Search for Charged Higgs Bosons Produced via Vector Boson Fusion and Decaying into a Pair of W and Z Bosons Using pp Collisions at $\sqrt{s} = 13$ TeV

A. M. Sirunyan *et al.*[*]
(CMS Collaboration)

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A search for charged Higgs bosons produced via vector boson fusion and decaying into W and Z bosons using proton-proton collisions at $\sqrt{s} = 13$ TeV is presented. The data sample corresponds to an integrated luminosity of 15.2 fb^{-1} collected with the CMS detector in 2015 and 2016. The event selection requires three leptons (electrons or muons), two jets with large pseudorapidity separation and high dijet mass, and missing transverse momentum. The observation agrees with the standard model prediction. Limits on the vector boson fusion production cross section times branching fraction for new charged physical states are reported as a function of mass from 200 to 2000 GeV and interpreted in the context of Higgs triplet models.

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The discovery [1,2] of a Higgs boson [3–8] at the CERN LHC marks an important milestone in the exploration of the electroweak (EW) sector of the standard model (SM) [9–11]. Many aspects of EW interactions at the energy scale of 1 TeV, however, remain to be explored. At the LHC, the study of vector boson scattering (VBS) may reveal hints to extensions of the SM. In particular, extended Higgs sectors with additional SU(2) doublets [12–15] or triplets [16–23] introduce couplings of vector bosons to heavy neutral or charged Higgs bosons.

Searches for charged Higgs bosons ($H^{\pm}$) at the LHC currently focus on the production and the decay via couplings to fermions [24–32], well motivated by the minimal supersymmetric standard model [33]. In this model, the $H^{\pm}tb$ coupling is the dominant one irrespective of the mass of the charged Higgs boson [$m(H^{\pm})$] and $\tan\beta$, the ratio of the vacuum expectation values of the two Higgs doublets. Couplings to vector bosons are, however, largely suppressed in these models.

Higgs sectors extended by SU(2) triplets, however, give rise to charged Higgs bosons with couplings to W and Z bosons at the tree level. Higgs triplets appear in left-right symmetric [34–36], little Higgs [37–39], and supersymmetric models [40,41] and can generate neutrino masses via the seesaw mechanism [17–19,42,43]. A particularly prominent model is the Georgi-Machacek (GM) model [44], where two SU(2) triplets (one real and one complex) are added to the SM Higgs sector and preserve custodial symmetry for large vacuum expectation values of the SU(2) triplets. In such models, the charged Higgs bosons are produced via vector boson fusion (VBF), and the couplings depend on $m(H^{\pm})$ and the parameter $\sin\theta_{\mathrm{H}}$, or s_{H}, where s_{H}^2 denotes the fraction of the W boson mass squared generated by the vacuum expectation value of the triplets. A representative Feynman diagram for the production by and decay into a W and Z boson pair is shown in Fig. 1.

In this Letter, we discuss the search for charged Higgs bosons that are produced via VBF and decay via couplings to W and Z bosons. The analysis is performed on a sample of proton-proton collisions collected at $\sqrt{s} = 13$ TeV center-of-mass energy by the CMS experiment at the LHC. The data sample corresponds to integrated luminosities of 2.3 and 12.9 fb^{-1} recorded during the years 2015 and 2016, respectively. The search is performed using W and Z bosons decaying into electrons and muons. The event selection requires two jets with large pseudorapidity separation and a high dijet mass to select a VBF topology. The data are compared to the predictions of the GM model for a charged Higgs boson mass range of $200 < m(H^{\pm}) < 1000$ GeV. In addition, an exclusion limit on the VBF production cross section times branching

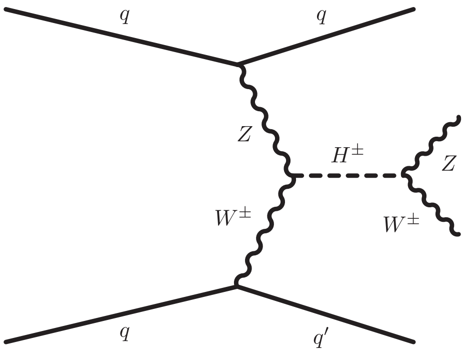

FIG. 1. Example of a Feynman diagram showing the production of charged Higgs bosons via VBF.

