

Search for single production of a vectorlike B' quark decaying to a top quark and a W boson in the single-lepton final state in proton-proton collisions at $\sqrt{s} = 13$ TeV

K. Tauqeer *et al.*^{*}
(CMS Collaboration)



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A search is presented for the production of a single narrow-width vectorlike B' quark that decays to a t quark and a W boson. This search targets a single-lepton final state, where a muon or electron originates either from the semileptonic decay of the t quark or from the leptonic decay of the W boson, with the other particle decaying hadronically. The (semi)leptonic portion of the event is reconstructed from an electron or muon, missing transverse momentum, and a small-radius jet identified as a b quark jet if the muon or electron originates from the t quark. The hadronic portion of the event is reconstructed as a single large-radius jet. The originating particle of the large-radius jet is identified using a neural-network-based tagger, and the dominant background contributions are modeled from data using a neural autoregressive flow network. The data were collected from 2016 to 2018 by the CMS experiment at the LHC in proton-proton collisions at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 138 fb^{-1} . This search is the most sensitive to date to the production of single narrow-width B' quarks. It excludes electroweak-singlet B' quarks with $\Gamma/m_{B'} = 5\%$ for masses between 0.8 and 1.23 TeV. Limits are also placed on the production cross section of single B' quarks produced in association with t quarks, and on the coupling factor of the B' quark to electroweak bosons.

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I. INTRODUCTION

Several models of physics beyond the standard model (SM) propose the existence of additional heavy fermions. Many of these extensions are motivated by the concern that the SM requires delicate tuning of its parameters to agree with the observed mass of the Higgs boson. To restore “naturalness” to the SM, some models propose that the Higgs boson is not a fundamental scalar at all energy scales [1,2]. Such models often introduce “vectorlike” quarks (VLQs) as new fermions whose left- and right-handed components transform identically under the electroweak (EW) symmetry groups, in contrast to the chiral nature of SM quarks [3,4]. The VLQs could have masses up to several TeV and would reduce the divergent effects of t quark quantum corrections to the observed Higgs boson mass.

Typically, the VLQs are proposed to mix predominantly with third-generation SM quarks. A vectorlike bottom quark (B') might decay to an SM t or b quark and a W ,

Z , or Higgs boson (tW , bZ , or bH), thereby producing high-momentum signatures as a result of its large mass. An example tree-level Feynman diagram for B' quark production in proton-proton (pp) collisions via an EW interaction is shown in Fig. 1. The B' quark is analogous to the SM b quark and has an electric charge of $-1/3e$, and a corresponding vectorlike T' quark is proposed with an electric charge of $+2/3e$. The B' quark may exist as an EW singlet, as part of a (T', B') doublet, or in a doublet or triplet with more exotic VLQs. Each multiplet assignment implies different branching fractions for the decays of T' or B' quarks. The benchmark scenarios considered in this paper are a singlet B' quark, expected to decay to tW approximately 50% of the time, and a B' quark in a (T', B') doublet that mixes only with up-type quarks. The B' quark in an up-type doublet is expected to decay exclusively to tW [3,4] and is produced only in association with a t quark.

This paper presents a search for the production of a single B' quark in association with a third-generation SM quark, where the B' decays into a t quark and a W boson. The search targets single-lepton events in which either the t quark decays semileptonically and the W boson decays hadronically, or the t quark decays hadronically and the W boson decays leptonically. Consequently, the final state contains a single isolated electron or muon, missing transverse momentum, and one hadronically decaying heavy object reconstructed as a large-radius jet. When

^{*}Full author list given at the end of the article.

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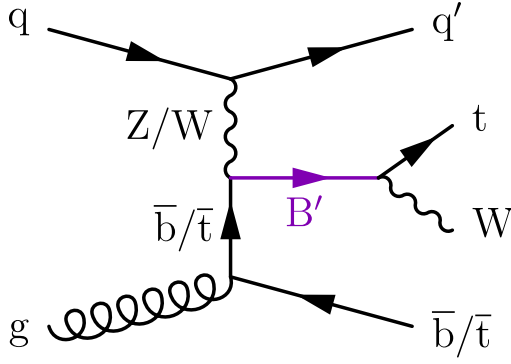


FIG. 1. Tree-level Feynman diagram showing the production of a single B' quark in association with an SM b quark or t quark, decaying in the tW channel.

the lepton originates from the semileptonic decay of the t quark, the event also contains a small-radius b -tagged jet associated with the t quark decay. This search targets the production of single B' quarks with masses in the range 0.8–2.0 TeV and decay widths for which the narrow-width approximation (NWA) is valid. Searches targeting narrow-width VLQs probe the regime of small EW couplings and therefore provide an important complement to finite-width studies, which are primarily sensitive to larger EW couplings. In the small-coupling regime, the interference between the signal and the irreducible SM background is negligible, allowing the signal to be modeled independently of the background [5]. Consequently, the experimental results can be interpreted with reduced dependence on the underlying signal model.

The CMS Collaboration has conducted three searches for the production of single B' quarks at $\sqrt{s} = 13$ TeV: searches for B' quarks decaying to tW [6] and bH [7] using a data sample corresponding to an integrated luminosity of 35.9 fb^{-1} , and a search for excited b quarks decaying to tW using the full Run 2 data set that also provided a B' quark interpretation [8]. Searches have also been conducted by the CMS Collaboration for the pair production of B' quarks via the strong interaction, excluding B' quarks decaying to tW with masses below 1.55 TeV [9]. The ATLAS Collaboration has searched for B' quarks decaying to tW at $\sqrt{s} = 8$ TeV with an integrated luminosity of 20.3 fb^{-1} [10], and to bH at $\sqrt{s} = 13$ TeV with an integrated luminosity of 139 fb^{-1} [11]. Of the previous searches in this channel, only Ref. [8] is sensitive to B' quarks with a decay width of 5%. That search excludes B' quarks with a relative width of 5% in the mass range 0.8–1.15 TeV (0.85–1.05 TeV) for production in association with b (t) quarks. The search presented in this paper extends these constraints, improving the upper limits on the production cross section by a factor of 2–3 for b -associated production across the entire mass spectrum, and by up to a factor of 3 for t -associated production for $m_{B'} > 1.0$ TeV.

The remainder of this paper is organized as follows. Section II introduces the CMS detector and the reconstruction of physics objects. Section III describes the data set and simulated events. The selection criteria and B' quark reconstruction are detailed in Secs. IV and V, respectively. Section VI describes the modeling of SM backgrounds using the “ABCDnn” technique, and systematic uncertainties are discussed in Sec. VII. Results are presented in Sec. VIII, and the paper is summarized in Sec. IX. Tabulated results are provided in the HEPData record for this search [12].

II. THE CMS DETECTOR AND EVENT RECONSTRUCTION

The CMS apparatus [13] is a multipurpose, nearly hermetic detector designed to trigger on [14–16] and identify electrons, muons, photons, and charged and neutral hadrons [17–19]. 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 endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage beyond that provided by the barrel and endcap detectors. Muons are reconstructed using gas-ionization detectors interleaved with the layers of the steel flux-return yoke outside the solenoid. More detailed descriptions of the CMS detector, along with a definition of the coordinate system and relevant kinematic variables, can be found in Refs. [13] and [20].

The primary pp interaction vertex (PV) is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone, as described in Sec. 9.4.1 of Ref. [21]. A particle-flow (PF) algorithm [22] aims to reconstruct and identify each individual particle in an event by combining information from the various elements of the CMS detector. Photon energies are directly measured in the ECAL. For electrons, the momentum at the primary interaction vertex as measured by the tracker is combined with the associated ECAL cluster energy and the summed energies of bremsstrahlung photons consistent with originating from the electron track. Muon momenta are obtained from the curvature of their reconstructed tracks. Charged hadrons are reconstructed using their tracker-measured momenta together with matched ECAL and HCAL energy deposits, with corrections applied to account for the calorimeter response to hadronic showers. Neutral hadrons are reconstructed from the corresponding corrected ECAL and HCAL energy measurements.

For each event, hadronic jets are clustered from PF candidates using the infrared- and collinear-safe anti- k_T algorithm [23,24] with a distance parameter of 0.4 (small-radius jets) or 0.8 (large-radius jets). The jet momentum is determined as the vector sum of the momenta of its

constituent particles, and it is found in simulation to agree with the true momentum to within 5%–10% across the full p_T spectrum and detector acceptance. Additional pp interactions within the same or nearby bunch crossings (pileup) can contribute extra tracks and calorimetric energy, increasing the apparent jet momentum. To mitigate this effect in small-radius jets, tracks identified as originating from pileup vertices are removed, and an offset correction is applied to account for the remaining contributions [25].

The pileup per particle identification algorithm (PUPPI) [25,26] 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 that 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 as originating from pileup vertices are discarded. For each neutral particle, a local shape variable is computed from 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 [25].

Jet energy corrections are derived from simulation to ensure that the average reconstructed jet energy matches that of particle-level jets. In situ measurements of momentum balance in dijet, γ + jet, Z + jet, and multijet events are used to determine residual differences between the jet energy scale in data and simulation, and corresponding corrections are applied [27]. Additional quality requirements are imposed to remove jets likely dominated by instrumental effects or reconstruction failures [25]. The jet energy resolution is typically 15%–20% at 30 GeV, 10% at 100 GeV, and 5% at 1 TeV [27].

Events of interest are selected using a two-tiered trigger system. The first level (L1) trigger, 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 4 μ s [14]. The second level, known as the high-level trigger (HLT), 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 a few kHz before data storage [15,16].

III. DATA AND SIMULATED SAMPLES

The data were collected during 2016–2018 in pp collisions at $\sqrt{s} = 13$ TeV by the CMS experiment at the LHC, corresponding to a total integrated luminosity of 138 fb $^{-1}$ [28–31]. Simulated event samples are produced

separately for each data-taking year to reflect the corresponding detector conditions.

Production of a single vectorlike B' quark with a narrow decay width is simulated at leading order (LO) using MadGraph5_aMC@NLO [32] version 2.6.5, with the model described in Refs. [33,34]. The simulated B' quark masses range from 0.8 to 2.0 TeV, with a step size of 0.1 TeV for 1.2–1.8 TeV and 0.2 TeV elsewhere. The decay width is set to 5 GeV, which is always smaller than 1% of the mass. The reconstructed B' quark mass has a significantly larger width than the generated width, so the reconstruction is not sensitive to small variations in the generated width as long as the width is narrow. The results can be compared with theory predictions for VLQs with relative decay widths of 1% and 5%, but the interpretation is limited to widths smaller than 10%. The simulation includes production of a t quark and a W boson in association with a b (t) quark and a light-flavor quark, denoted as bqB' (tqB'). The decays of the t quark and W boson are modeled using MADSPIN [35].

The production cross sections of a single VLQ are computed to LO, as described in Refs. [5,9]. The production cross section depends on the VLQ mass, width, and couplings. In the NWA, the cross section can be factorized into a reduced cross section $\hat{\sigma}_{\text{NWA}}$ that depends only on the B' mass, and couplings of the VLQ with SM quarks and bosons [5,9]. The b -associated (t -associated) production of B' quarks is assumed to proceed primarily through a coupling to Z (W) bosons. For a B' quark decaying to tW , the production cross sections for the $bqtW$ and $tqtW$ signatures via a B' quark, where q denotes a light-flavor quark, are given by

$$\sigma(bqtW) = \left(\frac{e}{2c_W s_W} \right)^2 \kappa^2 \hat{\sigma}_{\text{NWA}} \mathcal{B}, \quad (1)$$

$$\sigma(tqtW) = \left(\frac{e}{\sqrt{2}s_W} \right)^2 \kappa^2 \hat{\sigma}_{\text{NWA}} \mathcal{B}, \quad (2)$$

where e is the fundamental electric charge, c_W (s_W) is the cosine (sine) of the weak mixing angle, κ is a “coupling factor” that approximates the sine of the mixing angle between the VLQ and SM quark, and $\mathcal{B}$ denotes the branching fraction for $B' \rightarrow tW$ [5,9]. The reduced cross section $\hat{\sigma}_{\text{NWA}}$ depends only on the B' mass, while the coupling factor κ depends on the VLQ mass, width, and EW multiplet assignment. For the benchmark models considered in this search, the singlet scenario assumes $\kappa = \kappa_W = \kappa_Z = \kappa_H$, whereas the (T', B') doublet scenario assumes $\kappa = \kappa_W$. The branching fraction $\mathcal{B}$ is fixed to 0.5 for the singlet benchmark and to unity for the (T', B') doublet benchmark [9]. The values of κ and $\hat{\sigma}_{\text{NWA}}$ used in the singlet and doublet benchmarks for b -associated and t -associated production are summarized in Table I.

The MadGraph5_aMC@NLO generator is used at LO to simulate Drell-Yan and W boson production, as well as

TABLE I. Values of reduced cross section $\hat{\sigma}_{\text{NWA}}$ and coupling factor κ used to compute the cross sections for the production of a B' quark that is either a singlet or a member of a (T', B') doublet, based on the calculations described in Refs. [5,9]. The value of $\hat{\sigma}_{\text{NWA}}$ depends on the B' quark mass and production mode. The value of κ depends on the B' quark mass, width, and multiplet structure. All numerical values are rounded to two significant figures, and uncertainties due to renormalization and factorization scales are provided for $\hat{\sigma}_{\text{NWA}}$.

Mass (TeV)	$\hat{\sigma}_{\text{NWA}}$ (pb)		κ_{singlet}			κ_{doublet}	
	bqB'	tqB'	1%	5%	10%	1%	10%
0.8	33^{+10}_{-7}	13^{+4}_{-3}	0.16	0.36	0.51	0.23	0.74
0.9	23^{+7}_{-5}	$9.8^{+2.9}_{-2.0}$	0.14	0.32	0.45	0.21	0.65
1.0	16^{+5}_{-4}	$7.3^{+2.2}_{-1.6}$	0.13	0.28	0.40	0.18	0.58
1.1	12^{+4}_{-3}	$5.5^{+1.7}_{-1.2}$	0.11	0.26	0.36	0.16	0.52
1.2	$8.7^{+2.9}_{-2.0}$	$4.2^{+1.3}_{-0.9}$	0.10	0.23	0.33	0.15	0.47
1.3	$6.5^{+2.2}_{-1.5}$	$3.2^{+1.0}_{-0.7}$	0.096	0.22	0.30	0.14	0.44
1.4	$4.9^{+1.7}_{-1.1}$	$2.5^{+0.8}_{-0.6}$	0.089	0.20	0.28	0.13	0.40
1.5	$3.7^{+1.3}_{-0.9}$	$1.9^{+0.6}_{-0.4}$	0.083	0.19	0.26	0.12	0.38
1.6	$2.7^{+1.0}_{-0.7}$	$1.5^{+0.5}_{-0.4}$	0.078	0.17	0.25	0.11	0.35
1.7	$2.0^{+0.7}_{-0.5}$	$1.2^{+0.4}_{-0.3}$	0.073	0.16	0.23	0.10	0.33
1.8	$1.5^{+0.6}_{-0.4}$	$0.94^{+0.33}_{-0.22}$	0.069	0.15	0.22	0.098	0.31
1.9	$1.1^{+0.4}_{-0.3}$	$0.74^{+0.26}_{-0.18}$	0.065	0.15	0.21	0.093	0.29
2.0	$0.85^{+0.33}_{-0.22}$	$0.59^{+0.21}_{-0.14}$	0.062	0.14	0.20	0.088	0.28

QCD multijet events. For Drell-Yan and W boson production, the MLM matching scheme [36] is used to remove double counting of partons between the matrix element calculations and the parton shower. The `MadGraph5_aMC@NLO` generator is also used at next-to-leading order (NLO) in perturbative quantum chromodynamics (QCD) to simulate $t\bar{t}W$ and $t\bar{t}Z$ production, as well as s -channel single t quark production. For $t\bar{t}W$ production, the FxFx matching scheme [37] is used to avoid double counting of jets. The `POWHEGv2` generator is used to simulate $t\bar{t}$ [38], $t\bar{t}H$, and additional single t quark production processes [39,40] at NLO. Production of single t quarks via the t -channel is interfaced with `MADSPIN`. The `PYTHIA8.240` generator [41] is used to simulate WW , WZ , and ZZ production at LO. In figures and tables, minor background processes are grouped into “DY + VV” (containing Drell-Yan and diboson processes) and “ $t\bar{t} + X$ ” (containing $t\bar{t}W$, $t\bar{t}Z$, and $t\bar{t}H$ processes).

The NNPDF3.1 [42] parton distribution functions (PDFs) at next-to-NLO in perturbative QCD are used to generate all background and signal samples. Parton showering, fragmentation, and hadronization are performed using `PYTHIA` with the CP5 underlying event tune [43]. The response of the CMS detector to particles is simulated using the `Geant4` toolkit [44]. Simulated pileup interactions are included in the simulated samples. Simulated events are weighted so that the distribution in the number of interactions per bunch crossing matches that observed in data,

corresponding to an average of 23 simultaneous collisions in 2016 and 32 in 2017–2018.

IV. EVENT SELECTION

Events consistent with the decay $B' \rightarrow tW$ are selected in a final state containing a single electron or muon, missing transverse momentum, and a hadronically decaying heavy object reconstructed as a large-radius jet. The charged lepton and missing transverse momentum originate either from the semileptonic decay of the t quark or from the leptonic decay of the W boson produced directly in the B' decay. In the former case, the event also contains a small-radius jet originating from the accompanying b quark from the t quark decay. Signal events must pass one of the HLT triggers for electrons, photons, or muons. The electron triggers require either a nonisolated electron with transverse momentum $p_T > 115$ GeV, or an electron with $p_T > 50$ GeV in association with a small-radius jet with $p_T > 165$ GeV. During an early segment of the 2017 data-taking period, the primary electron trigger required a high-quality isolated electron with $p_T > 35$ GeV. To maintain good efficiency for high- p_T electrons, events passing a photon trigger with an energy threshold of 175 GeV in 2016 or 200 GeV in 2017–2018 are also accepted. The muon trigger requires a muon with $p_T > 50$ GeV, and is supplemented during most data-taking periods by a trigger selecting muons with $p_T > 100$ GeV based solely on tracker information.

Leptons are selected based on their position in the detector, reconstruction quality, and isolation from nearby energy deposits. The decay products from signal events are highly boosted because of the large mass of the B' quark, so the leptons are required to pass a tight isolation requirement on the variable I_{mini} [45], which is defined as the scalar p_T sum of charged hadron, neutral hadron, and photon PF candidates within a cone in η - ϕ space around the lepton, divided by the lepton p_T . The cone radius decreases from 0.2 for leptons with $p_T \leq 50$ GeV to 0.05 for $p_T > 200$ GeV. Selected leptons must satisfy $I_{\text{mini}} < 0.1$. The isolation variable is corrected for pileup using an effective area method [46].

Electron candidates must satisfy $|\eta| < 2.5$, with the transition region between the barrel and end cap calorimeters ($1.442 < |\eta| < 1.566$) excluded. A fraction of the hadronic end cap calorimeter was not functional during a portion of the 2018 data-taking period. Thus, electrons, small-radius jets, and large-radius jets in the inoperable detector region corresponding to $-2.5 < \eta < -1.479$ and $-1.55 < \phi < -0.9$ are excluded for the affected portion of the 2018 data and corresponding simulated samples. For electrons in the barrel (end cap) region, the longitudinal impact parameter relative to the PV must be less than 0.1 (0.2) cm, and the transverse impact parameter must be less than 0.05 (0.1) cm. Electron candidates must also satisfy the “tight” identification criteria described in Ref. [17],

except that the standard isolation requirement there is replaced by the one from the previous paragraph, because the standard requirement is too restrictive.

Muons are required to lie within the central region of the detector with $|\eta| < 2.4$, and to have a longitudinal (transverse) impact parameter less than 0.5 (0.2) cm with respect to the PV. Muon candidates must satisfy the “medium” identification requirement. The overall efficiency is calculated to be 99.5% from simulated W and Z events [18].

Signal events must contain exactly one lepton with $p_T > 55$ GeV that meets these criteria. Events are rejected if they contain any additional leptons satisfying the selection criteria with $25 < p_T < 55$ GeV.

The four-momentum of selected leptons is subtracted from overlapping small-radius jets. Jet energy scale and resolution corrections are then applied. Selected small-radius jets must have $p_T > 30$ GeV, and must be separated from the selected lepton by $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.4$ or have a relative p_T greater than 20 GeV with respect to the lepton. Small-radius jets must also satisfy a jet identification quality requirement which has an efficiency greater than 98%–99% [27]. Jets with $p_T < 50$ GeV are more likely to originate from pileup interactions, so they must additionally satisfy a pileup-rejection criterion with efficiencies of 99% for $|\eta| < 2.5$ and 95% for $|\eta| > 2.5$ [25]. Small-radius jets are labeled as “forward” if they have $|\eta| > 2.5$. Jets originating from b hadrons are identified using the DEEPIET algorithm with a working point that provides 98% efficiency for true b jets and a 10% misidentification rate for light-flavor quark and gluon jets [47,48].

Because of the large mass of the B' quark, the t quark and W boson from its decay often have large Lorentz boosts, such that their decay products are collimated. In such cases, the hadronic decay products of the t quark or W boson can be reconstructed as a large-radius jet. Selected large-radius jets must have $p_T > 200$ GeV and $|\eta| < 2.5$, and must satisfy the same jet identification requirements applied to small-radius jets. As B' quark decays are expected to yield a high- p_T jet well separated from the lepton in η - ϕ space, the selected jet is required to satisfy $\Delta R > \pi/2$ with respect to the lepton. Tagging of these jets as t quark or W boson candidates is performed using the PARTICLENET algorithm [49], with working points corresponding to a misidentification rate of 1% (5%) for classifying light-flavor quark jets as t quark (W boson) jets [49]. In simulated B' quark events, the efficiency for correctly identifying t (W) jets is 85%–90% (70%–90%) for jets with $p_T > 500$ (200) GeV. A given jet may satisfy both the t and W tagging criteria. The choice of whether to treat a jet as a t or W candidate follows the procedure described in Sec. V.

The missing transverse momentum vector, $\vec{p}_T^{\text{miss}}$, is computed as the negative vector sum of the transverse momenta of all PF candidates in the event [50]. Its magnitude is denoted as p_T^{miss} . Corrections to the

reconstructed jet energy scale are propagated to $\vec{p}_T^{\text{miss}}$. The transverse momentum of the selected lepton (denoted p_T^ℓ), p_T^{miss} , and the difference in azimuthal angle between the lepton and $\vec{p}_T^{\text{miss}}$ (denoted $\Delta\phi$) are used to construct the transverse mass of the W boson: $m_T = \sqrt{2p_T^\ell p_T^{\text{miss}}(1 - \cos \Delta\phi)}$.

Signal events are required to contain at least one selected large-radius jet, $p_T^{\text{miss}} > 60$ GeV, and $m_T < 200$ GeV. The scalar sum of the p_T of all selected small-radius jets must exceed 250 GeV. To ensure consistency with the electron trigger, events in the electron channel must contain a small-radius jet with $p_T > 185$ GeV for events with an electron of $p_T < 120$ GeV.

