. B. Yu,[84] D. Jeon,[85] H. Kim,[85] J. H. Kim,[85] J. S. H. Lee,[85] I. C. Park,[85] Y. Choi,[86] C. Hwang,[86] J. Lee,[86] I. Yu,[86] V. Dudenas,[87] A. Juodagalvis,[87] J. Vaitkus,[87] I. Ahmed,[88] Z. A. Ibrahim,[88] M. A. B. Md Ali,[88,hh] F. Mohamad Idris,[88,ii] W. A. T. Wan Abdullah,[88] M. N. Yusli,[88] Z. Zolkapli,[88] J. F. Benitez,[89] A. Castaneda Hernandez,[89] J. A. Murillo Quijada,[89] H. Castilla-Valdez,[90] E. De La Cruz-Burelo,[90] M. C. Duran-Osuna,[90] I. Heredia-De La Cruz,[90,jj] R. Lopez-Fernandez,[90] J. Mejia Guisao,[90] R. I. Rabadan-Trejo,[90] M. Ramirez-Garcia,[90] G. Ramirez-Sanchez,[90] R. Reyes-Almanza,[90] A. Sanchez-Hernandez,[90] S. Carrillo Moreno,[91] C. Oropeza Barrera,[91] F. Vazquez Valencia,[91] J. Eysermans,[92] I. Pedraza,[92] H. A. Salazar Ibarguen,[92] C. Uribe Estrada,[92] A. Morelos Pineda,[93] D. Krofcheck,[94] S. Bheesette,[95] P. H. Butler,[95] A. Ahmad,[96] M. Ahmad,[96] M. I. Asghar,[96] Q. Hassan,[96] H. R. Hoorani,[96] A. Saddique,[96] M. A. Shah,[96] M. Shoaib,[96] M. Waqas,[96] H. Bialkowska,[97] M. Bluj,[97] B. Boimska,[97] T. Frueboes,[97] M. Górski,[97] M. Kazana,[97] M. Szleper,[97] P. Traczyk,[97] P. Zalewski,[97] K. Bunkowski,[98] A. Byszuk,[98,kk] K. Doroba,[98] A. Kalinowski,[98] M. Konecki,[98] J. Krolikowski,[98] M. Misiura,[98] M. Olszewski,[98] A. Pyskir,[98] M. Walczak,[98] M. Araujo,[99] P. Bargassa,[99] C. Beirão Da Cruz E Silva,[99] A. Di Francesco,[99] P. Faccioli,[99] B. Galinhas,[99] M. Gallinaro,[99] J. Hollar,[99] N. Leonardo,[99] J. Seixas,[99] G. Strong,[99] O. Toldaiev,[99] J. Varela,[99] S. Afanasiev,[100] P. Bunin,[100] M. Gavrilenko,[100] I. Golutvin,[100] I. Gorbunov,[100] A. Kamenev,[100] V. Karjavine,[100] A. Lanev,[100] A. Malakhov,[100] V. Matveev,[100,ll,mm] P. Moisenz,[100] V. Palichik,[100] V. Perelygin,[100] S. Shmatov,[100] S. Shulha,[100] N. Skatchkov,[100] V. Smirnov,[100] N. Voytishin,[100] A. Zarubin,[100] V. Golovtsov,[101] Y. Ivanov,[101] V. Kim,[101,nn] E. Kuznetsova,[101,oo] P. Levchenko,[101] V. Murzin,[101] V. Oreshkin,[101] I. Smirnov,[101] D. Sosnov,[101] V. Sulimov,[101] L. Uvarov,[101] S. Vavilov,[101] A. Vorobyev,[101] Yu. Andreev,[102] A. Dermenev,[102] S. Gninenko,[102] N. Golubev,[102] A. Karneyeu,[102] M. Kirsanov,[102] N. Krasnikov,[102] A. Pashenkov,[102] D. Tlisov,[102] A. Toropin,[102] V. Epshteyn,[103] V. Gavrilov,[103] N. Lychkovskaya,[103] V. Popov,[103] I. Pozdnyakov,[103] G. Safronov,[103] A. Spiridonov,[103] A. Stepennov,[103] V. Stolin,[103] M. Toms,[103] E. Vlasov,[103] A. Zhokin,[103] T. Aushev,[104] M. Chadeeva,[105,pp] P. Parygin,[105] D. Philippov,[105] S. Polikarpov,[105,pp] E. Popova,[105] V. Rusinov,[105] V. Andreev,[106] M. Azarkin,[106] I. Dremin,[106,mm] M. Kirakosyan,[106] A. Terkulov,[106] A. Baskakov,[107] A. Belyaev,[107] E. Boos,[107] V. Bunichev,[107] M. Dubinin,[107,qq] L. Dudko,[107] A. Gribushin,[107] V. Klyukhin,[107] O. Kodolova,[107] I. Lokhtin,[107] I. Miagkov,[107] S. Obraztsov,[107] S. Petrushanko,[107] V. Savrin,[107] A. Snigirev,[107] A. Barnyakov,[108,rr] V. Blinov,[108,rr] T. Dimova,[108,rr] L. Kardapoltsev,[108,rr] Y. Skovpen,[108,rr] I. Azhgirey,[109] I. Bayshev,[109] S. Bitioukov,[109] D. Elumakhov,[109] A. Godizov,[109] V. Kachanov,[109] A. Kalinin,[109] D. Konstantinov,[109] P. Mandrik,[109] V. Petrov,[109] R. Ryutin,[109] S. Slabospitskii,[109] A. Sobol,[109] S. Troshin,[109] N. Tyurin,[109] A. Uzunian,[109] A. Volkov,[109] A. Babaev,[110] S. Baidali,[110] V. Okhotnikov,[110] P. Adzic,[111,ss] P. Cirkovic,[111] D. Devetak,[111] M. Dordevic,[111] J. Milosevic,[111] J. Alcaraz Maestre,[112] A. Álvarez Fernández,[112] I. Bachiller,[112] M. Barrio Luna,[112] J. A. Brochero Cifuentes,[112] M. Cerrada,[112] N. Colino,[112] B. De La Cruz,[112] A. Delgado Peris,[112] C. Fernandez Bedoya,[112] J. P. Fernández Ramos,[112] J. Flix,[112] M. C. Fouz,[112] O. Gonzalez Lopez,[112] S. Goy Lopez,[112] J. M. Hernandez,[112] M. I. Josa,[112] D. Moran,[112] A. Pérez-Calero Yzquierdo,[112] J. Puerta Pelayo,[112] I. Redondo,[112] L. Romero,[112] M. S. Soares,[112] A. Triossi,[112] C. Albajar,[113] J. F. de Trocóniz,[113] J. Cuevas,[114] C. Erice,[114] J. Fernandez Menendez,[114] S. Folgueras,[114] I. Gonzalez Caballero,[114] J. R. González Fernández,[114] E. Palencia Cortezon,[114] V. Rodríguez Bouza,[114] S. Sanchez Cruz,[114] P. Vischia,[114] J. M. Vizan Garcia,[114] I. J. Cabrillo,[115] A. Calderon,[115] B. Chazin Quero,[115] J. Duarte Campderros,[115] M. Fernandez,[115] P. J. Fernández Manteca,[115] A. García Alonso,[115] J. Garcia-Ferrero,[115] G. Gomez,[115] A. Lopez Virto,[115] J. Marco,[115] C. Martinez Rivero,[115] P. Martinez Ruiz del Arbol,[115] F. Matorras,[115] J. Piedra Gomez,[115] C. Prieels,[115] T. Rodrigo,[115] A. Ruiz-Jimeno,[115] L. Scodellaro,[115] N. Trevisani,[115] I. Vila,[115] R. Vilar