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[*] Full author list given at the end of the article.

fraction ($\mathcal{B}$) for $200 < m(H^{\pm}) < 2000$ GeV is derived. A similar search was performed by the ATLAS Collaboration in proton-proton collisions at $\sqrt{s} = 8$ TeV in the semileptonic ($WZ \rightarrow qq'\ell\ell$) final state [45]. Other experimental constraints on the GM model can be obtained from studies of b-meson decays [46] and $W^{\pm}W^{\pm}$ VBS processes [47,48].

The signal samples are produced with MadGraph5_aMC@NLO [49]. WZ production in association with two jets involving exclusively electroweak interactions at the tree level is generated at leading order (LO) using MadGraph5_aMC@NLO and is referred to as an EW WZ background. Two-jet-associated WZ production with both the strong and electroweak interaction vertices at the tree level is simulated at next-to-leading order (NLO) using POWHEG 2.0 [50–53] and is denoted as a QCD WZ background. The $Z+$jets, $Z\gamma$, tZq, $t\bar{t}V$, and VVV backgrounds, where V refers to a W or Z boson, are produced at NLO using MadGraph5_aMC@NLO. Simulated tZq and $t\bar{t}V$ events are included in the background referred to as VVV. The $gg \rightarrow ZZ$ sample is generated at LO with MCFM [54] and normalized to NLO with a K factor of 1.7 [55]. The ZZ production via $q\bar{q}$ annihilation is simulated at NLO with POWHEG and normalized to the next-to-next-to-leading order (NNLO) cross-section prediction with a K factor of 1.1 [56]. The PYTHIA 8 [57] package is used for parton showering, hadronization, and the underlying event simulation with parameters affecting the underlying event simulation set to the CUETP8M1 tune [58,59]. The NNPDF 3.0 [60] set is used as the default set of parton distribution functions (PDFs). For all processes, the detector response is simulated using a detailed description of the CMS detector, based on the Geant4 package [61], and event reconstruction is performed with the same algorithms as used for the data. The simulated samples include additional interactions per bunch crossing (pileup) matching the observed multiplicity in the data of about 11 and 20 interactions per bunch crossing in 2015 and 2016, respectively.

Details of the CMS detector, its performance, and the definition of the coordinate system can be found in Ref. [62]. The detector features a superconducting solenoid with a diameter of 6 m, providing a magnetic field of 3.8 T, and surrounding a silicon pixel and strip tracking detector, a lead tungstate electromagnetic calorimeter, and a brass scintillator hadronic calorimeter. Gas ionization detectors embedded into the steel-flux return yokes, the muon system, are installed around the solenoid. The subdetectors are composed into a barrel and two end cap sections. The hadron forward calorimeter provides calorimetry to pseudorapidities from $|\eta| > 3$ to $|\eta| < 5$. A particle-flow technique [63,64] is employed to identify and reconstruct the individual particles emerging from each collision.

Electrons are reconstructed within $|\eta| < 2.5$. The reconstruction combines the information from clusters of energy deposits in the electromagnetic calorimeter and the trajectory in the tracker [65]. The selection criteria depend on transverse momentum p_T and $|\eta|$ and on a categorization based on observables sensitive to the amount of bremsstrahlung emitted. Muons are reconstructed within $|\eta| < 2.4$ [66]. The reconstruction combines the information from both the tracker and the muon spectrometer. Leptons are required to be isolated from other charged and neutral particles in the event. The lepton relative isolation is defined as the ratio of the p_T sum of charged hadrons and neutral particles within a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$ (where ϕ is the azimuthal angle in radians) around the lepton and the lepton p_T. The relative isolation, corrected for pileup contributions, is required to be less than 6.5% (15%) for electrons (muons). Overall efficiencies of the reconstruction, identification, and isolation requirements for the prompt leptons are measured in the data in several bins of p_T and $|\eta|$ using a "tag-and-probe" technique [67] applied to a sample of leptonically decaying Z boson events.