V. THE VLQ RECONSTRUCTION AND EVENT CATEGORIZATION

The B' quark is assumed to decay to tW , with the charged lepton originating from either $W \rightarrow \ell\nu$ decay or $t \rightarrow bW \rightarrow b\ell\nu$ decay. A W boson candidate is therefore reconstructed in all events from the charged lepton and $\vec{p}_T^{\text{miss}}$, applying a W mass constraint. The z component of the neutrino momentum is taken as the real part of the solution that yields a W boson mass closest to the nominal value of 80.4 GeV. If a b -tagged small-radius jet is found within $\Delta R < \pi/2$ of the lepton, the event is categorized as a semileptonic t quark event and the t candidate is reconstructed from the W boson and the b -tagged jet. If no such b -tagged jet is found, the event is categorized as a leptonic W boson event. The other decay product of the B' quark, which does not produce a lepton, is assumed to correspond to the selected large-radius jet with the highest p_T . Based on the PARTICLENET identification of this large-radius jet, events are assigned to one of four reconstruction categories:

- (i) Case 1: leptonic W boson and a t -tagged large-radius jet,
- (ii) Case 2: semileptonic t candidate and a W -tagged large-radius jet,
- (iii) Case 3: semileptonic t candidate and a large-radius jet that is not W tagged,
- (iv) Case 4: leptonic W boson and a large-radius jet that is not t tagged.

Cases 1 and 2 provide the highest sensitivity to a B' quark signal, while cases 3 and 4 are dominated by background. Figure 2 shows the distribution of the reconstructed mass (m_{tW}) of the B' quark candidate, the scalar p_T sum (S_T) of all selected small-radius jets, the selected lepton, and p_T^{miss} , and the event yields in each case. The resolution of the m_{tW} distribution for signal events is approximately 10% of the generated B' quark mass.

In B' production in association with b (t) and light quarks, signal events tend to have more b -tagged jets than the W + jets background and more forward jets than SM backgrounds in general. As shown in Fig. 3, B' quark signal events tend to contain fewer b -tagged jets than the $t\bar{t}$

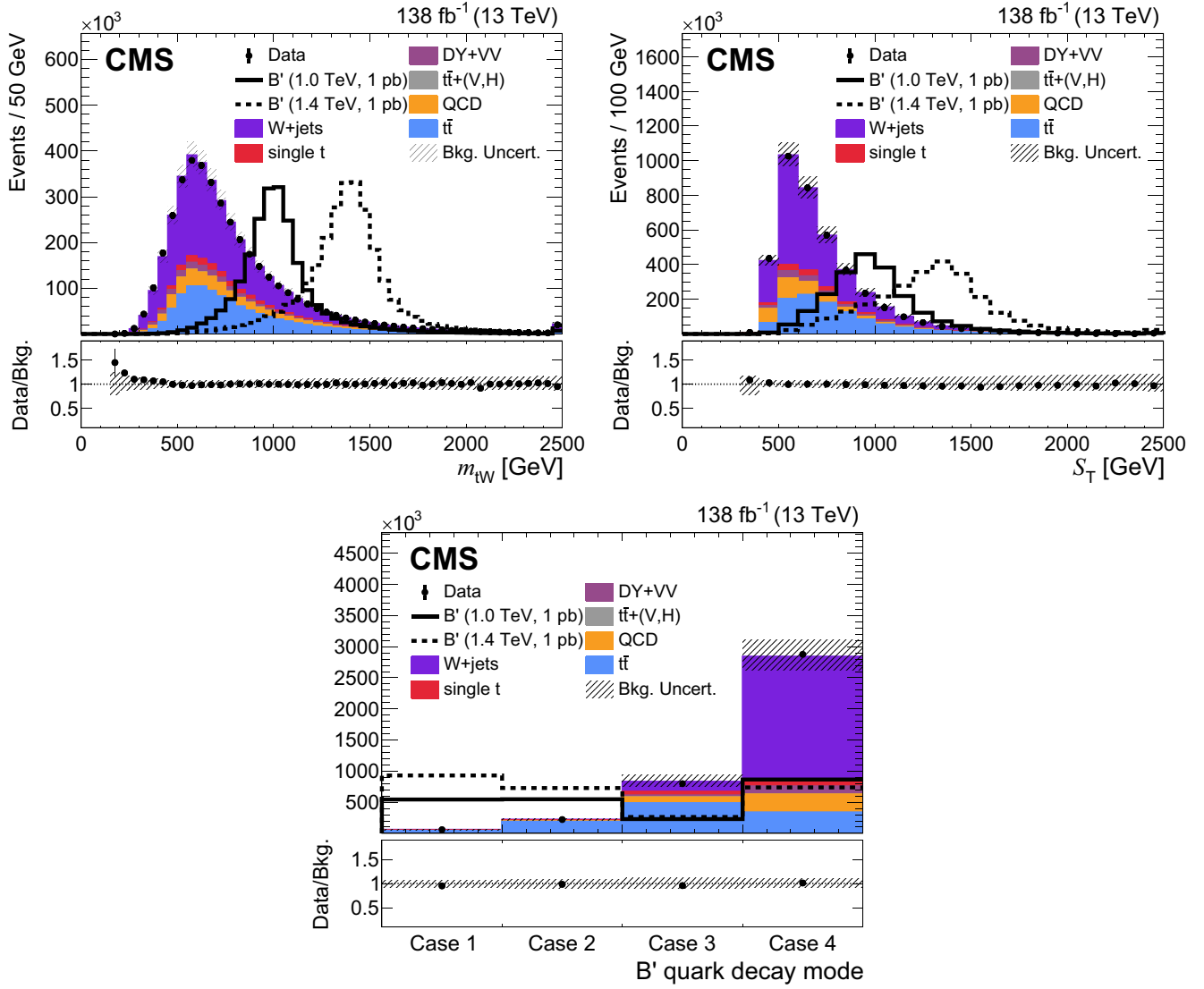


FIG. 2. Distributions of the reconstructed mass of the B' quark candidate, m_{TW} (upper left), the scalar p_T sum (S_T) of all selected small-radius jets, the selected lepton, and p_T^{miss} (upper right), and the reconstruction case (lower) for all selected events. The observed data are shown as black markers. Predicted bqB' quark signals with masses of 1.0 and 1.4 TeV are shown as solid and dashed lines, respectively, normalized to a cross section of 1 pb for visualization. Simulated background estimates are displayed as filled histograms. The lower panels show the ratio of the data to the background prediction. Statistical and systematic uncertainties in the background estimate are indicated by hatched bands.

background and a larger number of forward jets than any background process. Events are categorized into five control regions (CRs) and one signal region (SR) based on the numbers of b -tagged and forward small-radius jets, as illustrated in Fig. 4 (left). The two observables that define the regions are called “control variables.” The signal is concentrated in region D , whereas the CRs, labeled A , B , C , X , and Y , are dominated by background and are used to estimate the background distribution in region D , as described in Sec. VI.

This categorization is optimized for b -associated production. For t -associated production, region D remains the

most signal-enriched region, but signal events are more likely to fall into region C than for b -associated production. This occurs when the b quark from the associated t quark lies in the central detector region. Additional central leptons or b -tagged jets from the associated t quark also reduce the accuracy of the signal reconstruction, broadening the m_{TW} distribution in tqB' signals.

A low signal purity portion of the SR is used to construct validation regions (VRs) to assess the modeling of background processes. For cases 1 and 2, the VR is defined as events in region D with $S_T < 850$ GeV. For cases 3 and 4, the VR corresponds to the full region D because of the

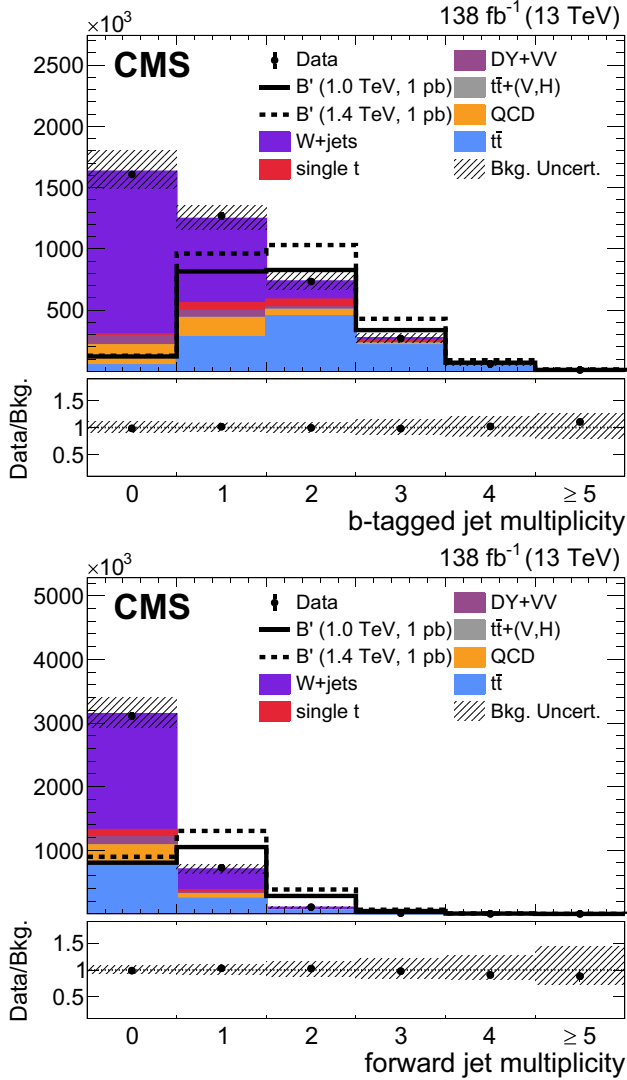


FIG. 3. Distributions of b -tagged jet multiplicity (upper) and forward jet multiplicity (lower) for all selected events. The observed data are shown as black markers. Predicted bqB' quark signals with masses of 1.0 and 1.4 TeV are shown as solid and dashed lines, respectively, normalized to a cross section of 1 pb for visualization. Simulated background estimates are displayed as filled histograms. The lower panels show the ratio of the data to the background prediction. Statistical and systematic uncertainties in the background estimate are indicated by hatched bands.

lower signal purity in these categories. Figure 4 (right) illustrates the definition of the VRs. The final fit to data will include all events in region D .

VI. BACKGROUND ESTIMATION

Relevant SM background processes include $t\bar{t}$, W + jets, QCD multijet, single t quark, Drell-Yan, diboson, $t\bar{t}V$, and $t\bar{t}H$ production. Processes in the $DY + VV$ and $t\bar{t}X$ groups, defined in Sec. III, comprise less than 4% of the total background in each reconstruction case. Therefore, they are

minor background sources and are modeled using simulation. The remaining processes constitute the major background and are predicted using a combination of data-driven shape and yield estimation methods.

The shape of the m_{tW} distribution for the major background processes is modeled using a method called “ABCDnn” [51], based on a neural network. This method was first used in a previous CMS search [52]. The ABCDnn network uses information from the five CRs, defined by two control variables, to learn transformations on one or more observables of interest and, as a result, maps their input distributions in simulation to the corresponding distributions in data. The variables, whose distributions are modified by the transformations, are referred to as transform variables.

This technique is an extension of the traditional “ABCD” method, in which two control variables are used to define four regions of interest, one of which is the SR. In the traditional method, a transfer factor is calculated from the ratio of the data yields in two neighboring CRs and applied to scale the data distribution in the remaining CR into a background prediction for the SR. This method requires the two control variables to be independent for the background processes. As shown in Ref. [53], predictions from the ABCD method can be improved, and the requirements on the independence of the observables weakened, by extending the method to use a larger number of regions.

This method is effective for estimating the overall background yield in the SR. However, a bin-by-bin extension may not accurately predict the distribution of an observable when residual correlations between the control variables vary as a function of that observable. Rather than transforming CR data into an SR background prediction using an analytic formula, the ABCDnn neural network employs neural autoregressive flows to learn a transformation that depends on the region defined by the control variables. This transformation is applied to the simulated values of a transform variable to reproduce a distribution that matches with the data in the CRs, and to extrapolate the distribution of the transform variable into the SR. Potential inadequacies in the extrapolation are covered by the systematic uncertainties described in Sec. VII.

For this search, the transform variables are m_{tW} and S_T . The m_{tW} variable is used as the primary discriminant for signal extraction, because it is highly sensitive to the presence of signal. Including S_T in the transformation allows the transformed S_T values to be used to define the VRs described in Sec. V. For both transform variables (expressed in units of GeV), the natural logarithm is taken to compress the dynamic range of the input distributions.

The transformation principle is expressed as

$$p_{\text{data}}(\vec{x}'|\vec{c}) = \mathcal{T}(\vec{x}'; \vec{x}|\vec{c}) * p_{\text{sim}}(\vec{x}|\vec{c}), \quad (3)$$

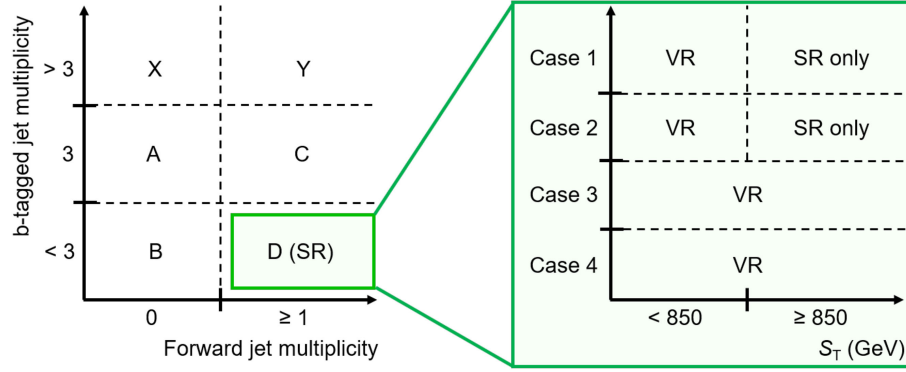


FIG. 4. Diagrams illustrating the definitions and labels of the CRs and SR (left), and the subsets of the SR used for validation (right).

where p_{data} and p_{sim} denote the distributions of the observable in data and simulation, respectively; $\vec{x}$ and $\vec{x}'$ are vectors of (m_{tW}, S_T) with the values coming from the original and transformed variable values, respectively; and $\vec{c}$ is a vector of length 6 that identifies the region [51]. The first through sixth elements of $\vec{c}$ correspond to regions A through Y, with the element corresponding to an event's region being set to 1, and all the other elements being set to 0. The $*$ symbol denotes the convolution operation. During the training, the network learns the transformation function $\mathcal{T}(\vec{x}'; \vec{x} | \vec{c})$ with $\vec{c}$ taking values corresponding to one of the CRs.

The learned transformation $\mathcal{T}(\vec{x}'; \vec{x} | \vec{c})$ is then applied to the simulated major backgrounds in the SR with $\vec{c}$ taking the value of $(0, 0, 0, 1, 0, 0)$, which denotes region D. This application produces transformed values of m_{tW} and S_T in each simulated event, which are accumulated into a transformed background distribution. The validity of this extrapolation is confirmed by comparing the prediction and data in the VR and is found to show bin-by-bin agreement within 20%.

The transformation is learned using neural autoregressive flows, which combine an autoregressive conditioner network with a transformer neural network [54]. The conditioner network encodes information about the transform variables and the region indices corresponding to the CRs and SR. The transformer is implemented as a deep sigmoidal flow [54] that acts on the values of $\ln(m_{tW}/\text{GeV})$ and $\ln(S_T/\text{GeV})$. Two ABCDnn models are trained separately on pairs of reconstruction cases that share the same leptonic decay channel: one for events with leptonic W bosons (cases 1 and 4, referred to as the “lepW” model), and one for events with semileptonic t quarks (cases 2 and 3, referred to as the “lepT” model). With this approach, the signal contamination across all CRs in the two training samples is no larger than 0.3%, assuming the predicted bqB' production cross sections at a relative decay width of $\Gamma/m_{B'} = 5\%$.

During each training epoch, one CR is selected at random, and the network is updated using samples of data and simulated distributions from that region.

For both the lepW and lepT models, the conditioner network uses the rectified linear unit activation function [55], and the transformer network uses a softplus activation function [56]. The numbers of hidden layers and nodes per layer in each network are optimized using a random search procedure. The loss function for training the transformer is based on the maximum mean discrepancy (MMD) [57], defined as

$$\text{MMD} = \frac{1}{m(m-1)} \sum_i \sum_{j \neq i} k(\mathbf{x}_i, \mathbf{x}_j) - \frac{2}{m^2} \sum_i \sum_j k(\mathbf{x}_i, \mathbf{y}_j) + \frac{1}{m(m-1)} \sum_i \sum_{j \neq i} k(\mathbf{y}_i, \mathbf{y}_j), \quad (4)$$

where m is the number of data points, $\mathbf{x}_i$ is a vector that denotes observed (m_{tW}, S_T) in data, $\mathbf{y}_i$ denotes the corresponding vector predicted by ABCDnn, and $k(\mathbf{x}_i, \mathbf{x}_j)$ is the radial basis function (RBF) kernel. The RBF kernel is defined as:

$$k(\mathbf{x}_i, \mathbf{x}_j) = e^{-\|\mathbf{x}_i - \mathbf{x}_j\|^2 / 2s^2}, \quad (5)$$

where $\|\mathbf{x}_i - \mathbf{x}_j\|$ is the distance between $\mathbf{x}_i$ and $\mathbf{x}_j$, defined as $\mathbf{x}_i^T \mathbf{x}_i - 2\mathbf{x}_i^T \mathbf{x}_j + \mathbf{x}_j^T \mathbf{x}_j$, and the scaling constant s controls the tolerance for differences between the two distributions. When the data distribution and the ABCDnn-generated distribution are identical, the MMD evaluates to zero. Larger values of s have a higher tolerance for differences between the two distributions and capture global distribution shifts, while smaller values capture fine-grained differences. Taking the average of the MMD calculations with different s values allows the loss function to capture differences across multiple scales and improves the robustness of the network. In this search, the loss function is defined as the average of three MMD calculations, each using a different s value. The number of s values and their optimal values are determined using a random search.

TABLE II. The ABCDnn architectures and RBF kernel sizes for the lepW and lepT models. The lepW model is trained on events in reconstruction cases 1 and 4, and the lepT model is trained on events in reconstruction cases 2 and 3.

Parameter	lepW Model	lepT Model
Hidden layers (conditioner net)	14	11
Nodes per layer (conditioner net)	5	10
Hidden layers (transformer net)	4	6
Nodes per layer (transformer net)	13	8
RBF kernel s_1	0.02	0.43
RBF kernel s_2	0.39	0.60
RBF kernel s_3	0.68	0.70

Model parameters are optimized by evaluating discrepancies between the data and the predicted m_{tW} distributions in the CRs. Comparisons are performed using the full CR sample, as well as subsets of SR events with $S_T < 850$ GeV. The architectures and the RBF kernel sizes of the lepW and lepT models are summarized in Table II. Figures 5 and 6 show the training performance of the lepW and lepT ABCDnn models, respectively, for m_{tW} . These figures show that the network is able to transform the unweighted distribution of the simulated major background events (labeled “MC”) to model the data in each region. Agreement between the data and the predictions, as functions of m_{tW} in the CRs, is within 20% and differences are treated as systematic uncertainties, as described in Sec. VII. The training performance for the S_T transform variable is evaluated in two bins, $S_T < 850$ GeV and $S_T > 850$ GeV, to validate the VR defined using this threshold. For S_T , the discrepancies between data and prediction in the five CRs are approximately 5% in regions far from the SR (e.g., region X), and approximately 1% in regions close to the SR (e.g., region B).

For each of the cases 1–4, the normalization of the ABCDnn prediction in the SR is defined as

$$N_{\text{SR}}^{\text{bkg}} = N_B^{\text{data-minor}} \frac{N_{\text{SR}}^{\text{sim}}}{N_B^{\text{sim}}}, \quad (6)$$

where $N_B^{\text{data-minor}}$ is the number of events in region B observed in data after subtraction of the minor background contributions estimated from simulation, and N_B^{sim} is the number of events in region B in the major background simulation. Region B is used for this normalization because it is adjacent to the SR and is well populated. The normalization factor is determined separately for each reconstruction case. For VRs defined with $S_T < 850$ GeV, the same S_T requirement is applied to data and simulation in region B when applying Eq. (6).

Figure 7 shows the m_{tW} distributions in the VR for each reconstruction case. The background estimate includes simulated minor background processes and the ABCDnn

prediction for the major background processes. The PARTICLENET tag information from the major background simulation is used to separate the ABCDnn prediction into the four reconstruction cases, as described in Sec. V. Overall, the agreement between the data and the background prediction demonstrates that the ABCDnn method successfully models the major backgrounds, although residual corrections are required. These corrections are derived empirically and applied to improve the prediction.

The bin-by-bin discrepancies between observed data and prediction in the VRs are evaluated in the two-dimensional (2D) distribution of m_{tW} and S_T to derive a closure correction, where both variables are taken from the ABCDnn prediction. Minor backgrounds modeled from simulation are subtracted from the data before these discrepancies are computed. The S_T axis is divided into variable-width bins to ensure that all bins contain nonzero ABCDnn predictions and that a bin boundary is placed at 850 GeV. For cases 1 and 2, bins in the parameter space exclusive to the SR with $S_T > 850$ GeV and $m_{tW} > 700$ GeV, where the signal contribution is non-negligible, are assigned values based on the discrepancies observed in the corresponding bins of CR B . The ABCDnn prediction is corrected by applying the measured discrepancy to each bin. The corrected 2D distributions are then projected into one-dimensional (1D) distributions of m_{tW} , and smoothed using the LOWESS technique [58,59]. This smoothing is applied in all regions where the correction is derived from the VR rather than from CR B , to reduce the dependence of the prediction on statistical fluctuations in the data. After this correction, agreement between data and prediction in the four SR distributions of m_{tW} is consistent with unity within uncertainties. The uncertainty associated with the closure correction procedure is described in Sec. VII. The ABCDnn method provides comparable or better agreement between the distributions of data and prediction, while greatly simplifying the estimation of the uncertainty associated with the dominant backgrounds by considering only five (four) sources for cases 1 and 2 (cases 3 and 4), as summarized in Sec. VII.

VII. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties affect both the normalization and the shape of the predicted background and signal distributions, and are summarized in Table III. The impact of shape-based uncertainties in processes modeled with simulation is evaluated by varying the corresponding inputs within their uncertainties. Systematic uncertainties are correlated across the data-taking periods and lepton flavors unless specified otherwise.

- (i) The uncertainty in the integrated luminosity for the combined 2016–2018 data-taking period is 0.73% [31].