Cortabitarte,[115] N. Wickramage,[116] D. Abbaneo,[117] B. Akgun,[117] E. Auffray,[117] G. Auzinger,[117] P. Baillon,[117] A. H. Ball,[117] D. Barney,[117] J. Bendavid,[117] M. Bianco,[117] A. Bocci,[117] C. Botta,[117] E. Brondolin,[117] T. Camporesi,[117] M. Cepeda,[117] G. Cerminara,[117] E. Chapon,[117] Y. Chen,[117] G. Cucciati,[117] D. d'Enterria,[117] A. Dabrowski,[117] N. Daci,[117] V. Daponte,[117] A. David,[117] A. De Roeck,[117] N. Deelen,[117] M. Dobson,[117] M. Dünser,[117] N. Dupont,[117] A. Elliott-Peisert,[117] P. Everaerts,[117] F. Fallavollita,[117,tt] D. Fasanella,[117] G. Franzoni,[117] J. Fulcher,[117] W. Funk,[117] D. Gigi,[117] A. Gilbert,[117] K. Gill,[117] F. Glege,[117] M. Gruchala,[117] M. Guilbaud,[117] D. Gulhan,[117] J. Hegeman,[117] C. Heidegger,[117] V. Innocente,[117] A. Jafari,[117] P. Janot,[117] O. Karacheban,[117,u] J. Kieseler,[117] A. Kornmayer,[117]

M. Krammer,[117,b] C. Lange,[117] P. Lecoq,[117] C. Lourenço,[117] L. Malgeri,[117] M. Mannelli,[117] A. Massironi,[117] F. Meijers,[117] J. A. Merlin,[117] S. Mersi,[117] E. Meschi,[117] P. Milenovic,[117,uu] F. Moortgat,[117] M. Mulders,[117] J. Ngadiuba,[117] S. Nourbakhsh,[117] S. Orfanelli,[117] L. Orsini,[117] F. Pantaleo,[117,r] L. Pape,[117] E. Perez,[117] M. Peruzzi,[117] A. Petrilli,[117] G. Petrucciani,[117] A. Pfeiffer,[117] M. Pierini,[117] F. M. Pitters,[117] D. Rabady,[117] A. Racz,[117] T. Reis,[117] M. Rovere,[117] H. Sakulin,[117] C. Schäfer,[117] C. Schwick,[117] M. Selvaggi,[117] A. Sharma,[117] P. Silva,[117] P. Sphicas,[117,vv] A. Stakia,[117] J. Steggemann,[117] D. Treille,[117] A. Tsirou,[117] V. Veckalns,[117,ww] M. Verzetti,[117] W. D. Zeuner,[117] L. Caminada,[118,xx] K. Deiters,[118] W. Erdmann,[118] R. Horisberger,[118] Q. Ingram,[118] H. C. Kaestli,[118] D. Kotlinski,[118] U. Langenegger,[118] T. Rohe,[118] S. A. Wiederkehr,[118] M. Backhaus,[119] L. Bäni,[119] P. Berger,[119] N. Chernyavskaya,[119] G. Dissertori,[119] M. Dittmar,[119] M. Donegà,[119] C. Dorfer,[119] T. A. Gómez Espinosa,[119] C. Grab,[119] D. Hits,[119] T. Klijnsma,[119] W. Lustermann,[119] R. A. Manzoni,[119] M. Marionneau,[119] M. T. Meinhard,[119] F. Micheli,[119] P. Musella,[119] F. Nessi-Tedaldi,[119] J. Pata,[119] F. Pauss,[119] G. Perrin,[119] L. Perrozzi,[119] S. Pigazzini,[119] M. Quittnat,[119] C. Reissel,[119] D. Ruini,[119] D. A. Sanz Becerra,[119] M. Schönenberger,[119] L. Shchutska,[119] V. R. Tavolaro,[119] K. Theofilatos,[119] M. L. Vesterbacka Olsson,[119] R. Wallny,[119] D. H. Zhu,[119] T. K. Aarrestad,[120] C. Amsler,[120,yy] D. Brzhechko,[120] M. F. Canelli,[120] A. De