Jets are reconstructed using the anti-k_T clustering algorithm [68] with a distance parameter $R = 0.4$, as implemented in the FastJet package [69,70], and jet energy corrections are applied [71,72]. To suppress the top-quark background contribution in its decay to b quarks, the combined secondary vertex b -tagging algorithm [73,74] requirement is used, corresponding to an efficiency of about 45% with a light flavor quark misidentification probability of 0.1%.

The missing transverse momentum vector $\vec{p}_T^{\rm miss}$ is defined as the negative vectorial sum of the momenta of all reconstructed particles in an event projected onto the plane perpendicular to the beams, corrected for the pileup contribution [75]. Its magnitude is referred to as $p_T^{\rm miss}$.

Events are selected by the trigger system requiring the presence of one or two high p_T electrons or muons. The trigger efficiency is greater than 99% for events that pass all other selection criteria explained in the following. The selection of events aims to single out three-lepton events with the VBF topology. The event selection requires three lepton (electron or muon) candidates that meet the isolation and identification requirements. Two leptons are required to have $p_T > 20$ GeV, and the third lepton is required to have $p_T > 10$ GeV. Events with an additional fourth lepton with $p_T > 10$ GeV are rejected. Events are required to have at least two jets with $p_T > 30$ GeV, and $|\eta| < 4.7$. The VBF topology is exploited by requiring that the two jets of highest p_T have a large dijet mass, $m_{jj} > 500$ GeV, and a large pseudorapidity separation, $|\Delta\eta_{jj}| > 2.5$. To reconstruct a Z boson candidate, a pair of same-flavor and opposite-charge leptons is required to have a dilepton invariant mass within 15 GeV of the nominal Z boson mass [76]. When there are two or more candidate pairs, the one with the mass closest to the nominal Z boson mass is chosen. The remaining lepton is associated with the W

boson decay, and it is required to have $p_T > 20$ GeV. The p_T^{miss} in the event is required to be larger than 30 GeV to select W boson decays. To reject the top-quark background, the event must not have jets passing the b-tagging selection. After these requirements, the signal efficiency is about 10%–15%, depending on $m(H^{\pm})$. For extraction of the signal, the shape of the distribution of the transverse mass variable (m_T) obtained from the WZ system is used:

$$m_T(WZ) = \sqrt{[E_T(W) + E_T(Z)]^2 - [\vec{p}_T(W) + \vec{p}_T(Z)]^2}, \quad (1)$$

where $\vec{p}_T(W)$ is reconstructed from the vectorial sum of $\vec{p}_T^{\text{miss}}$ and the lepton $\vec{p}_T$ and $E_T(W)$ is calculated from the scalar sum of the lepton transverse energy and p_T^{miss}. Variables such as the invariant mass of the leptonically decaying WZ system using constraints on the neutrino momentum from the W boson mass [77] may be explored in future analyses.

A combination of methods using control samples in the data and detailed simulation studies is used to estimate background contributions. The following background categories are considered: WZ, $ZZ \to 4\ell$, VVV, $Z\gamma$, and processes with nonprompt leptons.

The QCD and EW WZ background constitutes about 80% of the total expected SM background yield. The normalization of the QCD WZ background is obtained from a background-dominated sideband, outside of the search region and defined by the dijet variables, where the expected signal yield is negligible: $100 \text{ GeV} < m_{jj} < 500 \text{ GeV}$ and $|\Delta\eta_{jj}| < 2.5$. In this phase-space region, expected background contributions from EW WZ, $ZZ \to 4\ell$, VVV, $Z\gamma$ production, and nonprompt leptons are estimated to contribute about 40% to the yield and are subtracted from the overall 266 events observed in data. The simulated sample of QCD WZ processes is then normalized to match the observed number of events in this control region. The estimated normalization of events is consistent with the SM prediction obtained using the POWHEG NLO cross-section calculation. The EW WZ background contributes about 30% to the overall WZ background processes in the signal region.