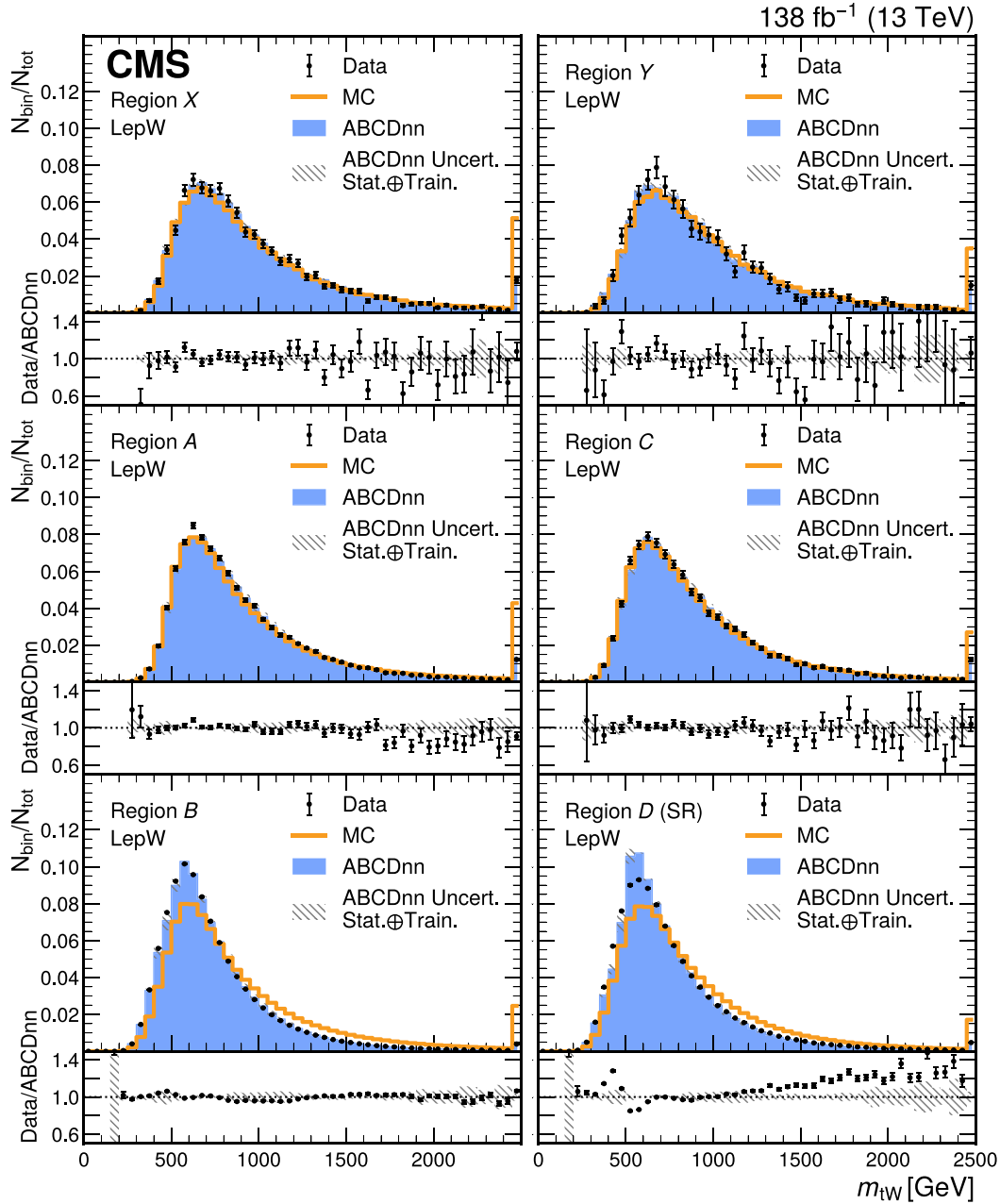


FIG. 5. Distributions of m_{lW} in the SR and CRs for the lepW ABCDnn model, normalized to unity. Observed data are shown as black markers with statistical uncertainties. Major background distributions from simulation are shown as orange solid lines with statistical uncertainties and are labeled “MC.” The ABCDnn predictions are shown as blue filled histograms. The lower panels show the ratio of the data to the ABCDnn prediction. Statistical and training uncertainties in the ABCDnn predictions are indicated by hatched bands, though they are too small to be visible in the upper panels.

- (ii) The uncertainty in the pileup weighting for simulation is evaluated by varying the total inelastic cross section $\sigma_{\text{inel}} = 69.2 \text{ mb}$ by $\pm 4.6\%$ [60].
- (iii) Single electron and single muon trigger efficiency corrections are applied to simulation to account for differences between data and simulation. The corresponding uncertainties are applied independently

for each lepton flavor and data-taking period as functions of p_T and η .

- (iv) An L1 trigger timing correction is applied in the 2016 and 2017 data-taking periods to account for a gradual shift in the ECAL L1 trigger timing in the region $|\eta| > 2.0$. The uncertainty in this correction is applied as a function of p_T and η .

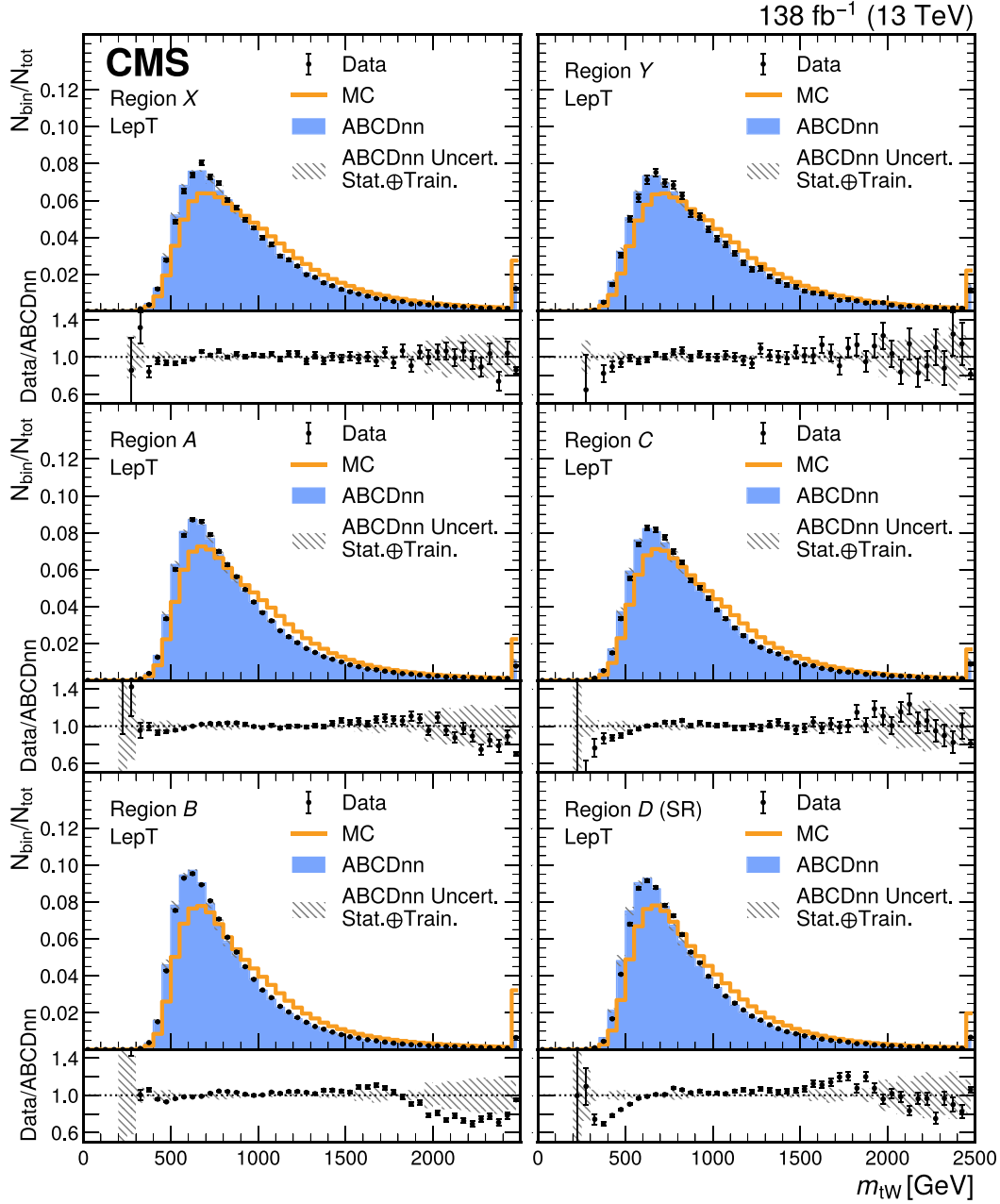


FIG. 6. Distributions of m_{W} in the SR and CRs for the lepT ABCDnn model, normalized to unity. Observed data are shown as black markers with statistical uncertainties. Major background distributions from simulation are shown as orange solid lines with statistical uncertainties and are labeled “MC.” The ABCDnn predictions are shown as blue filled histograms. The lower panels show the ratio of the data to the ABCDnn prediction. Statistical and training uncertainties in the ABCDnn predictions are indicated by hatched bands, though they are too small to be visible in the upper panels. These figures show that the network is able to transform the unweighted distribution of the simulated major background events (labeled “MC”) to model the data in each region.

- (v) Lepton scale factors are applied to correct for differences in the reconstruction, identification, and isolation efficiencies between data and simulation. The associated uncertainties are applied independently for each lepton flavor and correction component as functions of p_T and η .
- (vi) Jet energy scale and resolution uncertainties affect the momenta of both small- and large-radius jets.

These variations are propagated to p_T^{miss} and all jet-dependent observables. The resulting varied histograms are smoothed using the LOWESS algorithm. The uncertainties are treated independently for each data-taking period.

- (vii) The uncertainty in the pileup jet identification scale factor is applied as a function of p_T and η .

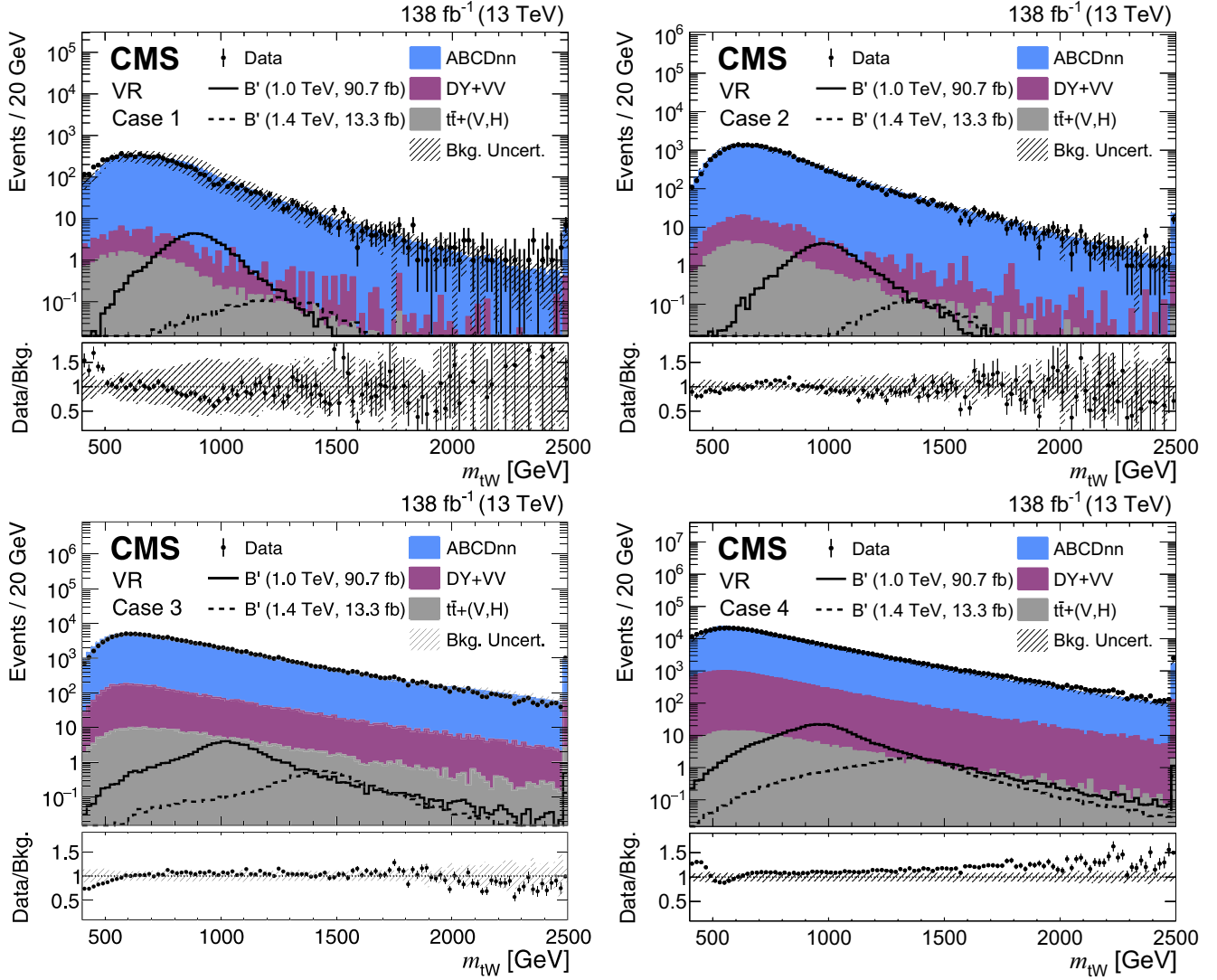


FIG. 7. Distributions of m_{tW} for VR events in case 1 (upper left) through case 4 (lower right). Observed data are shown as black markers. Predicted bqB' quark signals with masses of 1.0 and 1.4 TeV are shown as solid and dashed lines, respectively, normalized to the predicted cross section for singlet bqB' production with $\Gamma/m_{B'} = 5\%$. Background estimates are displayed as filled histograms, with the ABCDnn prediction shown prior to application of the closure correction. The lower panels show the ratio of the data to the background prediction. Statistical and systematic uncertainties in the background estimate are indicated by hatched bands.

- (viii) The DEEPIET b -tagging corrections are applied to simulation to match the tagging efficiencies observed in data. The uncertainties are separated into four components: b/c jet tagging is treated separately from light-quark/gluon misidentification [48]; and for each of these there is one component correlated across data-taking periods and one that is uncorrelated.
- (ix) Scale uncertainties are used to account for missing higher-order corrections. The renormalization and factorization scales (μ_R and μ_F) are varied independently up and down by factors of two for each simulated process group defined in Sec. III. The resulting variations are evaluated on a bin-by-bin

basis in m_{tW} . For the signal, the variations are normalized to preserve the total yield, such that the uncertainty affects only the shape.

- (x) The PDF uncertainties are correlated across all samples. The NNPDF 3.1 Hessian uncertainties are evaluated bin-by-bin in m_{tW} using 100 eigenvector variations and combined in quadrature. For the signal, the normalization effect is removed, such that only shape variations are considered.
- (xi) The PARTICLENET scale factors are applied to correct the efficiencies for tagging large-radius jets originating from generator-level t quarks or W bosons. The uncertainties are applied as functions of the jet p_T . The t tagging efficiency affects only events in

TABLE III. A summary of the systematic uncertainties impacting the search. Unless otherwise specified, all uncertainties are implemented as rate and shape variations using alternate template histograms. The numerical values represent the prefit rate impact and are given as ranges across the four reconstruction cases for either the 1.4 TeV signal or the ABCDnn background prediction, unless otherwise specified. The functional form in the third column indicates the quantities on which the uncertainty magnitude depends, where s.d. denotes one standard deviation. The final column indicates the affected predictions: simulated samples (including signal), “minor” refers to simulated minor background processes, and “ABCDnn” refers to the major background predicted using the ABCDnn method.

Uncertainty	Value	Formula	Affected samples
Integrated luminosity	0.73%	rate only	Simulation
Pileup	<1%	$\sigma_{\text{inel}} \pm 4.6\%$	Simulation
e trigger	<1%	$\pm \text{s.d.} (p_T, \eta)$	Simulation
μ trigger	<1%	$\pm \text{s.d.} (p_T, \eta)$	Simulation
L1 trigger timing	1%	$\pm \text{s.d.} (p_T, \eta)$	Simulation
Lepton scale factors	<1%	$\pm \text{s.d.} (p_T, \eta)$	Simulation
Jet energy scale	$\leq 2\%$	$\pm \text{s.d.} (p_T, \eta)$	Simulation
Jet energy res.	$\leq 1\%$	$\pm \text{s.d.} (\eta)$	Simulation
Pileup jet ident.	1%	$\pm \text{s.d.} (p_T, \eta)$	Simulation
b tag: b/c	$\leq 3\%$	$\pm \text{s.d.} (p_T)$	Simulation
b tag: light	$\leq 1\%$	$\pm \text{s.d.} (p_T)$	Simulation
Renormalization scale	4–11% (minor)	$\mu_R \times 0.5, \mu_R \times 2$	Simulation
Factorization scale	3–5% (minor)	$\mu_F \times 0.5, \mu_F \times 2$	Simulation
PDF	1–6% (minor)	$\pm \text{RMS (Hessian)}$	Simulation
PARTICLENET: t tag	9% (signal)	$\pm \text{s.d.} (p_T)$	all
PARTICLENET: W tag	14% (signal)	$\pm \text{s.d.} (p_T)$	all
Training accuracy	1–25%	$\pm \%(CR_{\text{pred}} - CR_{\text{data}})$	ABCDnn
VR closure	1–3%	$\text{corr.} \times 0, \text{corr.} \times 2$	ABCDnn
ABCDnn smoothing	1–2%	$\pm \Delta(2D - 1D)$	ABCDnn
ABCDnn normalization	2–8%	rate only	ABCDnn

case 1, and the W tagging efficiency affects only events in case 2. These uncertainties apply to both simulation and ABCDnn predictions.

- (xii) The ABCDnn training accuracy uncertainty accounts for differences between data (after subtraction of minor background predictions) and the ABCDnn prediction in the CRs. It is derived from the average percentage difference between data and the ABCDnn prediction in the CRs A , B , and C , evaluated in each bin of m_{tW} . Two alternate templates are formed by varying the prediction up and down by this amount. This uncertainty is evaluated separately for each reconstruction case as a function of m_{tW} and S_T . In Table III, this uncertainty is defined as the relative difference $(CR_{\text{pred}} - CR_{\text{data}})/CR_{\text{pred}}$, expressed in percent.
- (xiii) The VR closure uncertainty accounts for differences arising from the propagation of the ABCDnn transfer function, determined during training in the CRs, to the SR. It is evaluated by forming alternate templates in which the closure correction is either removed or doubled in each bin of m_{tW} and S_T . In Table III, this uncertainty is denoted as $\text{corr.} \times 0, \text{corr.} \times 2$.
- (xiv) The ABCDnn smoothing uncertainty is evaluated by comparing the corrected 1D m_{tW} distributions to

those obtained from smoothing the 2D (m_{tW}, S_T) distributions with a kernel method and projecting onto m_{tW} . Alternate templates are formed by varying the background prediction by this difference. In Table III, this uncertainty is denoted as $\Delta(2D - 1D)$.

- (xv) The ABCDnn normalization uncertainty accounts for the limited event counts used to compute the normalization factor in Eq. (6), as well as the differences between the predicted and observed event yields in the VRs. It is applied as an independent normalization uncertainty in each reconstruction case.

The uncertainties that have the largest impact on signal sensitivity are those associated with the PARTICLENET tagging scale factors. The ABCDnn background prediction uncertainty in cases 1 and 2 also contributes significantly to the overall uncertainty.

VIII. RESULTS

The strength of the B' quark signal hypothesis is tested using a binned maximum likelihood fit to the m_{tW} distribution in region D , with one distribution per reconstruction case. Cases 3 and 4 are fitted simultaneously with cases 1 and 2 to constrain nuisance parameters related to simulated processes. The histograms are binned in 10 GeV intervals, and bins at high m_{tW} values are merged

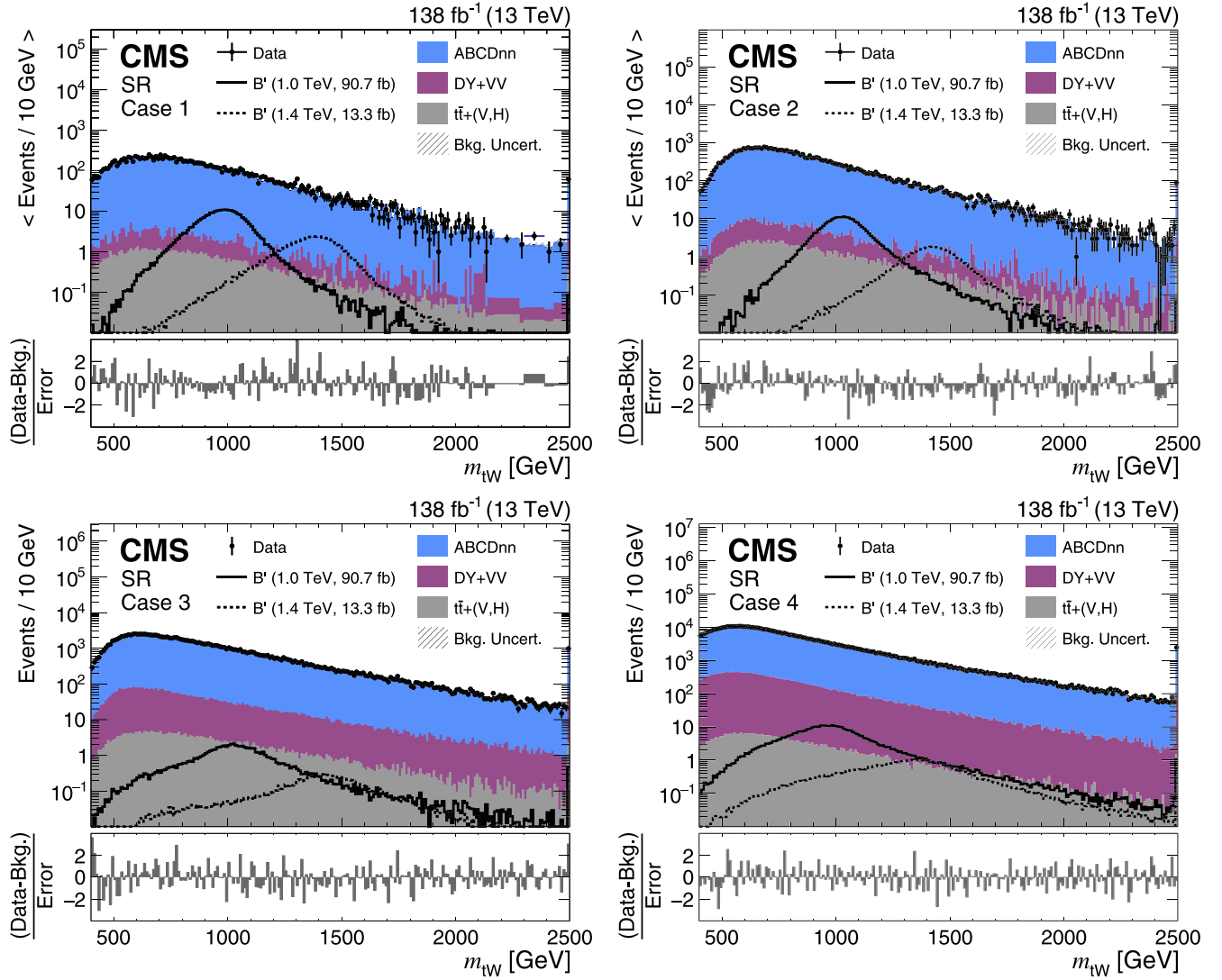


FIG. 8. Distributions of m_{tW} for events in the SR in case 1 (upper left) through case 4 (lower right). The observed data are shown as black markers. Predicted bqB' quark signals with masses of 1.0 and 1.4 TeV are shown as the solid and dashed lines, respectively, normalized to the predicted cross section for singlet bqB' production with $\Gamma/m_{B'} = 5\%$. The best-fit background prediction from a background-only fit to data is shown as the filled histograms. The lower panels show the difference between the data and the background prediction, divided by the total uncertainty in the background estimate.

to ensure that the total background in each bin has a statistical uncertainty below 20%. Signal distributions for B' quark masses of 0.9 and 1.1 TeV are created by fitting a double-sided Crystal Ball function, defined in Ref. [61], to the simulated signal m_{tW} distributions in each case. The function parameters are interpolated between neighboring simulated mass points, and the resulting formulas for the 0.9 TeV and 1.1 TeV B' quark masses are used to construct the m_{tW} histograms. The same procedure is used to model the systematic uncertainty variations. The CMS statistical analysis tool COMBINE [62], based on the ROOFIT [63] and ROOSTATS [64] frameworks, is used to perform the fit. Uncertainties due to limited event counts in simulation are included as Poisson-distributed nuisance parameters using the Barlow-Beeston method [65,66]. Systematic

uncertainties listed in Table III are included as lognormal-distributed nuisance parameters if they affect only the normalization of the background or signal predictions. Systematic uncertainties that affect the shapes of template distributions are implemented through template morphing with Gaussian-distributed nuisance parameters [66]. The fit model is validated using fits to data in the VRs and using pseudodata generated from the background estimate in the SR, with and without injected B' signal contributions. No bias in fitting injected signal is observed for either the bqB' or tqB' signals over a wide range of signal mass.