Cosa,[120] R. Del Burgo,[120] S. Donato,[120] C. Galloni,[120] T. Hreus,[120] B. Kilminster,[120] S. Leontsinis,[120] I. Neutelings,[120] G. Rauco,[120] P. Robmann,[120] D. Salerno,[120] K. Schweiger,[120] C. Seitz,[120] Y. Takahashi,[120] A. Zucchetta,[120] T. H. Doan,[121] R. Khurana,[121] C. M. Kuo,[121] W. Lin,[121] A. Pozdnyakov,[121] S. S. Yu,[121] P. Chang,[122] Y. Chao,[122] K. F. Chen,[122] P. H. Chen,[122] W.-S. Hou,[122] Arun Kumar,[122] Y. F. Liu,[122] R.-S. Lu,[122] E. Paganis,[122] A. Psallidas,[122] A. Steen,[122] B. Asavapibhop,[123] N. Srimanobhas,[123] N. Suwonjandee,[123] M. N. Bakirci,[124,zz] A. Bat,[124] F. Boran,[124] S. Damarseckin,[124] Z. S. Demiroglu,[124] F. Dolek,[124] C. Dozen,[124] E. Eskut,[124] S. Girgis,[124] G. Gokbulut,[124] Y. Guler,[124] E. Gurpinar,[124] I. Hos,[124,aaa] C. Isik,[124] E. E. Kangal,[124,bbb] O. Kara,[124] U. Kiminsu,[124] M. Oglakci,[124] G. Onengut,[124] K. Ozdemir,[124,ccc] S. Ozturk,[124,zz] D. Sunar Cerci,[124,ddd] B. Tali,[124,ddd] U. G. Tok,[124] H. Topakli,[124,zz] S. Turkcapar,[124] I. S. Zorbakir,[124] C. Zorbilmez,[124] B. Isildak,[125,eee] G. Karapinar,[125,fff] M. Yalvac,[125] M. Zeyrek,[125] I. O. Atakisi,[126] E. Gülmez,[126] M. Kaya,[126,ggg] O. Kaya,[126,hhh] S. Ozkorucuklu,[126,iii] S. Tekten,[126] E. A. Yetkin,[126,jjj] M. N. Agaras,[127] A. Cakir,[127] K. Cankocak,[127] Y. Komurcu,[127] S. Sen,[127,kkk] B. Grynyov,[128] L. Levchuk,[129] F. Ball,[130] J. J. Brooke,[130] D. Burns,[130] E. Clement,[130] D. Cussans,[130] O. Davignon,[130] H. Flacher,[130] J. Goldstein,[130] G. P. Heath,[130] H. F. Heath,[130] L. Kreczko,[130] D. M. Newbold,[130,lll] S. Paramesvaran,[130] B. Penning,[130] T. Sakuma,[130] D. Smith,[130] V. J. Smith,[130] J. Taylor,[130] A. Titterton,[130] K. W. Bell,[131] A. Belyaev,[131,mmm] C. Brew,[131] R. M. Brown,[131] D. Cieri,[131] D. J. A. Cockerill,[131] J. A. Coughlan,[131] K. Harder,[131] S. Harper,[131] J. Linacre,[131] K. Manolopoulos,[131] E. Olaiya,[131] D. Petyt,[131] C. H. Shepherd-Themistocleous,[131] A. Thea,[131] I. R. Tomalin,[131] T. Williams,[131] W. J. Womersley,[131] R. Bainbridge,[132] P. Bloch,[132] J. Borg,[132] S. Breeze,[132] O. Buchmuller,[132] A. Bundock,[132] D. Colling,[132] P. Dauncey,[132] G. Davies,[132] M. Della Negra,[132] R. Di Maria,[132] G. Hall,[132] G. Iles,[132] T. James,[132] M. Komm,[132] C. Laner,[132] L. Lyons,[132] A.