The $ZZ \to 4\ell$, VVV, and $Z\gamma$ contributions are estimated from simulated samples, with corrections to the lepton reconstruction, trigger and selection efficiencies, and momentum scale and resolution, estimated from data control samples. The overall expected contribution from these processes to the total background yield is about 10%, and the uncertainties in the estimates are dominated by the statistical component introduced by the number of simulated events passing the event selection requirements. The $ZZ \to 4\ell$ background is largely reduced by the p_T^{miss} requirement and the veto on events containing an additional lepton.

The main contributions to nonprompt leptons are from $Z +$ jets and top-quark ($t\bar{t}$ and tW) events, where at least one of the jets or a jet constituent is misidentified as an isolated lepton. The dominant background at the final-selection level is $Z +$ jets. According to the simulation, fewer than 10% of the background events with at least one nonprompt lepton come from top-quark processes. Data control samples are used to estimate this background. Lepton candidates selected with loose identification requirements are defined in a sample of events dominated by dijet production. The efficiency for candidates to pass the full lepton selection criteria is measured and is parametrized as a function of p_T and η. The calculated efficiencies are used as weights to extrapolate the yield of the sample of loose leptons to the sample of fully selected leptons. The background estimation method is validated on a nonprompt lepton $W +$ jets and $t\bar{t}$ enriched sample, selected by inverting the Z boson mass or b-tagging criteria, where good agreement between the data and prediction is observed.

Uncertainties in the data-to-simulation scale factors applied to leptons in simulated samples result in an overall 4% normalization uncertainty for backgrounds estimated from the simulation. The experimental uncertainties in the lepton momentum scale and resolution, p_T^{miss} modeling, and jet energy scale are applied in simulated events by smearing and scaling the relevant observables and propagating the effects to the kinematic variables used in the analysis, in particular, m_T. Uncertainties in the lepton momentum scale and resolution are smaller than 1% per lepton depending on the p_T and η of the lepton, and the effect on the yields at the analysis selection level is less than 1%. The uncertainties in the jet energy scale and resolution result in a 5% uncertainty in the signal yields. The uncertainty in the resolution of the p_T^{miss} measurement is 10%. Randomly smearing the measured p_T^{miss} by one standard deviation of the resolution gives rise to a 5% variation in the estimation of signal yields after the full selection. Uncertainties of 2.3% and 2.5% are assigned to the integrated luminosity measurements in the years 2015 and 2016, respectively [78,79]. The effect of higher-order corrections to the signal cross section in the GM model is taken from Ref. [80]. The theoretical uncertainty is dominated by missing higher-order EW corrections estimated to be 7%. Uncertainties in the signal acceptance due to PDF choice and renormalization and factorization scales are 2%–3% and less than 1%, respectively, estimated using the LO signal samples. Added in quadrature, the contributions result in an 8% uncertainty in the normalization of the signal samples.

The uncertainty in the estimation of the expected number of QCD WZ events is 12%, which is estimated from the measured yields in the two-jet control region. An uncorrelated uncertainty of 30% is assigned on the normalization of WZ events produced via EW processes, estimated from

TABLE I. Relative systematic uncertainties in the estimated signal and background yields, in units of percent.