Figure 8 shows the reconstructed m_{tW} distributions in the SR, separated by reconstruction case, after the background-only fit to data. No significant excess of data over the SM background estimate is observed in any reconstruction

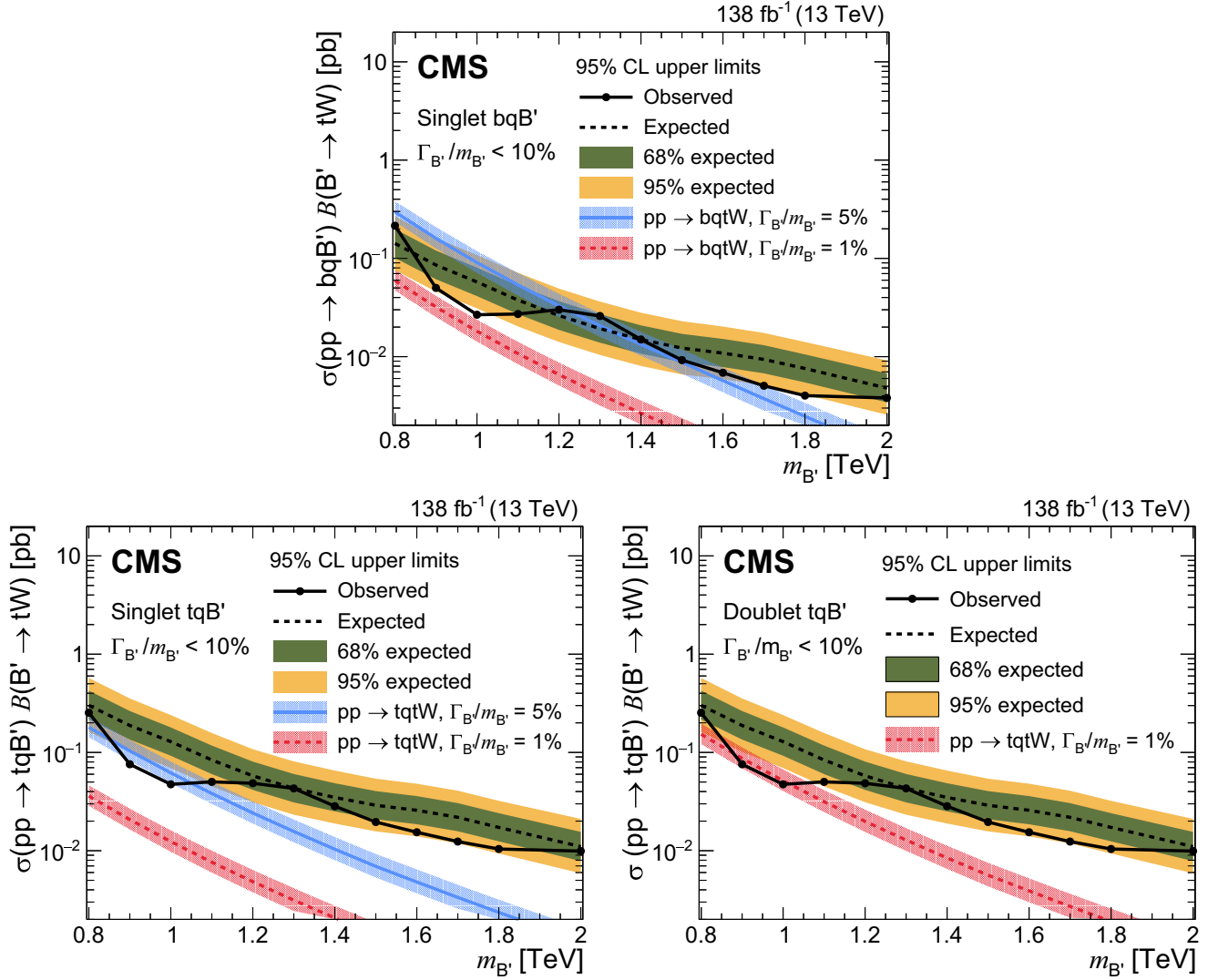


FIG. 9. Observed (solid black lines) and expected (dashed lines) 95% CL upper limits on the product of the production cross section and branching fraction $B(tW)$ for singlet bqB' production (upper), singlet tqB' production (lower left), and up-type doublet tqB' production (lower right), as functions of $m_{B'}$. Predicted cross sections for various B' quark relative widths are shown as dashed red and solid blue lines. The bands around the predicted cross sections represent the associated energy scale and PDF uncertainties.

case, and the background-only fit yields a p -value of 0.15 based on a saturated χ^2 test described in Ref. [62].

Upper limits at 95% confidence level (CL) on the product of the production cross section and the branching fraction for bqB' or tqB' production with $B' \rightarrow tW$ decay are computed using a profile likelihood test statistic in the asymptotic approximation [67], with the CLs method [68,69], and shown in Fig. 9. For production in association with a b quark, singlet B' quarks with a 5% relative decay width are excluded for masses below 1.23 TeV (1.35 TeV expected). The deficit observed for the $m_{B'} = 1.0$ TeV hypothesis has a local (global) significance of 2.5 (1.4) s.d. This deficit arises from the overpredictions visible in the case 1 and case 2 m_{tW} distributions of Fig. 8 in the range of approximately 900–1200 GeV. The overprediction in this

range of m_{tW} is statistically significant in case 2. For production in association with a t quark, the observed limits range from 230 fb at $m_{B'} = 0.8$ TeV to 10 fb at $m_{B'} = 2.0$ TeV. The overpredictions noted for cases 1 and 2 near $m_{tW} = 1.0$ TeV lead to the exclusion of the $m_{B'} = 0.9$ and 1.0 TeV hypotheses for t -associated production. These exclusions apply to a singlet B' quark with a 5% relative decay width and to a doublet B' quark with a 1% relative decay width. In this production mode, the deficit at 1.0 TeV has a local (global) significance of 3.6 (2.6) s.d. because of the wider m_{tW} resolution for tqB' signals. This search provides the most stringent sensitivity to date to production of single B' quarks with narrow decay widths. With the addition of data collected in 2017–2018 and improved techniques such as the PARTICLENET jet

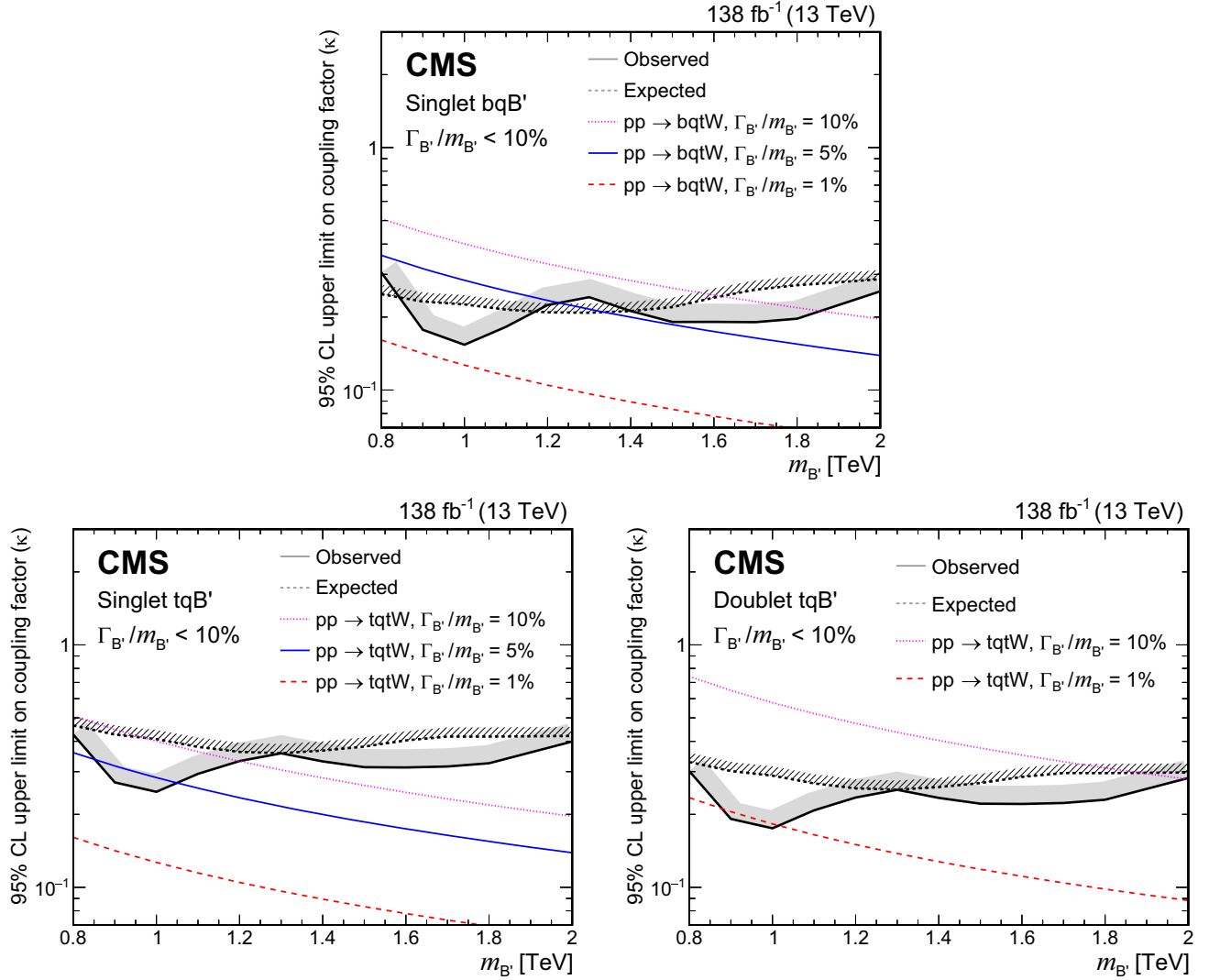


FIG. 10. Observed (solid black lines) and expected (dashed lines) 95% CL upper limits on the coupling factor κ for singlet bqB' production (upper), singlet tqB' production (lower left), and up-type doublet tqB' production (lower right), as functions of $m_{B'}$. The hatched and shaded regions indicate that the limits are upper bounds on the coupling factor. Predicted coupling values for various B' quark relative widths are shown as dashed red, solid blue, and dotted magenta lines.

identification algorithm, this search is able to probe smaller cross sections and coupling factor values compared to earlier CMS searches.

Figure 10 presents limits on the B' quark coupling factor κ , defined in Sec. III. The predicted couplings as a function of the B' quark mass can be extended to a 10% relative decay width. At this width, the natural width of the B' quark becomes comparable to the resolution of the m_{tW} distribution, and the narrow-width signal simulation used in this search may no longer provide an accurate description of the signal. Therefore, the coupling limits are only interpreted in the region where the observed upper limits of the coupling factor lie below the values corresponding to $\Gamma/m_{B'} = 10\%$. For singlet scenario of bqB' production, the upper limits on the coupling factor range from 0.15 to 0.31. The observed coupling factor limits become consistent with a B' quark

with a 10% relative decay width for masses above 1.8 TeV. For tqB' production, the upper limits on the coupling factor range from 0.25 to 0.43 in the singlet scenario and from 0.18 to 0.30 in the doublet scenario. In the singlet case, the observed coupling limits become consistent with a B' quark with a 10% relative decay width for masses above 1.2 TeV.

IX. SUMMARY

A search has been presented for the production of a single vectorlike B' quark that decays to a t quark and a W boson via the electroweak interaction. Proton-proton collision data collected with the CMS detector at a center-of-mass energy of 13 TeV are used, corresponding to an integrated luminosity of 138 fb⁻¹. Events are selected with one electron or muon, missing transverse momentum, and

at least one large-radius jet well separated from the charged lepton. A B' quark candidate is reconstructed and categorized according to the PARTICLENET identification of the large-radius jet. Minor background processes are modeled using simulation, while the major background contribution in the signal region is modeled from data in five control regions using a neural autoregressive flow network, referred to as ABCDnn. For bqB' production, singlet B' quarks with a 5% relative decay width and masses between 0.8 and 1.23 TeV are excluded at 95% confidence level (CL). Limits are also set on the product of the production cross section and the $B' \rightarrow tW$ branching fraction for tqB' production, excluding the 0.9 and 1.0 TeV mass hypotheses at 95% CL for both the 5%-width singlet and 1%-width doublet scenarios. For singlet bqB' production, coupling factor values above 0.31 are excluded for B' quark masses in the range 0.8–1.8 TeV. For tqB' production, coupling factor values above 0.43 are excluded at 95% CL for singlet B' quark masses in the range 0.8–1.2 TeV, and values above 0.30 are excluded at 95% CL for doublet B' quark masses in the range 0.8–2.0 TeV. These limits are the most stringent to date for the production cross section and coupling factors of narrow-width B' quarks.

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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 [70].

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K. Tauqeer,¹ A. Gevorgyan², A. Hayrapetyan,² V. Makarenko², A. Tumasyan^{2,a}, W. Adam³, L. Benato³, T. Bergauer³, M. Dragicevic³, S. Gundacker³, A. K. Guven³, P. S. Hussain³, M. Jeitler^{3,b}, N. Krammer³, A. Li³, D. Liko³, M. Matthewman,³ J. Schieck^{3,b}, R. Schöffbeck^{3,b}, M. Shoostari³, M. Sonawane³, N. Van Den Bossche³, W. Waltenberger³, C. E. Wulz^{3,b}, T. Janssen⁴, D. Ocampo Henao⁴, T. Van Laer⁴, P. Van Mechelen⁴, D. Ahmadi⁵, J. Bierkens⁵, N. Breugelmans,⁵ S. Dansana⁵, A. De Moor⁵, M. Delcourt⁵, S. Duponcheel⁵, C. Gupta,⁵ F. Heyen,⁵ Y. Hong⁵, K. Kang⁵, P. Kashko⁵, S. Lowette⁵, I. Makarenko⁵, S. Nandakumar⁵, S. Tavernier⁵, M. Tytgat^{5,c}, G. P. Van Onsem⁵, S. Van Putte⁵, T. Wybouw⁵, A. Beshr,⁶ B. Bilin⁶, F. Caviglia Roman,⁶ B. Clerbaux⁶, A. K. Das,⁶ I. De Bruyn⁶, G. De Lentdecker⁶, E. Ducarme⁶, H. Evard⁶, L. Favart⁶, I. Kalaitzidou⁶, A. Khalilzadeh,⁶ A. Malara⁶, M. A. Shahzad,⁶ L. Thomas⁶, M. Vanden Bemden⁶, C. Vander Velde⁶, P. Vanlaer⁶, C. Yuan⁶, F. Zhang⁶, A. Cauwels,⁷ M. De Coen⁷, D. Dobur⁷, C. Giordano⁷, G. Gokbulut⁷, K. Kaspar⁷, D. Kavtaradze,⁷ D. Marckx⁷, A. Mehta⁷, K. Skovpen⁷, A. M. Tomaru,⁷ J. van der Linden⁷, J. Vandenbroeck⁷, H. Aarup Petersen,⁸ A. Benecke⁸, A. Bethani⁸, G. Bruno⁸, A. Cappati⁸, J. De Favereau De Jeneret⁸, C. Delaere⁸, F. Gameiro Casalinho,⁸ A. Giammanco⁸, A. O. Guzel⁸, M. Hussain,⁸ Z. Lawrence,⁸ V. Lemaître,⁸ J. Lidrych⁸, P. Malek⁸, S. Turkcapar⁸, G. Alves⁹, M. Barroso Ferreira Filho⁹, E. Coelho⁹, M. V. Gonçalves Sales⁹, C. Hensel⁹, D. Matos Figueiredo,⁹ T. Menezes De Oliveira⁹, C. Mora Herrera⁹, P. Rebello Teles⁹, M. Soeiro⁹, E. J. Tonelli Manganote^{9,d}, A. Vilela Pereira⁹, W. L. Aldá Júnior¹⁰, H. Brandao Malbouisson¹⁰, W. Carvalho¹⁰, J. Chinellato^{10,e}, G. Correia Silva¹⁰, M. Costa Reis¹⁰, E. M. Da Costa¹⁰, D. Da Silva Dalto¹⁰, G. G. Da Silveira^{10,f}, D. De Jesus Damiao¹⁰, S. Fonseca De Souza¹⁰, R. Gomes De Souza¹⁰, S. Jesus¹⁰, T. Laux Kuhn^{10,f}, K. Maslova Gioseffi Defante¹⁰, K. Mota Amarilo¹⁰, L. Mundim¹⁰, H. Nogima¹⁰, J. P. Pinheiro¹⁰, A. Santoro¹⁰, A. Sznajder¹⁰, M. Thiel¹⁰, F. Torres Da Silva De Araujo^{10,g}, D. Torres Machado¹⁰, C. A. Bernardes¹¹, L. Calligaris¹¹, J. Carvalho Leite¹¹, F. Damas¹¹, E. De Moraes Gregores¹¹, B. Lopes Da Costa¹¹, I. Maietto Silverio¹¹, P. G. Mercadante¹¹, S. F. Novaes¹¹, S. Padula¹¹, M. Pereira Coelho¹¹, V. Scheurer,¹¹ T. Tomei¹¹, A. Aleksandrov¹², G. Antchev¹², P. Danev,¹² R. Hadjiiska¹², P. Iaydjiev¹², M. Shopova¹², G. Sultanov¹², A. Dimitrov¹³, L. Litov¹³, B. Pavlov¹³, P. Petkov¹³, A. Petrov¹³, D. Abbaneo¹⁴, C. Amendola¹⁴, R. Ardino¹⁴, E. Auffray¹⁴, J. Baechler,¹⁴ D. Barney¹⁴, J. Bendavid¹⁴, I. Bestintzanos,¹⁴ M. Bianco¹⁴, A. Bocci¹⁴, L. Borgonovi¹⁴, C. Botta¹⁴, A. Bragagnolo¹⁴, C. E. Brown¹⁴, C. Caillol¹⁴, G. Cerminara¹⁴, P. Connor¹⁴, K. Cormier¹⁴, D. D'Enterria¹⁴, A. Dabrowski¹⁴, P. Das¹⁴, A. David Tinoco Mendes¹⁴, A. De Roeck¹⁴, M. M. Defranchis¹⁴, M. Deile¹⁴, M. Dobson¹⁴