-M. Magnan,[132] S. Malik,[132] A. Martelli,[132] J. Nash,[132,nnn] A. Nikitenko,[132,h] V. Palladino,[132] M. Pesaresi,[132] D. M. Raymond,[132] A. Richards,[132] A. Rose,[132] E. Scott,[132] C. Seez,[132] A. Shtipliyski,[132] G. Singh,[132] M. Stoye,[132] T. Strebler,[132] S. Summers,[132] A. Tapper,[132] K. Uchida,[132] T. Virdee,[132,r] N. Wardle,[132] D. Winterbottom,[132] J. Wright,[132] S. C. Zenz,[132] J. E. Cole,[133] P. R. Hobson,[133] A. Khan,[133] P. Kyberd,[133] C. K. Mackay,[133] A. Morton,[133] I. D. Reid,[133] L. Teodorescu,[133] S. Zahid,[133] K. Call,[134] J. Dittmann,[134] K. Hatakeyama,[134] H. Liu,[134] C. Madrid,[134] B. McMaster,[134] N. Pastika,[134] C. Smith,[134] R. Bartek,[135] A. Dominguez,[135] A. Buccilli,[136] S. I. Cooper,[136] C. Henderson,[136] P. Rumerio,[136] C. West,[136] D. Arcaro,[137] T. Bose,[137] D. Gastler,[137] D. Pinna,[137] D. Rankin,[137] C. Richardson,[137] J. Rohlf,[137] L. Sulak,[137] D. Zou,[137] G. Benelli,[138] X. Coubez,[138] D. Cutts,[138] M. Hadley,[138] J. Hakala,[138] U. Heintz,[138] J. M. Hogan,[138,ooo] K. H. M. Kwok,[138] E. Laird,[138] G. Landsberg,[138] J. Lee,[138] Z. Mao,[138] M. Narain,[138] S. Sagir,[138,ppp] R. Syarif,[138] E. Usai,[138] D. Yu,[138] R. Band,[139] C. Brainerd,[139] R. Breedon,[139] D. Burns,[139] M. Calderon De La Barca Sanchez,[139] M. Chertok,[139] J. Conway,[139] R. Conway,[139] P. T. Cox,[139] R. Erbacher,[139] C. Flores,[139] G. Funk,[139] W. Ko,[139] O. Kukral,[139] R. Lander,[139] M. Mulhearn,[139] D. Pellett,[139] J. Pilot,[139] S. Shalhout,[139] M. Shi,[139] D. Stolp,[139] D. Taylor,[139] K. Tos,[139] M. Tripathi,[139] Z. Wang,[139] F. Zhang,[139] M. Bachtis,[140] C. Bravo,[140] R. Cousins,[140] A. Dasgupta,[140] A. Florent,[140] J. Hauser,[140] M. Ignatenko,[140] N. Mccoll,[140] S. Regnard,[140] D. Saltzberg,[140] C. Schnaible,[140] V. Valuev,[140] E. Bouvier,[141] K. Burt,[141] R. Clare,[141] J. W. Gary,[141] S. M. A. Ghiasi Shirazi,[141] G. Hanson,[141] G. Karapostoli,[141] E. Kennedy,[141] F. Lacroix,[141] O. R. Long,[141] M. Olmedo Negrete,[141] M. I. Paneva,[141] W. Si,[141] L. Wang,[141] H. Wei,[141] S. Wimpenny,[141] B. R. Yates,[141] J. G. Branson,[142] P. Chang,[142] S. Cittolin,[142] M. Derdzinski,[142] R. Gerosa,[142] D. Gilbert,[142] B. Hashemi,[142] A. Holzner,[142] D. Klein,[142] G. Kole,[142] V. Krutelyov,[142] J. Letts,[142] M. Masciovecchio,[142] D. Olivito,[142] S. Padhi,[142] M. Pieri,[142] M. Sani,[142]

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