Source	Signal	WZ	VVV	$Z\gamma$	ZZ	Nonprompt
Integrated luminosity 2015 (2016)	2.3 (2.5)	...	2.3 (2.5)	2.3 (2.5)	2.3 (2.5)	...
Lepton efficiency	4.0	...	4.0	4.0	4.0	...
Lepton momentum scale	1.0	1.0	1.0	1.0	1.0	...
Jet momentum scale	5.0	10.0	6.0	30.0	13.0	...
p_T^{miss} resolution	5.0	1.7	1.0	...	7.0	...
b tagging	2.0	...	2.0	2.0	2.0	...
QCD (EW) WZ bkg. normalization	...	12 (30)	...	...	...	...
Nonprompt bkg. normalization	...	...	...	...	...	30–80
GM uncertainties	8	...	...	...	...	...

the largest bin-by-bin differences after varying the renormalization and factorization scales. The total uncertainty in the prediction of the nonprompt background varies bin by bin in the m_T distribution between 30% and 80%, dominated by the low number of nonprompt leptons passing the sideband selection. A summary of the relative systematic uncertainties in the estimated signal and background yields is shown in Table I.

After applying the full selection, nine and 62 events are selected in the data collected in 2015 and 2016, respectively. The data yield together with the SM expectation for the different processes is given in Table II. The distribution of the m_T with bin boundaries given by $m_T = [0, 100, 200, 400, 600, 800, 1000, 1200, 1500, \infty)$ GeV (the last bin is an overflow bin) is shown in Fig. 2. No event with $m_T(WZ) > 800$ GeV is observed in the data, and overall agreement between the data and SM background prediction is observed.

A combined fit of the predicted signal and background yields in bins of m_T to the data is performed to derive expected and observed exclusion limits on $\sigma_{\text{VBF}}(H^\pm)\mathcal{B}(H^\pm \to WZ)$ at 95% confidence level using the CL$_s$ method [81–83]. The exclusion limits as a function of $m(H^\pm)$, assuming a small intrinsic width for $H^\pm$, are shown in Fig. 3 (left). Values for $\sigma_{\text{VBF}}(H^\pm)\mathcal{B}(H^\pm \to WZ)$ ranging from 573 fb at $m(H^\pm) = 200$ GeV to 36 fb at $m(H^\pm) = 2000$ GeV are excluded by the data.

TABLE II. Yields of selected events in 2015 and 2016 data, together with the expected yields from various background processes. The statistical and systematic uncertainties are shown. The signal yields are shown for values of $s_H = 0.7$.

Data set	2015	2016
Data	9	62
WZ	7.5 ± 1.2	44.4 ± 5.7
ZZ	0.2 ± 0.1	1.6 ± 0.2
VVV	0.8 ± 0.2	5.5 ± 0.9
$Z\gamma$	0.2 ± 0.1	1.0 ± 0.6
Nonprompt	1.3 ± 1.0	7.4 ± 5.4
Total bkg.	10.0 ± 1.6	59.9 ± 8.0
Signal $[m(H^\pm) = 700$ GeV$]$	0.9 ± 0.1	4.7 ± 0.5

The model-independent exclusion limits are compared to the predicted cross sections at NNLO in the GM model [80] in the $s_{\text{H}} - m(H^\pm)$ plane. For the probed parameter space and m_T distribution used for signal extraction, the varying width as a function of s_{H} is assumed to have negligible impact on the result. The value of the branching fraction