P. J. Fernández Manteca¹⁴, E. Fialova¹⁴, B. A. Fontana Santos Alves¹⁴, E. Fontanesi¹⁴, W. Funk¹⁴, A. Gaddi¹⁴, S. Giani¹⁴, D. Gigi¹⁴, K. Gill¹⁴, F. Glege¹⁴, M. Glowacki¹⁴, A. Gruber¹⁴, J. Hegeman¹⁴, R. Hofsaess¹⁴, B. Huber¹⁴, T. James¹⁴, P. Janot¹⁴, L. Jappe¹⁴, O. Kaluzinska¹⁴, O. Karacheban^{14,h}, G. Karathanasis¹⁴, S. Laurila¹⁴, P. Lecoq¹⁴, E. Leutgeb¹⁴, J. León Holgado¹⁴, C. Lourenco¹⁴, A. m. Lyon¹⁴, M. Magherini¹⁴, L. Malgeri¹⁴, E. Manca¹⁴, M. Mannelli¹⁴, F. Meijers¹⁴, J. A. Merlin¹⁴, S. Mersi¹⁴, E. Meschi¹⁴, M. Migliorini¹⁴, F. Monti¹⁴, F. Moortgat¹⁴, M. C. Muehltnikel¹⁴, M. Mulders¹⁴, M. Musich¹⁴, I. Neutelings¹⁴, S. Orfanelli¹⁴, F. Pantaleo¹⁴, M. Pari¹⁴, F. Pereira Carneiro¹⁴, G. Petrucciani¹⁴, A. Pfeiffer¹⁴, M. Pierini¹⁴, M. Pitt¹⁴, H. Qu¹⁴, A. Reimers¹⁴, B. Ribeiro Lopes¹⁴, F. Riti¹⁴, P. Rosado¹⁴, M. Rovere¹⁴, H. Sakulin¹⁴, R. Salvatico¹⁴, S. Scarfi¹⁴, S. F. Schaefer¹⁴, M. Selvaggi¹⁴, P. Silva¹⁴, P. Sphicas^{14,i}, A. G. Stahl Leiton¹⁴, A. Steen¹⁴, S. Summers¹⁴, G. Terragni¹⁴, D. Treille¹⁴, P. Tropea¹⁴, E. Vernazza¹⁴, M. Vojinovic¹⁴, J. Wanczyk^{14,j}, S. Wuchterl¹⁴, M. Zarucki¹⁴, P. Zehetner¹⁴, P. Zejdl¹⁴, G. Zevi Della Porta¹⁴, S. Keshri¹⁵, D. N. Laroze Navarrete¹⁵, M. Meena¹⁵, S. Thakur¹⁵, W. Brooks¹⁶, T. Cheng¹⁷, L. Wang¹⁷, L. Yuan¹⁷, J. Gu¹⁸, Z. Hu¹⁸, Z. Liang¹⁸, J. Liu¹⁸, X. Wang¹⁸, Y. Wang¹⁸, H. Yang¹⁸, S. Zhang¹⁸, Y. Zhao¹⁸, N. Bi^{19,k}, G. M. Chen^{19,k}, H. S. Chen^{19,k}, M. Chen^{19,k}, Y. Chen¹⁹, B. Hou^{19,k}, Q. Hou¹⁹, F. Iemmi¹⁹, C. H. Jiang¹⁹, P. z. Lai¹⁹, H. Liao¹⁹, G. Liu¹⁹, Z. Liu^{19,l}, S. Song^{19,k}, J. Tao¹⁹, C. Wang^{19,k}, J. Wang¹⁹, A. Zada^{19,k}, H. Zhang¹⁹, J. Zhao¹⁹, Y. Ban²⁰, A. Carvalho Antunes De Oliveira²⁰, S. Deng²⁰, X. Geng²⁰, B. Guo²⁰, Q. Guo²⁰, Z. He²⁰, C. Jiang²⁰, A. Levin²⁰, C. Li²⁰, L. Li²⁰, Q. Li²⁰, Y. Mao²⁰, S. Qian²⁰, S. J. Qian²⁰, X. Qin²⁰, C. Quaranta²⁰, X. Sun²⁰, D. Wang²⁰, J. Wang²⁰, T. Yang²⁰, M. Zhang²⁰, M. Zhang²⁰, Y. Zhao²⁰, C. Zhou²⁰, X. Hua²¹, S. Yang²¹, Z. You²², N. Lu²³, G. Bauer^{24,m,n}, L. Chen²⁴, Z. Cui^{24,n}, B. Li^{24,o}, H. Wang²⁴, K. Yi^{24,p}, J. Zhang²⁴, F. Zhu²⁴, C. Li²⁵, Y. Li²⁶, Z. Wang²⁶, Y. Zhou^{26,q}, Z. Lin²⁷, C. Lu²⁷, M. Xiao^{27,r}, C. Avila²⁸, A. Cabrera²⁸, C. Florez²⁸, J. A. Reyes Vega²⁸, C. Rendón²⁹, M. Rodriguez²⁹, A. A. Ruales Barbosa²⁹, J. D. Ruiz Alvarez²⁹, N. Godinovic³⁰, D. Lelas³⁰, I. Puljak³⁰, A. Sculac³⁰, M. Kovac³¹, A. Petkovic³¹, T. Sculac³¹, P. Bargassa³², V. Brigljevic³², D. Ferencek³², K. Jakovcic³², A. Starodumov³², T. Susa³², A. Attikis³³, S. Konstantinou³³, C. Leonidou³³, L. Paizanos³³, F. Ptochos³³, P. A. Razis³³, H. Saka³³, A. Stepennov³³, M. Finger³⁴, M. Finger Jr.³⁴, A. Kveton³⁴, E. Acurio³⁵, E. Carrera Jarrin³⁶, A. A. Abdelalim^{37,s,t}, S. Elgammal^{37,u}, A. Ellithi Kamel^{37,v}, A. Hussein³⁸, H. Mohammed³⁸, Y. Mohammed³⁸, M. A. A. Muhammad³⁸, K. Jaffel³⁹, M. Kadastik³⁹, T. Lange³⁹, C. Nielsen³⁹, J. Pata³⁹, M. Raidal³⁹, N. Seeba³⁹, L. Tani³⁹, E. Brücken⁴⁰, A. Milieva⁴⁰, K. Osterberg⁴⁰, M. Voutilainen⁴⁰, F. I. Garcia Fuentes⁴¹, T. Hilden⁴¹, P. Inkaew⁴¹, K. T. S. Kallonen⁴¹, R. Kumar Verma⁴¹, T. Lampén⁴¹, K. Lassila-Perini⁴¹, B. Lehtela⁴¹, S. Lehti⁴¹, T. Lindén⁴¹, N. R. Mancilla Xinto⁴¹, M. Myllymäki⁴¹, M. m. Rantanen⁴¹, S. Saariokari⁴¹, N. T. Toikka⁴¹, J. Tuominiemi⁴¹, E. Veikkola⁴¹, N. Bin Norjoharuddeen⁴², H. Kirschenmann⁴², P. R. Luukka⁴², H. Petrow⁴², M. Besancon⁴³, F. Couderc⁴³, M. Dejjardin⁴³, D. Denegri⁴³, P. Devoue⁴³, J. L. Faure⁴³, F. Ferri⁴³, P. Gaigne⁴³, S. Ganjour⁴³, P. Gras⁴³, F. Guilloux⁴³, G. Hamel de Monchenault⁴³, M. Kumar⁴³, V. Lohezic⁴³, Y. Maidannyk⁴³, J. Malcles⁴³, F. Orlandi⁴³, L. Portales⁴³, S. Ronchi⁴³, M. Ö. Sahin⁴³, P. Simkina⁴³, M. Titov⁴³, M. Tornago⁴³, R. Amella Ranz⁴⁴, F. Beaudette⁴⁴, K. Biriukov⁴⁴, G. Boldrini⁴⁴, P. Busson⁴⁴, C. Charlot⁴⁴, M. Chiusi⁴⁴, T. D. Cuisset⁴⁴, O. Davignon⁴⁴, A. De Wit⁴⁴, T. Debnath⁴⁴, I. T. Ehle⁴⁴, S. Ghosh⁴⁴, A. Gilbert⁴⁴, R. Granier de Cassagnac⁴⁴, M. Manoni⁴⁴, M. Nguyen⁴⁴, S. Obraztsov⁴⁴, C. Ochando⁴⁴, L. m. Ravour⁴⁴, R. Salerno⁴⁴, J. B. Sauvan⁴⁴, Y. Sirois⁴⁴, G. Sokmen⁴⁴, Y. Song⁴⁴, L. Urda Gómez⁴⁴, B. Voirin⁴⁴, A. Zabi⁴⁴, A. Zghiche⁴⁴, J. L. Agram^{45,w}, J. Andrea⁴⁵, D. Bloch⁴⁵, E. C. Chabert⁴⁵, C. Collard⁴⁵, G. Coulon⁴⁵, C. Eschenlauer⁴⁵, S. Falke⁴⁵, U. Goerlach⁴⁵, A. C. Le Bihan⁴⁵, G. Saha⁴⁵, A. Savoy-Navarro^{45,x}, P. Vaucelle⁴⁵, A. Di Florio⁴⁶, G. Mauceri⁴⁶, B. Orzari⁴⁶, D. Amram⁴⁷, S. Beauceron⁴⁷, B. Blancon⁴⁷, G. Boudoul⁴⁷, N. Chanon⁴⁷, D. Contardo⁴⁷, J. Daniel⁴⁷, P. Depasse⁴⁷, H. El Mamouni⁴⁷, J. Fay⁴⁷, E. Fillaudeau⁴⁷, S. Gascon⁴⁷, M. Gouzevitch⁴⁷, C. Greenberg⁴⁷, B. Ille⁴⁷, E. Jourdain⁴⁷, M. Lethuillier⁴⁷, K. Long⁴⁷, B. Massoteau⁴⁷, L. Mirabito⁴⁷, A. Purohit⁴⁷, M. Vander Donckt⁴⁷, C. Verollet⁴⁷, D. Chokheli⁴⁸, I. Lomidze⁴⁸, Z. Tsamalaidze^{48,y}, K. F. Adamowicz⁴⁹, V. Botta⁴⁹, S. Consuegra Rodríguez⁴⁹, L. Feld⁴⁹, K. Klein⁴⁹, M. Lipinski⁴⁹, P. Nattland⁴⁹, V. Oppenländer⁴⁹, A. Pauls⁴⁹, D. Pérez Adán⁴⁹, C. Daumann⁵⁰, S. Diekmann⁵⁰, E. Ehler⁵⁰, N. Eich⁵⁰, D. Eliseev⁵⁰, F. Engelke⁵⁰, J. Erdmann⁵⁰, M. Erdmann⁵⁰, M. Z. Farkas⁵⁰, B. Fischer⁵⁰, T. Hebbeker⁵⁰, K. Hoepfner⁵⁰, A. Jung⁵⁰, N. Kumar⁵⁰, M. y. Lee⁵⁰, F. Mausolf⁵⁰, M. Merschmeyer⁵⁰, A. Meyer⁵⁰, A. Pozdnyakov⁵⁰, W. Redjeb⁵⁰, H. Reithler⁵⁰, U. Sarkar⁵⁰, V. Sarkisovi⁵⁰, A. Schmidt⁵⁰, J. G. Schulz⁵⁰, C. Seth⁵⁰, A. Sharma⁵⁰

- J. L. Spah⁵⁰, V. Vaulin⁵⁰, U. Willemsen⁵⁰, S. Zaleski⁵⁰, F. P. Zinn⁵⁰, M. R. Beckers⁵¹, G. Flügge⁵¹, N. Hoeflich⁵¹, T. Kress⁵¹, A. Nowack⁵¹, O. Pooth⁵¹, A. Stahl⁵¹, A. R. Alves Andrade⁵², M. Antonello⁵², S. Bollweg⁵², M. Bonanomi⁵², L. Ebeling⁵², K. El Morabit⁵², Y. Fischer⁵², M. Frahm⁵², P. P. Gadow⁵², E. Garutti⁵², A. Grohsjean⁵², A. A. Guvenli⁵², J. Haller⁵², D. Hundhausen⁵², M. Jalalvandi⁵², G. Kasieczka⁵², P. Keicher⁵², R. Klanner⁵², W. Korcaric⁵², T. Kramer⁵², C. c. Kuo⁵², J. Lange⁵², A. Lobanov⁵², J. Matthiesen⁵², L. Moureaux⁵², K. Nikolopoulos⁵², K. J. Pena Rodriguez⁵², N. Prouvost⁵², B. Raciti⁵², M. Rieger⁵², D. Savoie⁵², P. Schleper⁵², M. Schröder⁵², J. Schwandt⁵², M. Sommerhalder⁵², H. Stadie⁵², G. Steinbrück⁵², T. von Schwartz⁵², R. Ward⁵², B. Wiederspan⁵², M. Wolf⁵², C. Yede⁵², A. Abel⁵³, A. Akhil⁵³, M. Aldaya Martin⁵³, J. Alimena⁵³, Y. An⁵³, I. Andreev⁵³, J. Bach⁵³, S. Baxter⁵³, H. Becerril Gonzalez⁵³, O. Behnke⁵³, F. Blekman^{53,z}, K. Borras^{53,aa}, A. Campbell⁵³, S. Chatterjee⁵³, L. X. Coll Saravia⁵³, G. Eckerlin⁵³, D. Eckstein⁵³, E. Gallo^{53,z}, A. Geiser⁵³, M. Guthoff⁵³, A. Hinzmann⁵³, U. Husemann⁵³, M. Kasemann⁵³, C. Kleinwort⁵³, R. Kogler⁵³, M. Komm⁵³, D. Krücker⁵³, F. Labe⁵³, W. Lange⁵³, D. Leyva Pernia⁵³, J. h. Li⁵³, K. y. Lin⁵³, K. Lipka^{53,bb}, W. Lohmann^{53,h}, J. Malvaso⁵³, R. Mankel⁵³, I. A. Melzer-Pellmann⁵³, M. Mendizabal Morentin⁵³, A. B. Meyer⁵³, G. Milella⁵³, K. Moral Figueroa⁵³, A. Mussgiller⁵³, L. P. Nair⁵³, J. Niedziela⁵³, A. Nürnberg⁵³, J. Park⁵³, E. Ranken⁵³, A. Raspereza⁵³, D. Rastorguev⁵³, L. Rygaard⁵³, M. Scham^{53,cc,aa}, S. Schnake^{53,aa}, C. Schwanenberger^{53,z}, D. Schwarz⁵³, P. Schütze⁵³, D. Selivanova⁵³, K. Sharke⁵³, M. Shchedrolosiev⁵³, A. Sritharan⁵³, D. Stafford⁵³, M. Torkian⁵³, S. Vashishtha⁵³, A. Ventura Barroso⁵³, R. Walsh⁵³, D. Wang⁵³, Q. Wang⁵³, K. Wichmann⁵³, L. Wiens^{53,aa}, C. Wissing⁵³, Y. Yang⁵³, S. Zakharov⁵³, A. Zimmermann Castro Santos⁵³, J. Ahäuser⁵⁴, A. Brusamolino⁵⁴, E. Butz⁵⁴, Y. M. Chen⁵⁴, T. Chwalek⁵⁴, A. Dierlamm⁵⁴, G. G. Dincer⁵⁴, U. Elicabuk⁵⁴, N. Faltermann⁵⁴, M. Giffels⁵⁴, A. Gottmann⁵⁴, F. Hartmann^{54,dd}, F. Hummer⁵⁴, J. Kieseler⁵⁴, M. Klute⁵⁴, H. A. Krause⁵⁴, R. Kunnilan Muhammed Rafeek⁵⁴, O. Lavoryk⁵⁴, J. M. Lawhorn⁵⁴, S. Maier⁵⁴, N. Meenamthuruthil Radhakrishnan⁵⁴, T. Mehner⁵⁴, M. Molch⁵⁴, A. A. Monsch⁵⁴, M. Mormile⁵⁴, T. Müller⁵⁴, E. Pfeffer⁵⁴, M. Presilla⁵⁴, G. Quast⁵⁴, K. Rabbertz⁵⁴, B. Regnery⁵⁴, R. Schmieder⁵⁴, T. Selezneva⁵⁴, N. Shadskiy⁵⁴, L. Sowa⁵⁴, L. Stockmeier⁵⁴, M. Toms⁵⁴, B. Topko⁵⁴, N. Trevisani⁵⁴, C. Verstege⁵⁴, T. Voigtländer⁵⁴, R. F. Von Cube⁵⁴, J. Von Den Driesch⁵⁴, C. Winter⁵⁴, R. Wolf⁵⁴, W. D. Zeuner⁵⁴, X. Zuo⁵⁴, G. Anagnostou⁵⁵, G. Daskalakis⁵⁵, A. Kyriakis⁵⁵, P. Iosifidou⁵⁶, P. Katris⁵⁶, M. Kotsarini⁵⁶, G. Melachroinos⁵⁶, Z. Painesis⁵⁶, N. Plastiras⁵⁶, N. Saoulidou⁵⁶, K. Theofilatos⁵⁶, E. Tzovara⁵⁶, K. Vellidis⁵⁶, I. Zisopoulos⁵⁶, T. Chatzistavrou⁵⁷, G. Karapostoli⁵⁷, K. Kousouris⁵⁷, K. Paschos⁵⁷, L. P. Rouseliotaki⁵⁷, E. Siamarkou⁵⁷, A. Taxeidi⁵⁷, G. Tsiopolitis⁵⁷, I. Evangelou⁵⁸, C. Foudas⁵⁸, P. Katsoulis⁵⁸, P. Kokkas⁵⁸, P. G. Kosmoglou Kioseoglou⁵⁸, N. Manthos⁵⁸, I. Papadopoulos⁵⁸, J. Strogas⁵⁸, E. Tziaferi⁵⁹, C. Hajdu⁶⁰, D. Horvath^{60,ee,ff}, Á. Kadlecik⁶⁰, C. Lee⁶⁰, K. Márton⁶⁰, A. J. Rádl^{60,gg}, F. Sikler⁶⁰, V. Veszpremi⁶⁰, G. Balint⁶¹, M. Csanad⁶¹, K. Farkas⁶¹, A. Fehérkuti^{61,hh}, M. M. A. Gadallah^{61,ii}, M. León Coello⁶¹, G. Pasztor⁶¹, G. I. Veres⁶¹, B. Ujvari⁶², G. Zilizi⁶², G. Bencze⁶³, S. Czellar⁶³, J. Molnar⁶³, Z. Szillasi⁶³, T. F. Csorgo^{64,hh}, F. Nemes^{64,hh}, T. Novak⁶⁴, I. Szanyi^{64,jj}, S. Bahinipati⁶⁵, R. Raturi⁶⁵, S. Bansal⁶⁶, V. Bhatnagar⁶⁶, B. Chauhan⁶⁶, S. Chauhan⁶⁶, N. Dhingra^{66,kk}, A. Kaur⁶⁶, H. Kaur⁶⁶, S. Kumar⁶⁶, T. Sheokand⁶⁶, A. Singla⁶⁶, K. Verma⁶⁶, A. Bhardwaj⁶⁷, A. Chhetri⁶⁷, B. C. Choudhary⁶⁷, A. Kumar⁶⁷, A. Kumar⁶⁷, M. Naimuddin⁶⁷, S. Phor⁶⁷, C. Prakash⁶⁷, K. Ranjan⁶⁷, M. K. Saini⁶⁷, M. Kumari⁶⁸, P. Palni⁶⁸, S. Rana⁶⁸, A. Rathore⁶⁸, A. Sarkar⁶⁸, S. Acharya^{69,ll}, B. Gumber⁶⁹, S. K. Satapathy⁶⁹, S. Mukherjee⁷⁰, S. Bhattacharya⁷¹, S. Das Gupta⁷¹, S. Dutta⁷¹, S. Dutta⁷¹, S. Sarkar⁷¹, M. M. Ameen⁷², P. K. Behera⁷², S. Chatterjee⁷², G. Dash⁷², A. Dattamunsi⁷², P. Jana⁷², P. Kalbhor⁷², S. Kamble⁷², J. R. Komaragiri^{72,mm}, P. R. Pujahari⁷², A. K. Sikdar⁷², R. K. Singh⁷², P. Verma⁷², S. Verma⁷², A. Vijay⁷², A. Chauhan⁷³, S. Nayak⁷³, H. Rajpoot⁷³, B. K. Sirasva⁷³, L. Bhatt⁷⁴, S. Dugad⁷⁴, T. Mishra⁷⁴, G. B. Mohanty⁷⁴, M. Shelake⁷⁴, P. Suryadevara⁷⁴, A. Bala⁷⁵, S. Banerjee⁷⁵, S. Barman^{75,nn}, R. M. Chatterjee⁷⁵, J. Chhikara⁷⁵, M. Guchait⁷⁵, S. Jain⁷⁵, A. Jaiswal⁷⁵, S. Kumar⁷⁵, M. Maity^{75,nn}, G. Majumder⁷⁵, K. Mazumdar⁷⁵, R. Pramanik⁷⁵, R. Saxena⁷⁵, P. Sharma⁷⁵, A. Thachayath⁷⁵, R. Kumar Agrawal⁷⁶, D. Maity^{76,oo}, P. Mal⁷⁶, K. Naskar^{76,oo}, A. Nayak^{76,oo}, K. Pal⁷⁶, P. Sadangi⁷⁶, S. Shuchi⁷⁶, S. K. Swain⁷⁶, S. Varghese^{76,oo}, D. Vats^{76,oo}, S. Dube⁷⁷, P. Hazarika⁷⁷, B. Kansal⁷⁷, A. Laha⁷⁷, R. Sharma⁷⁷, S. Sharma⁷⁷, K. Y. Vaish⁷⁷, C. Agrawal⁷⁸, B. Babu⁷⁸, S. Ghosh⁷⁸, H. Bakhshiansohi^{79,pp}, A. Jafari^{79,qq}, V. Sedighzadeh Dalavi⁷⁹, M. Zeinali^{79,rr}, S. Bashiri⁸⁰, S. Chenarani^{80,ss}, S. M. Etesami⁸⁰, Y. Hosseini⁸⁰, M. Khakzad⁸⁰, E. Khazaie⁸⁰, M. Mohammadi Najafabadi⁸⁰, M. Nourbakhsh⁸⁰, S. Tizchang^{80,tt}, M. Felcini⁸¹, M. Grunewald⁸¹

M. Abbrescia^{82a,82b} M. Buonsante^{82a,82b} A. Colaleo^{82a,82b} D. Creanza^{82a,82c} N. De Filippis^{82a,82c}
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S. Dogra⁹⁷, J. Hong⁹⁷, J. Kim⁹⁷, J. Kim⁹⁷, T. Kim⁹⁷, D. Lee⁹⁷, H. Lee⁹⁷, J. Lee⁹⁷, S. W. Lee⁹⁷, C. S. Moon⁹⁷, Y. D. Oh⁹⁷, S. Sekmen⁹⁷, B. Tae⁹⁷, Y. C. Yang⁹⁷, M. S. Kim⁹⁸, G. Bak⁹⁹, P. Gwak⁹⁹, H. Kim⁹⁹, H. Lee⁹⁹, S. Lee⁹⁹, D. H. Moon⁹⁹, J. Seo⁹⁹, K. Lee¹⁰⁰, Y. Lee¹⁰⁰, E. Asilar¹⁰¹, F. Carnevali¹⁰¹, J. Choi^{101,fff}, T. J. Kim¹⁰¹, Y. Ryou¹⁰¹, J. Song¹⁰¹, T. Yang¹⁰¹, S. Ha¹⁰², B. S. Hong¹⁰², J. Kim¹⁰², K. Lee¹⁰², K. Lee¹⁰², S. Lee¹⁰², J. Padmanaban¹⁰², B. A. N. Putra¹⁰², J. Yoo¹⁰², J. Goh¹⁰³, J. Shin¹⁰³, S. Yang¹⁰³, L. Kalipoliti¹⁰⁴, Y. Kang¹⁰⁴, H. Kim¹⁰⁴, Y. Kim¹⁰⁴, B. Ko¹⁰⁴, S. Lee¹⁰⁴, J. H. Bhyun¹⁰⁵, J. Choi¹⁰⁵, J. Choi¹⁰⁵, W. Jun¹⁰⁵, H. Kim¹⁰⁵, J. Kim¹⁰⁵, J. Kim¹⁰⁵, T. Kim¹⁰⁵, Y. Kim¹⁰⁵, Y. W. Kim¹⁰⁵, S. Ko¹⁰⁵, H. Lee¹⁰⁵, J. Lee¹⁰⁵, J. Lee¹⁰⁵, B. H. Oh¹⁰⁵, J. Shin¹⁰⁵, U. Yang¹⁰⁵, I. Yoon¹⁰⁵, S. Calzaferri¹⁰⁶, W. Heo¹⁰⁶, W. Jang¹⁰⁶, D. Kim¹⁰⁶, S. Kim¹⁰⁶, J. S. H. Lee¹⁰⁶, Y. Roh¹⁰⁶, I. J. Watson¹⁰⁶, G. Cho¹⁰⁷, Y. Eo¹⁰⁷, K. Hwang¹⁰⁷, H. Jang¹⁰⁷, B. Kim¹⁰⁷, D. Kim¹⁰⁷, S. Kim¹⁰⁷, G. Moccasin¹⁰⁷, H. D. Yoo¹⁰⁷, Y. Lee¹⁰⁸, I. Yu¹⁰⁸, T. Beyrouthy¹⁰⁹, Y. Gharbia¹⁰⁹, F. Alazemi¹¹⁰, K. Dreimanis¹¹¹, O. M. Eberlins¹¹¹, A. Gaile¹¹¹, J. K. Heikkilä¹¹¹, M. Klevs¹¹¹, C. Munoz Diaz¹¹¹, D. Osite¹¹¹, G. Pikurs¹¹¹, R. Plese¹¹¹, A. Potrebko¹¹¹, M. Seidel¹¹¹, D. Sidiropoulos Kontos¹¹¹, N. R. Strautnieks¹¹², M. Ambrozaitis¹¹³, A. Juodagalvis¹¹³, S. Nargelas¹¹³, S. Nayak¹¹³, G. Tamulaitis¹¹³, I. Yusuff^{114,ggg}, Z. Zolkapli¹¹⁴, J. P. Barajas Ibarria¹¹⁵, J. F. Benitez¹¹⁵, A. Castaneda Hernandez¹¹⁵, A. Cota Rodriguez¹¹⁵, L. E. Cuevas Picos¹¹⁵, H. A. Encinas Acosta¹¹⁵, L. G. Gallegos Maríñez¹¹⁵, J. A. Murillo Quijada¹¹⁵, L. Valencia Palomo¹¹⁵, G. Ayala¹¹⁶, H. Castilla-Valdez¹¹⁶, H. Crotte Ledesma¹¹⁶, R. Lopez-Fernandez¹¹⁶, J. Mejia Guisao¹¹⁶, R. Reyes-Almanza¹¹⁶, A. Sánchez Hernández¹¹⁶, C. Oropeza Barrera¹¹⁷, D. L. Ramirez Guadarrama¹¹⁷, M. Ramírez García¹¹⁷, I. Bautista¹¹⁸, F. E. Neri Huerta¹¹⁸, I. Pedraza¹¹⁸, H. A. Salazar Ibarguen¹¹⁸, C. Uribe Estrada¹¹⁸, I. Bujanja¹¹⁹, J. Mijuskovic¹¹⁹, N. Raicevic¹¹⁹, A. Ahmad¹²⁰, M. I. Asghar¹²⁰, A. Awais¹²⁰, M. I. M. Awan¹²⁰, W. A. Khan¹²⁰, I. Sohail¹²⁰, V. Avati¹²¹, L. Forthomme¹²¹, L. Grzanka¹²¹, M. Malawski¹²¹, K. Piotrkowski¹²¹, H. Awedikian¹²², M. Bluj¹²², M. Ghimiray¹²², M. Górski¹²², M. Kazana¹²², M. Szeleper¹²², P. Zalewski¹²², K. Bunkowski¹²³, K. Doroba¹²³, A. Kalinowski¹²³, M. Konecki¹²³, J. Krolikowski¹²³, W. Matyszkiewicz¹²³, A. Muhammad¹²³, S. Slawinski¹²³, P. Fokow¹²⁴, K. Pozniak¹²⁴, W. Zabolotny¹²⁴, M. Araujo¹²⁵, C. Beirão Da Cruz E. Silva¹²⁵, A. Boletti¹²⁵, M. Bozzo¹²⁵, T. Camporesi^{125,ddd,hhh}, G. Da Molin¹²⁵, M. Gallinaro¹²⁵, R. Guitton¹²⁵, J. Hollar¹²⁵, H. Legoinha¹²⁵, N. Leonardo^{125,iii}, G. B. Marozzo¹²⁵, A. Petrilli¹²⁵, M. Pisano¹²⁵, J. Seixas¹²⁵, J. Varela¹²⁵, J. W. Wulff¹²⁵, P. Adzic¹²⁶, L. Markovic¹²⁶, P. Milenovic¹²⁶, V. Milosevic¹²⁶, D. Devetak¹²⁷, M. Dordevic¹²⁷, J. Milosevic¹²⁷, L. Nadder¹²⁷, V. Rekovic¹²⁷, M. Stojanovic¹²⁷, M. Alcalde Martinez¹²⁸, J. Alcaraz Maestre¹²⁸, J. A. Brochero Cifuentes¹²⁸, M. Cepeda¹²⁸, M. Cerrada¹²⁸, N. Colino¹²⁸, B. De La Cruz¹²⁸, A. Escalante Del Valle¹²⁸, C. Fernandez Bedoya¹²⁸, D. Fernández Del Val¹²⁸, J. P. Fernández Ramos¹²⁸, J. Flix¹²⁸, M. C. Fouz¹²⁸, M. Gonzalez Hernandez¹²⁸, O. Gonzalez Lopez¹²⁸, S. Goy Lopez¹²⁸, J. M. Hernandez¹²⁸, M. I. Josa¹²⁸, J. Llorente Merino¹²⁸, O. Manzanilla¹²⁸, C. Martin Perez¹²⁸, E. Martin Viscasillas¹²⁸, D. Moran¹²⁸, C. M. Morcillo Perez¹²⁸, Á. Navarro Tobar¹²⁸, J. Puerta Pelayo¹²⁸, A. M. Pérez-Calero Yzquierdo¹²⁸, I. Redondo¹²⁸, D. D. Redondo Ferrero¹²⁸, J. Vazquez Escobar¹²⁸, J. F. de Trocóniz¹²⁹, E. Aller Gutierrez¹³⁰, B. Alvarez Gonzalez¹³⁰, J. Ayllon Torresano¹³⁰, A. Cardini¹³⁰, J. Cuevas¹³⁰, J. Del Riego Badas¹³⁰, D. Estrada Acevedo¹³⁰, J. Fernandez Menendez¹³⁰, S. Folgueras¹³⁰, I. Gonzalez Caballero¹³⁰, P. Leguina¹³⁰, M. Obeso Menendez¹³⁰, E. Palencia Cortezon¹³⁰, J. Prado Pico¹³⁰, S. Sanchez Cruz¹³⁰, A. Soto Rodríguez¹³⁰, P. Vischia¹³⁰, S. Blanco Fernández¹³¹, I. J. Cabrillo¹³¹, A. Calderon¹³¹, M. Caserta¹³¹, J. Duarte Campderros¹³¹, M. Fernandez¹³¹, G. Gomez¹³¹, C. Lasasoa García¹³¹, R. Lopez Ruiz¹³¹, C. Martinez Rivero¹³¹, P. Martinez Ruiz del Arbol¹³¹, F. Matorras¹³¹, P. Matorras Cuevas¹³¹, E. Navarrete Ramos¹³¹, J. Piedra Gomez¹³¹, C. Quintana San Emeterio¹³¹, V. Rodriguez¹³¹, L. Scodellaro¹³¹, I. Vila¹³¹, R. Vilar Cortabitarte¹³¹, J. M. Vizan Garcia¹³¹, B. Kailasapathy^{132,jjj}, W. G. Dharmaratna^{133,kkk}, N. Perera¹³³, L. Caminada^{134,III}, W. Erdmann¹³⁴, R. Horisberger¹³⁴, Q. Ingram¹³⁴, H. C. Kaestli¹³⁴, D. Kotlinski¹³⁴, C. Lange¹³⁴, U. Langenegger¹³⁴, A. Nigamova¹³⁴, L. Noehte^{134,III}, L. Redard-Jacot^{134,III}, T. Rohe¹³⁴, A. Samalan¹³⁴, T. K. Aarrestad¹³⁵, M. Backhaus¹³⁵, A. Belvedere¹³⁵, T. Bevilacqua^{135,III}, G. Bonomelli¹³⁵, C. Cazzaniga¹³⁵, K. Datta¹³⁵, P. De Bryas Dexmiers D'Archiacchiac^{135,j}, A. De Cosa¹³⁵, G. Dissertori¹³⁵, M. Dittmar¹³⁵, M. Donegà¹³⁵, F. Glessgen¹³⁵, C. Grab¹³⁵, T. G. Harte¹³⁵, N. Härringer¹³⁵, B. Kaynak¹³⁵, M. Koppel¹³⁵, W. Lustermann¹³⁵, M. Malucchi¹³⁵, R. A. Manzoni¹³⁵, L. Marchese¹³⁵, F. Nessi-Tedaldi¹³⁵, F. Pauss¹³⁵, A. A. Petre¹³⁵, J. Prendi¹³⁵, B. Ristic¹³⁵, S. Rohletter¹³⁵, P. M. Sander¹³⁵, R. Seidita¹³⁵, J. Steggemann^{135,j}, A. Tarabini¹³⁵, C. Z. Tee¹³⁵, D. Valsecchi¹³⁵, P. H. Wagner¹³⁵, R. Wallny¹³⁵, C. Amsler^{136,mmm}, F. Bilandzija¹³⁶

P. Bärtschi¹³⁶, M. F. Canelli¹³⁶, G. Celotto¹³⁶, Z. Ghafoor¹³⁶, T. A. Goldschmidt¹³⁶, V. Guglielmi¹³⁶,
A. Jofrehei¹³⁶, B. Kilminster¹³⁶, T. H. Kwok¹³⁶, S. Leontsinis¹³⁶, V. Lukashenko¹³⁶, A. Macchiolo¹³⁶,
F. Meng¹³⁶, J. Motta¹³⁶, P. Robmann¹³⁶, E. Shokr¹³⁶, F. Stäger¹³⁶, R. Tramontano¹³⁶, P. Viscone¹³⁶,
D. Bhowmik¹³⁷, Y. h. Chou¹³⁷, C. M. Kuo¹³⁷, P. K. Rout¹³⁷, S. Taj¹³⁷, P. C. Tiwari^{137,mm}, L. Ceard¹³⁸, K. F. Chen¹³⁸,
Z. g. Chen¹³⁸, A. De Iorio¹³⁸, G. W. S. Hou¹³⁸, T. h. Hsu¹³⁸, Y. w. Kao¹³⁸, S. Karmakar¹³⁸, F. Khuzaimah¹³⁸,
G. Kole¹³⁸, Y. y. Li¹³⁸, R. S. Lu¹³⁸, E. Paganis¹³⁸, X. f. Su¹³⁸, J. Thomas-Wilsker¹³⁸, L. s. Tsai¹³⁸, D. Tsiounou¹³⁸,
H. y. Wu¹³⁸, E. Yazgan¹³⁸, C. Asawatangtrakuldee¹³⁹, N. Srimanobhas¹³⁹, Y. Maghrbi¹⁴⁰, D. Agyel¹⁴¹,
F. Dolek¹⁴¹, I. Dumanoglu^{141,nnn}, Y. Guler^{141,ooo}, E. Gurpinar Guler^{141,ooo}, A. Kayis Topaksu¹⁴¹, G. Onengut¹⁴¹,
K. Ozdemir^{141,ppp}, B. Tali^{141,qqq}, U. G. Tok¹⁴¹, E. Uslan¹⁴¹, S. Sen¹⁴², B. Akgun¹⁴³, I. O. Atakisi^{143,rrr},
E. Gülmez¹⁴³, M. Kaya^{143,sss}, O. Kaya^{143,ttt}, M. A. Sarkisla^{143,uuu}, S. Tekten^{143,vvv}, D. Boncukcu¹⁴⁴, A. Cakir¹⁴⁴,
K. Cankocak^{144,nnn,www}, M. Gumustekin¹⁴⁴, A. D. Gungordu¹⁴⁴, B. Haciasahinoglu¹⁴⁵, I. Hos^{145,xxx},
S. Ozkorucuklu¹⁴⁵, O. Potok¹⁴⁵, H. Sert¹⁴⁵, C. Simsek¹⁴⁵, C. Zorbilmez¹⁴⁵, S. Cerci¹⁴⁶, C. Dozen^{146,yyy},
E. Iren^{146,zzz}, B. Isildak¹⁴⁶, E. Simsek¹⁴⁶, D. Sunar Cerci¹⁴⁶, T. Yetkin^{146,yyy}, O. Dadazhanova¹⁴⁷, B. Grynyov¹⁴⁷,
K. Klimenko¹⁴⁸, O. Kurov¹⁴⁸, L. Levchuk¹⁴⁸, S. Lukyanenko¹⁴⁸, A. Pristavka¹⁴⁸, D. Soroka¹⁴⁸, J. J. Brooke¹⁴⁹,
A. Bundock¹⁴⁹, F. J. J. Bury¹⁴⁹, E. Clement¹⁴⁹, D. Cussans¹⁴⁹, D. Dharmender¹⁴⁹, H. Flacher¹⁴⁹, J. Goldstein¹⁴⁹,
H. F. Heath¹⁴⁹, M. I. Holmberg¹⁴⁹, A. Karakoulaki¹⁴⁹, L. Kreczko¹⁴⁹, S. Paramesvaran¹⁴⁹, L. Robertshaw¹⁴⁹,
M. S. Sanjrani^{149,pp}, J. Segal¹⁴⁹, V. J. Smith¹⁴⁹, A. Ball¹⁵⁰, K. W. Bell¹⁵⁰, A. Belyaev^{150,aaaa}, C. Brew¹⁵⁰,
R. M. Brown¹⁵⁰, D. J. Cockerill¹⁵⁰, A. Elliot¹⁵⁰, K. V. Ellis¹⁵⁰, J. Gajownik¹⁵⁰, K. Harder¹⁵⁰, S. Harper¹⁵⁰,
J. Linacre¹⁵⁰, K. Manolopoulos¹⁵⁰, M. Moallemi¹⁵⁰, D. M. Newbold¹⁵⁰, E. Olaiya¹⁵⁰, D. Petyt¹⁵⁰, T. Reis¹⁵⁰,
A. R. Sahasransu¹⁵⁰, T. Schuh¹⁵⁰, C. Shepherd-Themistocleous¹⁵⁰, I. R. Tomalin¹⁵⁰, K. C. Whalen¹⁵⁰,
T. Williams¹⁵⁰, I. Andreou¹⁵¹, S. Awan¹⁵¹, R. Bainbridge¹⁵¹, P. Bloch¹⁵¹, O. Buchmuller¹⁵¹,
C. A. Carrillo Montoya¹⁵¹, D. Colling¹⁵¹, A. Cox¹⁵¹, I. Das¹⁵¹, P. Dauncey¹⁵¹, G. Davies¹⁵¹, M. Della Negra¹⁵¹,
S. Fayer¹⁵¹, G. Fedi¹⁵¹, G. Hall¹⁵¹, H. R. Hoorani¹⁵¹, A. Howard¹⁵¹, G. Iles¹⁵¹, C. R. Knight¹⁵¹, P. Krueper¹⁵¹,
J. Langford¹⁵¹, K. H. Law¹⁵¹, L. Lyons¹⁵¹, A. M. Magnan¹⁵¹, B. Maier¹⁵¹, S. Mallios¹⁵¹, A. Mastronikolis¹⁵¹,
J. Nash^{151,bbbb}, M. Pesaresi¹⁵¹, P. B. Pradeep¹⁵¹, E. V. Protopapa¹⁵¹, B. C. Radburn-Smith¹⁵¹, A. Richards¹⁵¹,
A. Rose¹⁵¹, T. B. Runtig¹⁵¹, L. Russell¹⁵¹, K. Savva¹⁵¹, R. Schmitz¹⁵¹, C. Seez¹⁵¹, R. Shukla¹⁵¹, A. Tapper¹⁵¹,
T. Travis¹⁵¹, K. Uchida¹⁵¹, G. P. Uttley¹⁵¹, T. Virdee^{151,dd}, N. Wardle¹⁵¹, D. Winterbottom¹⁵¹, J. Xiao¹⁵¹,
J. Cole¹⁵², L. Juckett¹⁵², A. Khan¹⁵², P. Kyberd¹⁵², I. Reid¹⁵², B. Bam¹⁵³, A. Buchot Perraguin¹⁵³, S. Campbell¹⁵³,
R. Chudasama¹⁵³, S. Cooper¹⁵³, C. Crovella¹⁵³, G. Fidalgo¹⁵³, S. V. Gleyzer¹⁵³, R. Kaur¹⁵³,
A. Khukhunaishvili¹⁵³, K. Matchev¹⁵³, E. Pearson¹⁵³, P. Rumerio^{153,cccc}, E. Usai¹⁵³, R. Yi¹⁵³, S. Abbott¹⁵⁴,
S. Baradia¹⁵⁴, B. Barton¹⁵⁴, R. Breedon¹⁵⁴, H. Cai¹⁵⁴, M. Calderon De La Barca Sanchez¹⁵⁴, E. Cannataert¹⁵⁴,
M. Chertok¹⁵⁴, M. Citron¹⁵⁴, J. Conway¹⁵⁴, P. T. Cox¹⁵⁴, F. Eble¹⁵⁴, R. Erbacher¹⁵⁴, C. Fairchild¹⁵⁴,
O. Kukral¹⁵⁴, S. Ostrom¹⁵⁴, I. Salazar Segovia¹⁵⁴, J. H. Steenis¹⁵⁴, J. S. Tafoya Vargas¹⁵⁴, W. Wei¹⁵⁴, S. Yoo¹⁵⁴,
A. Aportela¹⁵⁵, A. Arora¹⁵⁵, J. G. Branson¹⁵⁵, S. Cittolin¹⁵⁵, B. D'Anzi¹⁵⁵, D. Diaz¹⁵⁵, J. Duarte¹⁵⁵,
L. Giannini¹⁵⁵, Y. Gu¹⁵⁵, J. Guiang¹⁵⁵, V. Krutelyov¹⁵⁵, R. Lee¹⁵⁵, J. Letts¹⁵⁵, H. Li¹⁵⁵, R. Marroquin Solares¹⁵⁵,
M. Masciovecchio¹⁵⁵, F. Mokhtar¹⁵⁵, S. Morovic¹⁵⁵, S. Mukherjee¹⁵⁵, M. Pieri¹⁵⁵, D. Primosch¹⁵⁵,
M. Quinnan¹⁵⁵, V. Sharma¹⁵⁵, M. Tadel¹⁵⁵, E. Vourliotis¹⁵⁵, F. Würthwein¹⁵⁵, A. Yagil¹⁵⁵, Z. Zhao¹⁵⁵,
K. Adamidis¹⁵⁶, H. Ancelin¹⁵⁶, M. Bachtis¹⁵⁶, D. Campos¹⁵⁶, R. Cousins¹⁵⁶, S. Crossley¹⁵⁶, G. Flores Avila¹⁵⁶,
J. Hauser¹⁵⁶, M. Ignatenko¹⁵⁶, M. A. Iqbal¹⁵⁶, T. Lam¹⁵⁶, Y. f. Lo¹⁵⁶, A. Nunez Del Prado¹⁵⁶, D. Saltzberg¹⁵⁶,
V. Valuev¹⁵⁶, A. Albert¹⁵⁷, S. Bhattacharya¹⁵⁷, A. Bornheim¹⁵⁷, O. Cerri¹⁵⁷, Z. Hao¹⁵⁷, L. Mori¹⁵⁷,
H. B. Newman¹⁵⁷, G. Reales Gutiérrez¹⁵⁷, T. Sievert¹⁵⁷, P. Sommerling¹⁵⁷, E. Sledge¹⁵⁷, M. Spiropulu¹⁵⁷, C. Sun¹⁵⁷,
J. R. Vlimant¹⁵⁷, R. A. Wynne¹⁵⁷, S. Xie¹⁵⁷, R. Y. Zhu¹⁵⁷, R. Clare¹⁵⁸, J. W. Gary¹⁵⁸, G. Hanson¹⁵⁸,
A. Barzdukas¹⁵⁹, L. Brennan¹⁵⁹, C. Campagnari¹⁵⁹, S. Carron Montero^{159,dddd}, K. Downham¹⁵⁹, C. Grieco¹⁵⁹,
J. S. Guo¹⁵⁹, M. M. Hussain¹⁵⁹, D. Imani¹⁵⁹, J. Incandela¹⁵⁹, M. W. K. Lai¹⁵⁹, A. J. Li¹⁵⁹, P. Masterson¹⁵⁹,
J. J. H. Ockenfuss¹⁵⁹, J. Richman¹⁵⁹, S. N. Santpur¹⁵⁹, D. Stuart¹⁵⁹, T. Á. Vami¹⁵⁹, X. Yan¹⁵⁹, D. Zhang¹⁵⁹,
J. P. Cumalat¹⁶⁰, W. T. Ford¹⁶⁰, J. Fraticelli¹⁶⁰, A. Hart¹⁶⁰, M. Herrmann¹⁶⁰, S. Kwan¹⁶⁰, J. Pearkes¹⁶⁰,
N. Schonbeck¹⁶⁰, K. Stenson¹⁶⁰, K. Ulmer¹⁶⁰, S. R. Wagner¹⁶⁰, N. Zipper¹⁶⁰, D. Zuolo¹⁶⁰, R. Bartek¹⁶¹,
A. Dominguez¹⁶¹, S. Raj¹⁶¹, B. Sahu¹⁶¹, A. E. Simsek¹⁶¹, B. Singhal¹⁶¹, S. S. Yu¹⁶¹, C. Aruta¹⁶², P. Avery¹⁶²,
D. Bourilkov¹⁶², P. Chang¹⁶², V. Cherepanov¹⁶², M. Dittrich¹⁶², R. D. Field¹⁶², C. Huh¹⁶², E. Koenig¹⁶²

- M. Kolosova¹⁶², J. Konigsberg¹⁶², A. Korytov¹⁶², G. Mitselmakher¹⁶², K. Mohrman¹⁶²,
A. Muthirakalayil Madhu¹⁶², N. Rawal¹⁶², S. Rosenzweig¹⁶², Y. Takahashi¹⁶², J. Wang¹⁶², B. Alsufyani¹⁶³,
S. Das¹⁶³, S. Demarest¹⁶³, L. Hasa¹⁶³, M. Hohmann¹⁶³, M. Lavinsky¹⁶³, E. Yanes¹⁶³, T. Adams¹⁶⁴,
A. Al Kadhimi¹⁶⁴, D. Alam¹⁶⁴, A. Askew¹⁶⁴, S. Bower¹⁶⁴, R. Goff¹⁶⁴, R. Hashmi¹⁶⁴, A. Hassani¹⁶⁴,
T. Kolberg¹⁶⁴, G. Martinez¹⁶⁴, M. Mazza¹⁶⁴, H. Prosper¹⁶⁴, P. R. Prova¹⁶⁴, R. Yohay¹⁶⁴, M. Albrow¹⁶⁵,
M. Alyari¹⁶⁵, O. Amram¹⁶⁵, G. Apollinari¹⁶⁵, A. Apresyan¹⁶⁵, L. A. Bauerdick¹⁶⁵, D. Berry¹⁶⁵, J. Berryhill¹⁶⁵,
P. C. Bhat¹⁶⁵, K. Burkett¹⁶⁵, J. N. Butler¹⁶⁵, A. Canepa¹⁶⁵, G. B. Cerati¹⁶⁵, H. Cheung¹⁶⁵, F. Chlebana¹⁶⁵,
C. Cosby¹⁶⁵, G. Cummings¹⁶⁵, I. Dutta¹⁶⁵, V. D. Elvira¹⁶⁵, J. Freeman¹⁶⁵, A. Gandrakota¹⁶⁵, Z. Gece¹⁶⁵,
L. Gray¹⁶⁵, D. Green¹⁶⁵, A. Grummer¹⁶⁵, S. Grünendahl¹⁶⁵, D. Guerrero¹⁶⁵, O. Gutsche¹⁶⁵, R. M. Harris¹⁶⁵,
J. Hirschauer¹⁶⁵, V. Innocente¹⁶⁵, B. Jayatilaka¹⁶⁵, S. Jindariani¹⁶⁵, M. Johnson¹⁶⁵, R. S. Kim¹⁶⁵, S. Lammel¹⁶⁵,
D. Lincoln¹⁶⁵, R. Lipton¹⁶⁵, T. Liu¹⁶⁵, K. Maeshima¹⁶⁵, D. Mason¹⁶⁵, P. McBride¹⁶⁵, P. Merkel¹⁶⁵,
S. Mrenna¹⁶⁵, S. Nahn¹⁶⁵, J. Ngadiuba¹⁶⁵, D. Noonan¹⁶⁵, S. Norberg¹⁶⁵, V. Papadimitriou¹⁶⁵, N. Pastika¹⁶⁵,
K. Pedro¹⁶⁵, C. Pena^{165,eeee}, C. E. Perez Lara¹⁶⁵, V. Perovic¹⁶⁵, F. Ravera¹⁶⁵, A. Reinsvold Hall^{165,ffff},
L. Ristori¹⁶⁵, M. Safdari¹⁶⁵, E. Sexton-Kennedy¹⁶⁵, E. Smith¹⁶⁵, N. Smith¹⁶⁵, A. Soha¹⁶⁵, L. Spiegel¹⁶⁵,
S. Stoynev¹⁶⁵, J. Strait¹⁶⁵, L. Taylor¹⁶⁵, S. Tkaczyk¹⁶⁵, N. V. Tran¹⁶⁵, L. Uplegger¹⁶⁵, E. W. Vaandering¹⁶⁵,
C. Wang¹⁶⁵, I. Zoi¹⁶⁵, M. R. Adams¹⁶⁶, N. Barnett¹⁶⁶, A. Baty¹⁶⁶, C. Bennett¹⁶⁶, N. Brandman-hughes¹⁶⁶,
R. Cavanaugh¹⁶⁶, S. J. Das¹⁶⁶, R. Escobar Franco¹⁶⁶, O. Evdokimov¹⁶⁶, C. E. Gerber¹⁶⁶, H. Gupta¹⁶⁶,
M. Hawksworth¹⁶⁶, A. Hingrajiya¹⁶⁶, D. J. Hofman¹⁶⁶, Z. Huang¹⁶⁶, J. h. Lee¹⁶⁶, C. Mills¹⁶⁶, S. Nanda¹⁶⁶,
G. Nigmatkulov¹⁶⁶, B. Ozek¹⁶⁶, V. Pant¹⁶⁶, T. Phan¹⁶⁶, D. Pilipovic¹⁶⁶, R. Pradhan¹⁶⁶, E. Prifti¹⁶⁶, T. Roy¹⁶⁶,
D. Shekar¹⁶⁶, N. Singh¹⁶⁶, F. Strug¹⁶⁶, A. Thielen¹⁶⁶, M. Tonjes¹⁶⁶, N. Varelas¹⁶⁶, M. A. Wadud¹⁶⁶, A. Wang¹⁶⁶,
J. Yoo¹⁶⁶, S. Dittmer¹⁶⁷, K. A. Hahn¹⁶⁷, S. King¹⁶⁷, D. Li¹⁶⁷, M. McGinnis¹⁶⁷, Y. Miao¹⁶⁷, D. G. Monk¹⁶⁷,
M. H. Schmitt¹⁶⁷, A. Taliencio¹⁶⁷, M. Velasco¹⁶⁷, J. Wang¹⁶⁷, D. Wilbern¹⁶⁷, N. Parashar¹⁶⁸, A. Pathak¹⁶⁸,
E. Shumka¹⁶⁸, G. Agarwal¹⁶⁹, R. Band¹⁶⁹, R. Bucci¹⁶⁹, S. Castells¹⁶⁹, A. Das¹⁶⁹, A. Datta¹⁶⁹, A. Ehnis¹⁶⁹,
R. Goldouzian¹⁶⁹, M. Hildreth¹⁶⁹, T. Ivanov¹⁶⁹, C. Jessop¹⁶⁹, K. Lannon¹⁶⁹, J. Lawrence¹⁶⁹, D. Lutton¹⁶⁹,
J. Mariano¹⁶⁹, N. Marinelli¹⁶⁹, P. Mastrapasqua¹⁶⁹, A. Masud¹⁶⁹, T. McCauley¹⁶⁹, C. Mcgrady¹⁶⁹, C. Moore¹⁶⁹,
Y. Musienko^{169,gggg}, H. Nelson¹⁶⁹, M. Osherson¹⁶⁹, A. Piccinelli¹⁶⁹, R. Ruchti¹⁶⁹, A. Townsend¹⁶⁹, Y. Wan¹⁶⁹,
M. Wayne¹⁶⁹, H. Yockey¹⁶⁹, S. Chandra¹⁷⁰, A. Gu¹⁷⁰, L. Gutay¹⁷⁰, L. He¹⁷⁰, M. Huwiler¹⁷⁰, M. Jones¹⁷⁰,
A. W. Jung¹⁷⁰, I. G. Karlioglu¹⁷⁰, D. Kondratyev¹⁷⁰, J. Li¹⁷⁰, M. Liu¹⁷⁰, M. Macedo¹⁷⁰, G. Negro¹⁷⁰,
N. Neumeister¹⁷⁰, G. Paspalaki¹⁷⁰, S. Piperov¹⁷⁰, N. R. Saha¹⁷⁰, J. F. Schulte¹⁷⁰, R. Sharma¹⁷⁰, F. Wang¹⁷⁰,
A. L. Wesolek¹⁷⁰, A. Wildridge¹⁷⁰, W. Xie¹⁷⁰, Y. Yao¹⁷⁰, Y. Zhong¹⁷⁰, M. Alhusseini¹⁷¹, D. Blend¹⁷¹,
K. Dilsiz^{171,hhhh}, O. K. Köseyan¹⁷¹, A. Mestvirishvili^{171,hhh}, O. Neogi¹⁷¹, H. Ogul^{171,iiii}, Y. Onel¹⁷¹, A. Penzo¹⁷¹,
C. Snyder¹⁷¹, A. Abreu¹⁷², L. F. Alcerro Alcerro¹⁷², J. Anguiano¹⁷², S. Arteaga Escatel¹⁷², P. Baringer¹⁷²,
A. Bean¹⁷², R. Bhattacharya¹⁷², M. Chukwuka¹⁷², Z. Flowers¹⁷², D. Grove¹⁷², J. King¹⁷², G. Krintiras¹⁷²,
M. Lazarovits¹⁷², C. Le Mahieu¹⁷², J. Marquez¹⁷², M. Murray¹⁷², M. Nickel¹⁷², E. Reynolds¹⁷², C. Rogan¹⁷²,
C. Royon¹⁷², S. Rudrabhatla¹⁷², S. Sanders¹⁷², J. A. Velazquez Corral¹⁷², G. Wilson¹⁷², A. Ahmad¹⁷³,
B. Allmond¹⁷³, N. Islam¹⁷³, A. Ivanov¹⁷³, K. Kaadze¹⁷³, Y. Maravin¹⁷³, J. Natoli¹⁷³, G. G. Reddy¹⁷³, D. Roy¹⁷³,
G. Sorrentino¹⁷³, B. Blumenfeld¹⁷⁴, J. Davis¹⁷⁴, A. Gritsan¹⁷⁴, Z. Huang¹⁷⁴, L. Kang¹⁷⁴, P. Maksimovic¹⁷⁴,
N. Pinto¹⁷⁴, M. Roguljic¹⁷⁴, S. Sekhar¹⁷⁴, M. V. Srivastav¹⁷⁴, M. Swartz¹⁷⁴, Z. Alton¹⁷⁵, D. Baden¹⁷⁵,
A. Belloni¹⁷⁵, J. Bistany-riebman¹⁷⁵, S. C. Eno¹⁷⁵, N. J. Hadley¹⁷⁵, S. Jabeen¹⁷⁵, R. G. Kellogg¹⁷⁵, T. Koeth¹⁷⁵,
B. Kronheim¹⁷⁵, S. Lascio¹⁷⁵, J. Lee¹⁷⁵, P. Major¹⁷⁵, A. Mignerey¹⁷⁵, C. Palmer¹⁷⁵, C. Papageorgakis¹⁷⁵,
M. M. Paranjpe¹⁷⁵, E. Popova^{175,gggg}, A. Shevelev¹⁷⁵, M. Wrotny¹⁷⁵, L. Zhang¹⁷⁵, S. Cholak¹⁷⁶, Z. Demiragli¹⁷⁶,
C. Erice¹⁷⁶, C. Fangmeier¹⁷⁶, C. Fernandez Madrazo¹⁷⁶, J. Fulcher¹⁷⁶, J. Garcia De Castro¹⁷⁶, F. Golf¹⁷⁶,
S. Jeon¹⁷⁶, G. Linney¹⁷⁶, J. O'Cain¹⁷⁶, I. Reed¹⁷⁶, J. Rohlf¹⁷⁶, D. Sperka¹⁷⁶, I. Suarez¹⁷⁶, A. Tsatsos¹⁷⁶,
E. Wurtz¹⁷⁶, A. G. Zecchinelli¹⁷⁶, A. Aarif¹⁷⁷, G. Alverson¹⁷⁷, E. Barberis¹⁷⁷, S. Bein¹⁷⁷, J. Bonilla¹⁷⁷,
B. Bylsma¹⁷⁷, M. Campana¹⁷⁷, R. Clark¹⁷⁷, J. Dervan¹⁷⁷, Y. Haddad¹⁷⁷, Y. Han¹⁷⁷, I. Israr¹⁷⁷, A. Krishna¹⁷⁷,
M. Lu¹⁷⁷, N. Manganelli¹⁷⁷, R. McCarthy¹⁷⁷, D. M. Morse¹⁷⁷, T. Orimoto¹⁷⁷, L. Skinnari¹⁷⁷, C. S. Thoreson¹⁷⁷,
E. Tsai¹⁷⁷, D. Wood¹⁷⁷, C. Baldenegro Barrera¹⁷⁸, H. Bossi¹⁷⁸, S. Bright-Thonney¹⁷⁸, I. A. Cali¹⁷⁸,
Y. c. Chen¹⁷⁸, P. c. Chou¹⁷⁸, M. D'Alfonso¹⁷⁸, K. Devereaux¹⁷⁸, J. Eysermans¹⁷⁸, C. Freer¹⁷⁸,
G. Gomez Ceballos¹⁷⁸, M. Goncharov¹⁷⁸, G. Grosso¹⁷⁸, P. Harris¹⁷⁸, D. Hoang¹⁷⁸, G. M. Innocenti¹⁷⁸, K. Ivanov¹⁷⁸

G. Kopp¹⁷⁸, D. Kovalskyi¹⁷⁸, J. Lang¹⁷⁸, L. Lavezzo¹⁷⁸, Y. J. Lee¹⁷⁸, P. Lugato¹⁷⁸, C. McGinn¹⁷⁸, E. Moreno¹⁷⁸,
A. Novak¹⁷⁸, M. I. Park¹⁷⁸, C. Paus¹⁷⁸, C. Reissel¹⁷⁸, C. Roland¹⁷⁸, G. Roland¹⁷⁸, S. Rothman¹⁷⁸,
T. a. Sheng¹⁷⁸, G. Stephans¹⁷⁸, D. Walter¹⁷⁸, J. Wang¹⁷⁸, Z. Wang¹⁷⁸, B. Wyslouch¹⁷⁸, T. Yang¹⁷⁸, K. Yoon¹⁷⁸,
P. E. Karchin¹⁷⁹, A. Alpana¹⁸⁰, B. Crossman¹⁸⁰, W. J. Jackson¹⁸⁰, C. Kapsiak¹⁸⁰, D. Mahon¹⁸⁰, J. Mans¹⁸⁰,
B. Marzocchi¹⁸⁰, R. Rusack¹⁸⁰, O. Sancar¹⁸⁰, R. Saradhy¹⁸⁰, N. Strobbe¹⁸⁰, J. M. Hogan¹⁸¹, K. Howey¹⁸¹,
K. Johnson¹⁸¹, B. Luetke¹⁸¹, K. Bloom¹⁸², D. R. Claes¹⁸², S. V. Dixit¹⁸², G. Haza¹⁸², J. Hossain¹⁸², C. Joo¹⁸²,
I. Kravchenko¹⁸², K. H. M. Kwok¹⁸², Y. Mehra¹⁸², J. Morris¹⁸², A. Rohilla¹⁸², J. E. Siado¹⁸², A. Vagnerini¹⁸²,
A. Wightman¹⁸², B. Chiarito¹⁸³, J. P. Chou¹⁸³, S. V. Clark¹⁸³, S. Donnelly¹⁸³, D. Gadkari¹⁸³, Y. Gershtein¹⁸³,
E. Halkiadakis¹⁸³, C. Houghton¹⁸³, D. Jaroslawski¹⁸³, A. Kaur¹⁸³, A. Kobert¹⁸³, I. Laflotte¹⁸³, A. Lath¹⁸³,
J. Martins¹⁸³, P. Meltzer¹⁸³, M. Perez Prada¹⁸³, K. Ramdin¹⁸³, B. Rand¹⁸³, J. Reichert¹⁸³, P. Saha¹⁸³, S. Salur¹⁸³,
S. Somalwar¹⁸³, R. Stone¹⁸³, S. A. Thayil¹⁸³, S. Thomas¹⁸³, J. Vora¹⁸³, H. Bouchamaoui¹⁸⁴, G. Dezoort¹⁸⁴,
P. Elmer¹⁸⁴, A. Frankenthal¹⁸⁴, M. Galli¹⁸⁴, B. Greenberg¹⁸⁴, K. Kennedy¹⁸⁴, Y. Lai¹⁸⁴, D. Lange¹⁸⁴,
A. Loeliger¹⁸⁴, D. Marlow¹⁸⁴, I. Ojalvo¹⁸⁴, J. Olsen¹⁸⁴, F. Simpson¹⁸⁴, D. Stickland¹⁸⁴, C. Tully¹⁸⁴, S. Yoon¹⁸⁴,
H. Bandyopadhyay¹⁸⁵, H. w. Hsia¹⁸⁵, I. Iashvili¹⁸⁵, A. Kalogeropoulos¹⁸⁵, A. Kharchilava¹⁸⁵, A. Mandal¹⁸⁵,
C. McLean¹⁸⁵, M. Morris¹⁸⁵, D. Nguyen¹⁸⁵, O. Poncet¹⁸⁵, S. Rappoccio¹⁸⁵, H. Rejeb Sfar¹⁸⁵, W. Terrill¹⁸⁵,
A. Williams¹⁸⁵, D. Yu¹⁸⁵, J. Alexander¹⁸⁶, X. Chen¹⁸⁶, G. De Castro¹⁸⁶, J. Dickinson¹⁸⁶, A. Duquette¹⁸⁶, J. Fan¹⁸⁶,
X. Fan¹⁸⁶, J. Grassi¹⁸⁶, P. Kotamnives¹⁸⁶, K. Krzyzanska¹⁸⁶, J. Monroy¹⁸⁶, G. Niendorf¹⁸⁶, M. Oshiro¹⁸⁶,
J. R. Patterson¹⁸⁶, A. Ryd¹⁸⁶, J. Thom¹⁸⁶, H. A. Weber¹⁸⁶, B. Weiss¹⁸⁶, P. Wittich¹⁸⁶, Y. Wu¹⁸⁶, R. Zou¹⁸⁶,
L. Zygala¹⁸⁶, O. Bessidskaia Bylund¹⁸⁷, A. Bodek¹⁸⁷, P. de Barbaro¹⁸⁷, R. Demina¹⁸⁷, A. Garcia-Bellido¹⁸⁷,
H. S. Hare¹⁸⁷, O. Hindrichs¹⁸⁷, N. Parmar¹⁸⁷, P. Parygin^{187,gggg}, H. Seo¹⁸⁷, R. Taus¹⁸⁷, Y. h. Yu¹⁸⁷,
M. Carrigan¹⁸⁸, R. De Los Santos¹⁸⁸, L. S. Durkin¹⁸⁸, C. Hill¹⁸⁸, M. Joyce¹⁸⁸, L. Nestor¹⁸⁸, D. A. Wenzl¹⁸⁸,
B. L. Winer¹⁸⁸, B. Yates¹⁸⁸, J. Alison¹⁸⁹, S. An¹⁸⁹, M. Cremonesi¹⁸⁹, V. Dutta¹⁸⁹, E. Y. Ertorer¹⁸⁹,
T. Ferguson¹⁸⁹, T. A. Gómez Espinosa¹⁸⁹, A. Harilal¹⁸⁹, A. Kallil Tharayil¹⁸⁹, M. Kanemura¹⁸⁹, A. Khanal¹⁸⁹,
C. Liu¹⁸⁹, M. Marchegiani¹⁸⁹, P. Meiring¹⁸⁹, S. Murthy¹⁸⁹, P. Palit¹⁸⁹, K. Park¹⁸⁹, M. Paulini¹⁸⁹, A. Roberts¹⁸⁹,
A. Sanchez¹⁸⁹, Y. Zhou¹⁸⁹, S. Malik¹⁹⁰, R. Sharma¹⁹⁰, G. Barone¹⁹¹, G. Benelli¹⁹¹, D. Cutts¹⁹¹, S. Ellis¹⁹¹,
S. Gottlieb¹⁹¹, L. Gouskos¹⁹¹, M. Hadley¹⁹¹, L. Hay¹⁹¹, U. Heintz¹⁹¹, K. W. Ho¹⁹¹, R. Jain¹⁹¹, T. Kwon¹⁹¹,
L. Lambrecht¹⁹¹, G. Landsberg¹⁹¹, K. T. Lau¹⁹¹, M. LeBlanc¹⁹¹, J. Luo¹⁹¹, S. Mondal¹⁹¹, J. Roloff¹⁹¹,
T. Russell¹⁹¹, S. Sagir^{191,jjjj}, X. Shen¹⁹¹, M. Stamenkovic¹⁹¹, S. Sunnarborg¹⁹¹, J. Tang¹⁹¹,
N. Venkatasubramanian¹⁹¹, A. Abdelhamid¹⁹², D. Ally¹⁹², A. G. Delannoy¹⁹², S. Fiorendi¹⁹², J. Harris¹⁹²,
T. Holmes¹⁹², A. R. Kanuganti¹⁹², N. Karunaratna¹⁹², J. Lawless¹⁹², L. Lee¹⁹², E. Nibigira¹⁹², B. Skipworth¹⁹²,
S. Spanier¹⁹², C. Thompson¹⁹², A. Vendasco¹⁹², U. Acharya¹⁹³, E. Appelt¹⁹³, Y. Chen¹⁹³, S. Greene¹⁹³,
A. Gurrola¹⁹³, W. Johns¹⁹³, R. Kunnawalkam Elayavalli¹⁹³, A. Melo¹⁹³, D. Rathjens¹⁹³, F. Romeo¹⁹³,
I. Shvetsov¹⁹³, S. Tuo¹⁹³, J. Velkovska¹⁹³, J. Zhang¹⁹³, D. Aebi¹⁹⁴, M. Ahmad¹⁹⁴, T. Akhter¹⁹⁴, K. Androsov¹⁹⁴,
A. Basnet¹⁹⁴, A. Bolshov¹⁹⁴, O. Bouhali^{194,kkkk}, A. Cagnotta¹⁹⁴, S. Cooperstein¹⁹⁴, V. D'Amante¹⁹⁴, R. Eusebi¹⁹⁴,
P. Flanagan¹⁹⁴, J. Gilmore¹⁹⁴, Y. Guo¹⁹⁴, T. Kamon¹⁹⁴, R. Mueller¹⁹⁴, G. Pizzati¹⁹⁴, A. Safonov¹⁹⁴, D. Acosta¹⁹⁵,
A. Agrawal¹⁹⁵, C. Arbour¹⁹⁵, T. Carnahan¹⁹⁵, K. M. Ecklund¹⁹⁵, F. J. Geurts¹⁹⁵, I. Krommydas¹⁹⁵, N. Lewis¹⁹⁵,
W. Li¹⁹⁵, J. Lin¹⁹⁵, X. Liu¹⁹⁵, C. Loizides¹⁹⁵, O. Miguel Colin¹⁹⁵, B. P. Padley¹⁹⁵, R. Redjimi¹⁹⁵, J. Rotter¹⁹⁵,
C. Vico Villalba¹⁹⁵, M. Wulansatiti¹⁹⁵, E. Yigitbasi¹⁹⁵, Y. Zhang¹⁹⁵, N. Akchurin¹⁹⁶, J. Damgov¹⁹⁶, Y. Feng¹⁹⁶,
N. Gogate¹⁹⁶, W. Jin¹⁹⁶, S. W. Lee¹⁹⁶, C. Madrid¹⁹⁶, S. Magedov¹⁹⁶, A. Mankel¹⁹⁶, T. Peltola¹⁹⁶,
I. Volobouev¹⁹⁶, S. Abdullin¹⁹⁷, A. Brinkerhoff¹⁹⁷, E. Collins¹⁹⁷, M. R. Darwish¹⁹⁷, J. Dittmann¹⁹⁷,
K. Hatakeyama¹⁹⁷, V. Hegde¹⁹⁷, J. Hiltbrand¹⁹⁷, B. McMaster¹⁹⁷, J. Samudio¹⁹⁷, S. Sawant¹⁹⁷,
C. Sutantawibul¹⁹⁷, J. Wilson¹⁹⁷, B. Cardwell¹⁹⁸, H. Chung¹⁹⁸, B. Cox¹⁹⁸, J. Hakala¹⁹⁸,
G. Hamilton Ilha Machado¹⁹⁸, R. Hirosky¹⁹⁸, M. Jose¹⁹⁸, A. Ledovskoy¹⁹⁸, C. Mantilla¹⁹⁸,
R. Menon Raghunandan¹⁹⁸, C. Neu¹⁹⁸, C. Ramón Álvarez¹⁹⁸, Z. Wu¹⁹⁸, A. Aravind¹⁹⁹, S. Banerjee¹⁹⁹,
K. Black¹⁹⁹, T. Bose¹⁹⁹, E. Chavez¹⁹⁹, R. Cruz¹⁹⁹, S. Dasu¹⁹⁹, P. Everaerts¹⁹⁹, C. Galloni¹⁹⁹, H. He¹⁹⁹,
M. Herndon¹⁹⁹, A. Herve¹⁹⁹, C. K. Koraka¹⁹⁹, S. Lomte¹⁹⁹, R. Loveless¹⁹⁹, J. Marquez¹⁹⁹, A. Mohammadi¹⁹⁹,
S. Mondal¹⁹⁹, T. Nelson¹⁹⁹, G. Parida¹⁹⁹, D. Pinna¹⁹⁹, A. Savin¹⁹⁹, V. Sharma¹⁹⁹, R. Simeon¹⁹⁹, W. H. Smith¹⁹⁹,
D. Teague¹⁹⁹, M. Thakore¹⁹⁹, A. Thete¹⁹⁹, A. Warden¹⁹⁹, L. Dudko²⁰¹, V. Kim^{201,gggg}, V. Murzin²⁰¹,
V. Oreshkin²⁰¹, D. Sosnov²⁰¹, S. Afanasiev²⁰⁰, V. Alexakhin²⁰⁰, Y. Andreev²⁰⁰, D. Budkouski²⁰⁰, R. Chistov²⁰⁰

M. Danilov²⁰⁰, T. Dimova²⁰⁰, I. Gorbunov²⁰⁰, A. Kamenev²⁰⁰, V. Karjavine²⁰⁰, O. Kodolova^{200,IIII},
 V. Korenkov²⁰⁰, I. Korsakov²⁰⁰, A. Kozyrev²⁰⁰, A. Lanev²⁰⁰, A. Malakhov²⁰⁰, V. Matveev²⁰⁰,
 A. Nikitenko^{200,mmmm,IIII}, V. Palichik²⁰⁰, V. Perelygin²⁰⁰, O. Radchenko²⁰⁰, M. Savina²⁰⁰, V. Shalaev²⁰⁰,
 S. Shmatov²⁰⁰, S. Shulha²⁰⁰, Y. Skovpen²⁰⁰, K. Slizhevskiy²⁰⁰, V. Smirnov²⁰⁰, O. Teryaev²⁰⁰, A. Toropin²⁰⁰,
 N. Voytishin²⁰⁰, A. Zarubin²⁰⁰ and I. Zhizhin²⁰⁰

(CMS Collaboration)

- ¹University of Tirana and Polytechnic University of Tirana, TIRANA, Albania
²Yerevan Physics Institute, Yerevan, Armenia
³Marietta Blau Institute for Particle Physics, Vienna, Austria
⁴Universiteit Antwerpen, Antwerpen, Belgium
⁵Vrije Universiteit Brussel, Brussel, Belgium
⁶Université Libre de Bruxelles, Bruxelles, Belgium
⁷Ghent University, Ghent, Belgium
⁸Université Catholique de Louvain, Louvain-la-Neuve, Belgium
⁹Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
¹⁰Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
¹¹Universidade Estadual Paulista (a), Universidade Federal do ABC (b), São Paulo, Brazil
¹²Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
¹³University of Sofia, Sofia, Bulgaria
¹⁴CERN, European Organization for Nuclear Research, Geneva, Switzerland
¹⁵Instituto de Alta Investigación, Universidad de Tarapacá, Arica, Chile
¹⁶Universidad Técnica Federico Santa María, Valparaíso, Chile
¹⁷Beihang University, Beijing, China
¹⁸Department of Physics, Tsinghua University, Beijing, China
¹⁹Institute of High Energy Physics, Beijing, China
²⁰State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
²¹State Key Laboratory of Nuclear Physics and Technology, Institute of Quantum Matter, South China Normal University, Guangzhou, China, Guangzhou, China
²²Sun Yat-Sen University, Guangzhou, China
²³University of Science and Technology of China, Hefei, China
²⁴Nanjing Normal University, Nanjing, China
²⁵Institute of Frontier and Interdisciplinary Science, Shandong University, Qingdao, China
²⁶Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
²⁷Zhejiang University - Department of Physics, Zhejiang, China
²⁸Universidad de Los Andes, Bogotá, Colombia
²⁹Universidad de Antioquia, Medellín, Colombia
³⁰University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
³¹University of Split, Faculty of Science, Split, Croatia
³²Institute Rudjer Boskovic, Zagreb, Croatia
³³University of Cyprus, Nicosia, Cyprus
³⁴Charles University, Prague, Czech Republic
³⁵Escuela Politécnica Nacional, Quito, Ecuador
³⁶Universidad San Francisco de Quito, Quito, Ecuador
³⁷Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
³⁸Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
³⁹National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
⁴⁰Department of Physics, University of Helsinki, Helsinki, Finland
⁴¹Helsinki Institute of Physics, Helsinki, Finland
⁴²Lappeenranta-Lahti University of Technology, Lappeenranta, Finland
⁴³IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

- ⁴⁴*Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France*
- ⁴⁵*Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS/IN2P3, Strasbourg, France*
- ⁴⁶*Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France*
- ⁴⁷*Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France*
- ⁴⁸*Georgian Technical University, Tbilisi, Georgia*
- ⁴⁹*RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*
- ⁵⁰*RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
- ⁵¹*RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*
- ⁵²*University of Hamburg, Hamburg, Germany*
- ⁵³*Deutsches Elektronen-Synchrotron, Hamburg, Germany*
- ⁵⁴*Institut für Experimentelle Teilchenphysik, Karlsruhe, Germany*
- ⁵⁵*Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece*
- ⁵⁶*National and Kapodistrian University of Athens, Athens, Greece*
- ⁵⁷*National Technical University of Athens, Athens, Greece*
- ⁵⁸*University of Ioánnina, Ioánnina, Greece*
- ⁵⁹*Department of Physics, School of Sciences Democritus, University of Thrace, Kavala, Greece*
- ⁶⁰*HUN-REN Wigner Research Centre for Physics, Budapest, Hungary*
- ⁶¹*MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary*
- ⁶²*Faculty of Informatics, University of Debrecen, Debrecen, Hungary, Debrecen, Hungary*
- ⁶³*HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary*
- ⁶⁴*Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary*
- ⁶⁵*Indian Institute of Technology Bhubaneswar, Bhubaneswar, India*
- ⁶⁶*Panjab University, Chandigarh, India*
- ⁶⁷*University of Delhi, Delhi, India*
- ⁶⁸*Indian Institute of Technology Mandi (IIT-Mandi), Himachal Pradesh, India*
- ⁶⁹*University of Hyderabad, Hyderabad, India*
- ⁷⁰*Indian Institute of Technology Kanpur, Kanpur, India*
- ⁷¹*Saha Institute of Nuclear Physics, HBNI, Kolkata, India*
- ⁷²*Indian Institute of Technology Madras, Madras, India*
- ⁷³*Indian Institute of Science Education and Research Mohali, Mohali, India*
- ⁷⁴*Tata Institute of Fundamental Research-A, Mumbai, India*
- ⁷⁵*Tata Institute of Fundamental Research-B, Mumbai, India*
- ⁷⁶*National Institute of Science Education and Research, Jatni, Khorda, Odisha 752050, India Homi Bhabha National Institute, Training School Complex, Anushakti Nagar, Mumbai 400094, India, Odisha, India*
- ⁷⁷*Indian Institute of Science Education and Research (IISER), Pune, India*
- ⁷⁸*Indian Institute of Technology Hyderabad, Telangana, India*
- ⁷⁹*Isfahan University of Technology, Isfahan, Iran*
- ⁸⁰*Institute for Research in Fundamental Sciences (IPM), Tehran, Iran*
- ⁸¹*University College Dublin, Dublin, Ireland*
- ^{82a}*INFN Sezione di Bari, Bari, Italy*
- ^{82b}*Università di Bari, Bari, Italy*
- ^{82c}*Politecnico di Bari, Bari, Italy*
- ^{83a}*INFN Sezione di Bologna, Bologna, Italy*
- ^{83b}*Università di Bologna, Bologna, Italy*
- ^{84a}*INFN Sezione di Catania, Catania, Italy*
- ^{84b}*Università di Catania, Catania, Italy*
- ^{85a}*INFN Sezione di Firenze, Firenze, Italy*
- ^{85b}*Università di Firenze, Firenze, Italy*
- ⁸⁶*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
- ^{87a}*INFN Sezione di Genova, Genova, Italy*
- ^{87b}*Università di Genova, Genova, Italy*
- ^{88a}*INFN Sezione di Milano-Bicocca, Milano-Bicocca, Italy*

- ^{88b} *Università di Milano-Bicocca , Milano, Milano-Bicocca, Italy*
^{89a} *INFN Sezione di Napoli, Napoli, Italy*
^{89b} *Università di Napoli 'Federico II' , Napoli, Italy*
^{89c} *Università della Basilicata (Potenza) , Napoli, Italy*
^{89d} *Scuola Superiore Meridionale (SSM), Napoli, Italy*
^{90a} *INFN Sezione di Padova, Padova, Italy*
^{90b} *Università di Padova , Padova, Italy*
^{90c} *Università degli Studi di Cagliari , Padova, Italy*
^{91a} *INFN Sezione di Pavia, Pavia, Italy*
^{91b} *Università di Pavia , Pavia, Italy*
^{92a} *INFN Sezione di Perugia, Perugia, Italy*
^{92b} *Università di Perugia , Perugia, Italy*
^{93a} *INFN Sezione di Pisa, Pisa, Italy*
^{93b} *Università di Pisa , Pisa, Italy*
^{93c} *Scuola Normale Superiore di Pisa, Pisa, Italy*
^{93d} *Università di Siena , Pisa, Italy*
^{94a} *INFN Sezione di Roma, Roma, Italy*
^{94b} *Sapienza Università di Roma , Roma, Italy*
^{95a} *INFN Sezione di Torino, Torino, Italy*
^{95b} *Università di Torino , Torino, Italy*
^{95c} *Università del Piemonte Orientale (Novara) , Torino, Italy*
^{96a} *INFN Sezione di Trieste, Trieste, Italy*
^{96b} *Università di Trieste , Trieste, Italy*
⁹⁷ *Kyungpook National University, Daegu, Korea*
⁹⁸ *Department of Mathematics and Physics - Gangneung-Wonju National University, Gangneung, Korea*
⁹⁹ *Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea*
¹⁰⁰ *Department of Physics, Chung-Ang University, Seoul, Korea*
¹⁰¹ *Hanyang University, Seoul, Korea*
¹⁰² *Korea University, Seoul, Korea*
¹⁰³ *Kyung Hee University, Department of Physics, Seoul, Korea*
¹⁰⁴ *Sejong University, Seoul, Korea*
¹⁰⁵ *Seoul National University, Seoul, Korea*
¹⁰⁶ *University of Seoul, Seoul, Korea*
¹⁰⁷ *Yonsei University, Department of Physics, Seoul, Korea*
¹⁰⁸ *Sungkyunkwan University, Suwon, Korea*
¹⁰⁹ *College of Engineering and Technology, American University of the Middle East (AUM),
Dasman, Kuwait*
¹¹⁰ *Kuwait University - College of Science - Department of Physics, Safat, Kuwait*
¹¹¹ *Riga Technical University, Riga, Latvia*
¹¹² *University of Latvia (LU), Riga, Latvia*
¹¹³ *Vilnius University, Vilnius, Lithuania*
¹¹⁴ *National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia*
¹¹⁵ *University of Sonora (UNISON), Hermosillo, Mexico*
¹¹⁶ *Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico*
¹¹⁷ *Universidad Iberoamericana, Mexico City, Mexico*
¹¹⁸ *Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*
¹¹⁹ *University of Montenegro, Podgorica, Montenegro*
¹²⁰ *National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*
¹²¹ *AGH University of Krakow, Krakow, Poland*
¹²² *National Centre for Nuclear Research, Swierk, Poland*
¹²³ *Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*
¹²⁴ *Warsaw University of Technology, Warsaw, Poland*
¹²⁵ *Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal*
¹²⁶ *Faculty of Physics, University of Belgrade, Belgrade, Serbia*
¹²⁷ *Vinca Institute of Nuclear Science, Belgrade, Serbia*
¹²⁸ *Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*
¹²⁹ *Universidad Autónoma de Madrid, Madrid, Spain*

- ¹³⁰*Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain*
- ¹³¹*Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain*
- ¹³²*University of Colombo, Colombo, Sri Lanka*
- ¹³³*University of Ruhuna, Department of Physics, Matara, Sri Lanka*
- ¹³⁴*PSI Center for Neutron and Muon Sciences, Villigen, Switzerland*
- ¹³⁵*ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland*
- ¹³⁶*Universität Zürich, Zurich, Switzerland*
- ¹³⁷*National Central University, Chung-Li, Taiwan*
- ¹³⁸*National Taiwan University (NTU), Taipei, Taiwan*
- ¹³⁹*High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand*
- ¹⁴⁰*Tunis El Manar University, Tunis, Tunisia*
- ¹⁴¹*Çukurova University, Adana, Türkiye*
- ¹⁴²*Hacettepe University, Ankara, Türkiye*
- ¹⁴³*Bogazici University, Istanbul, Türkiye*
- ¹⁴⁴*Istanbul Technical University, Istanbul, Türkiye*
- ¹⁴⁵*Istanbul University, Istanbul, Türkiye*
- ¹⁴⁶*Yildiz Technical University, Istanbul, Türkiye*
- ¹⁴⁷*Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine*
- ¹⁴⁸*National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine*
- ¹⁴⁹*University of Bristol, Bristol, United Kingdom*
- ¹⁵⁰*Rutherford Appleton Laboratory, Didcot, United Kingdom*
- ¹⁵¹*Imperial College, London, United Kingdom*
- ¹⁵²*Brunel University, Uxbridge, United Kingdom*
- ¹⁵³*The University of Alabama, Tuscaloosa, Alabama, USA*
- ¹⁵⁴*University of California, Davis, Davis, California, USA*
- ¹⁵⁵*University of California, San Diego, La Jolla, California, USA*
- ¹⁵⁶*University of California, Los Angeles, California, USA*
- ¹⁵⁷*California Institute of Technology, Pasadena, California, USA*
- ¹⁵⁸*University of California, Riverside, Riverside, California, USA*
- ¹⁵⁹*University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA*
- ¹⁶⁰*University of Colorado Boulder, Boulder, Colorado, USA*
- ¹⁶¹*The Catholic University of America, Washington, DC, USA*
- ¹⁶²*University of Florida, Gainesville, Florida, USA*
- ¹⁶³*Florida Institute of Technology, Melbourne, Florida, USA*
- ¹⁶⁴*Florida State University, Tallahassee, Florida, USA*
- ¹⁶⁵*Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
- ¹⁶⁶*University of Illinois Chicago, Chicago, Illinois, USA*
- ¹⁶⁷*Northwestern University, Evanston, Illinois, USA*
- ¹⁶⁸*Purdue University Northwest, Hammond, Indiana, USA*
- ¹⁶⁹*University of Notre Dame, Notre Dame, Indiana, USA*
- ¹⁷⁰*Purdue University, West Lafayette, Indiana, USA*
- ¹⁷¹*The University of Iowa, Iowa City, Iowa, USA*
- ¹⁷²*The University of Kansas, Lawrence, Kansas, USA*
- ¹⁷³*Kansas State University, Manhattan, Kansas, USA*
- ¹⁷⁴*Johns Hopkins University, Baltimore, Maryland, USA*
- ¹⁷⁵*University of Maryland, College Park, Maryland, USA*
- ¹⁷⁶*Boston University, Boston, Massachusetts, USA*
- ¹⁷⁷*Northeastern University, Boston, Massachusetts, USA*
- ¹⁷⁸*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
- ¹⁷⁹*Wayne State University, Detroit, Michigan, USA*
- ¹⁸⁰*University of Minnesota, Minneapolis, Minnesota, USA*
- ¹⁸¹*Bethel University, St. Paul, Minnesota, USA*
- ¹⁸²*University of Nebraska-Lincoln, Lincoln, Nebraska, USA*
- ¹⁸³*Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA*
- ¹⁸⁴*Princeton University, Princeton, New Jersey, USA*

¹⁸⁵*State University of New York at Buffalo, Buffalo, New York, USA*¹⁸⁶*Cornell University, Ithaca, New York, USA*¹⁸⁷*University of Rochester, Rochester, New York, USA*¹⁸⁸*The Ohio State University, Columbus, Ohio, USA*¹⁸⁹*Carnegie Mellon University, Pittsburgh, Pennsylvania, USA*¹⁹⁰*University of Puerto Rico, Mayaguez, Puerto Rico, USA*¹⁹¹*Brown University, Providence, Rhode Island, USA*¹⁹²*University of Tennessee, Knoxville, Tennessee, USA*¹⁹³*Vanderbilt University, Nashville, Tennessee, USA*¹⁹⁴*Texas A&M University, College Station, Texas, USA*¹⁹⁵*Rice University, Houston, Texas, USA*¹⁹⁶*Texas Tech University, Lubbock, Texas, USA*¹⁹⁷*Baylor University, Waco, Texas, USA*¹⁹⁸*University of Virginia, Charlottesville, Virginia, USA*¹⁹⁹*University of Wisconsin - Madison, Madison, Wisconsin, USA*²⁰⁰*An institute or international laboratory covered by a cooperation agreement with CERN*²⁰¹*An institute formerly covered by a cooperation agreement with CERN*^aAlso at Yerevan State University, Yerevan, Armenia.^bAlso at Technische Universität Wien, Vienna, Austria.^cAlso at Ghent University, Ghent, Belgium.^dAlso at FACAMP—Faculdades de Campinas, Sao Paulo, Brazil.^eAlso at Universidade Estadual de Campinas, Campinas, Brazil.^fAlso at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.^gAlso at The University of the State of Amazonas, Manaus, Brazil.^hAlso at Brandenburg University of Technology, Cottbus, Germany.ⁱAlso at National and Kapodistrian University of Athens, Athens, Greece.^jAlso at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland.^kAlso at University of Chinese Academy of Sciences, Beijing, China.^lAlso at University of Chinese Academy of Sciences, Beijing, China.^mAlso at School of Physics, Zhengzhou University, Zhengzhou, China.ⁿAlso at Henan Normal University, Xinxiang, China.^oAlso at University of Shanghai for Science and Technology, Shanghai, China.^pAlso at The University of Iowa, Iowa City, Iowa, USA.^qAlso at Nanjing Normal University, Nanjing, China.^rAlso at Center for High Energy Physics, Peking University, Beijing, China, Beijing, China.^sAlso at Helwan University, Cairo, Egypt.^tAlso at Zewail City of Science and Technology, Zewail, Egypt.^uAlso at British University in Egypt, Cairo, Egypt.^vAlso at Cairo University, Cairo, Egypt.^wAlso at Université de Haute Alsace, Mulhouse, France.^xAlso at Purdue University, West Lafayette, Indiana, USA.^yAlso at Another institute or international laboratory covered by a cooperation agreement with CERN.^zAlso at University of Hamburg, Hamburg, Germany.^{aa}Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.^{bb}Also at Bergische University Wuppertal (BUW), Wuppertal, Germany.^{cc}Also at Institute for Advanced Simulation—Jülich Supercomputing Centre, Jülich, Germany.^{dd}Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.^{ee}Also at HUN-REN ATOMKI—Institute of Nuclear Research, Debrecen, Hungary.^{ff}Also at Universitatea Babes-Bolyai—Facultatea de Fizica, Cluj-Napoca, Romania.^{gg}Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.^{hh}Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary.ⁱⁱAlso at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt.^{jj}Also at The University of Kansas, Lawrence, Kansas, USA.^{kk}Also at Punjab Agricultural University, Ludhiana, India.^{ll}Also at University of Hyderabad, Hyderabad, India.^{mm}Also at Indian Institute of Science (IISc), Bangalore, India.

- ⁿⁿAlso at University of Visva-Bharati, Santiniketan, India.
- ^{oo}Also at Institute of Physics, Bhubaneswar, India.
- ^{pp}Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
- ^{qq}Also at Isfahan University of Technology, Isfahan, Iran.
- ^{rr}Also at Sharif University of Technology, Tehran, Iran.
- ^{ss}Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.
- ^{tt}Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran.
- ^{uu}Also at Kocaeli University, Kocaeli, Türkiye.
- ^{vv}Also at Centro Siciliano di Fisica Nucleare e di Struttura della Materia, Catania, Italy.
- ^{ww}Also at James Madison University, Harrisonburg, Virginia, USA.
- ^{xx}Also at Università degli Studi Guglielmo Marconi, Roma, Italy.
- ^{yy}Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy.
- ^{zz}Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA.
- ^{aaa}Also at Lulea University of Technology, Lulea, Sweden.
- ^{bbb}Also at Ain Shams University, Cairo, Egypt.
- ^{ccc}Also at Consiglio Nazionale delle Ricerche—Istituto Officina dei Materiali, Perugia, Italy.
- ^{ddd}Also at Boston University, Boston, Massachusetts, USA.
- ^{eee}Also at UPES—University of Petroleum and Energy Studies, Dehradun, India.
- ^{fff}Also at Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France.
- ^{ggg}Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia.
- ^{hhh}Also at Georgian Technical University, Tbilisi, Georgia.
- ⁱⁱⁱAlso at Departamento de Física Instituto Superior Técnico Universidade de Lisboa, Lisbon, Portugal.
- ^{jjj}Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.
- ^{kkk}Also at Saegis Campus, Nugegoda, Sri Lanka.
- ^{lll}Also at Universität Zürich, Zurich, Switzerland.
- ^{mmm}Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria.
- ⁿⁿⁿAlso at Near East University, Research Center of Experimental Health Science, Mersin, Türkiye.
- ^{ooo}Also at Konya Technical University, Konya, Türkiye.
- ^{ppp}Also at Izmir Bakircay University Faculty of Engineering and Architecture, Izmir, Türkiye.
- ^{qqq}Also at Adiyaman University, Adiyaman, Türkiye.
- ^{rrr}Also at Istanbul Sabahattin Zaim University, Istanbul, Türkiye.
- ^{sss}Also at Marmara University, Istanbul, Türkiye.
- ^{ttt}Also at Milli Savunma University, Naval Academy, Istanbul, Türkiye.
- ^{uuu}Also at The Science and Technological research Council of Türkiye, Informatics and Information Security Research Center, Gebze/Kocaeli, Türkiye.
- ^{vvv}Also at Kafkas University, Kars, Türkiye.
- ^{www}Also at Istanbul Okan University, Istanbul, Türkiye.
- ^{xxx}Also at Istanbul University—Cerrahpasa, Faculty of Engineering, Istanbul, Türkiye.
- ^{yyy}Also at Istinye University, Istanbul, Türkiye.
- ^{zzz}Also at Mimar Sinan University, Istanbul, Istanbul, Türkiye.
- ^{aaaa}Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- ^{bbbb}Also at Monash University, Faculty of Science, Clayton, Australia.
- ^{cccc}Also at Università di Torino, Torino, Italy.
- ^{dddd}Also at California Lutheran University, Thousand Oaks, California, USA.
- ^{eeee}Also at California Institute of Technology, Pasadena, California, USA.
- ^{fff}Also at United States Naval Academy—Physics Department, Annapolis, Maryland, USA.
- ^{gggg}Also at Another institute formerly covered by a cooperation agreement with CERN.
- ^{hhhh}Also at Bingol University, Bingol, Türkiye.
- ⁱⁱⁱⁱAlso at Sinop University, Sinop, Türkiye.
- ^{jjjj}Also at Karamanoğlu Mehmetbey University, Karaman, Türkiye.
- ^{kkkk}Also at Hamad Bin Khalifa University (HBKU), Doha, Qatar.
- ^{llll}Also at Yerevan Physics Institute, Yerevan, Armenia.
- ^{mmmm}Also at Imperial College, London, United Kingdom.