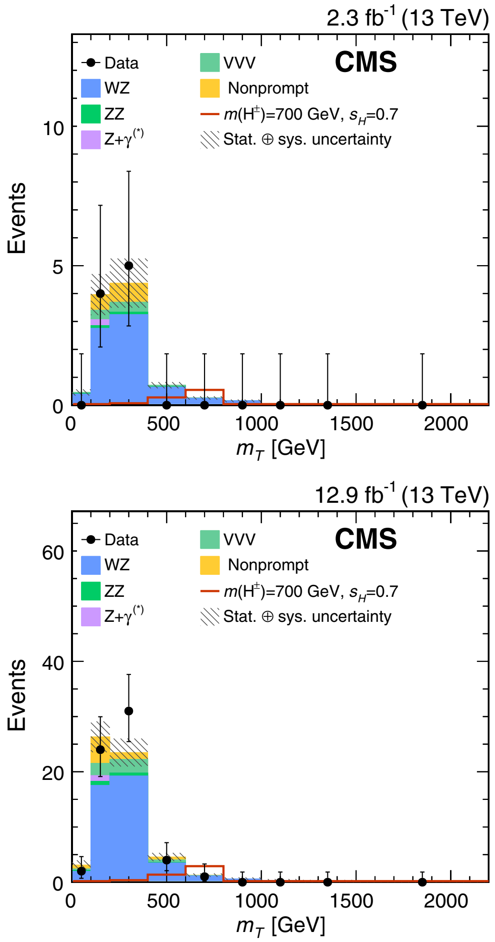

FIG. 2. Transverse mass distributions after full selection, for data collected in 2015 (left) and 2016 (right). The background yield predictions correspond to the background-only hypothesis fit result. The signal distribution is shown for $m(H^\pm) = 700$ GeV and the cross-section prediction in the GM model at $s_H = 0.7$.

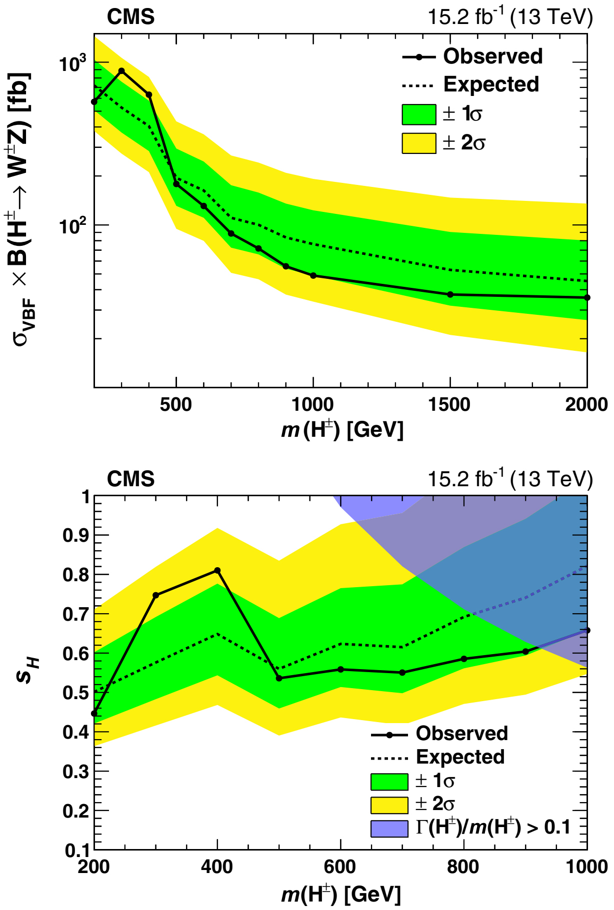

FIG. 3. Expected and observed exclusion limits at 95% confidence level as a function of $m(H^{\pm})$ for $\sigma_{\mathrm{VBF}}(H^{\pm})\mathcal{B}(H^{\pm} \to WZ)$ (left) and on the ratio of vacuum expectation values in the GM model (right) for 15.2 fb^{-1} of proton-proton collisions at 13 TeV collected in 2015 and 2016. The blue shaded area covers the theoretically not allowed parameter space [80].

$\mathcal{B}(H^{\pm} \to WZ)$ is assumed to be one. In Fig. 3 (right), the excluded s_{H} values as a function of $m(H^{\pm})$ are shown. The blue shaded region shows the parameter space for which the $H^{\pm}$ total width exceeds 10% of $m(H^{\pm})$, where the model is not applicable due to perturbativity and vacuum stability requirements [80]. The observed limit excludes s_{H} values greater than 0.45, 0.81, and 0.66 at $m(H^{\pm}) = 200$, 400, and 1000 GeV, respectively.

In summary, we present a search for charged Higgs bosons produced via vector boson fusion and decaying into W and Z bosons in proton-proton collisions at $\sqrt{s} = 13$ TeV based on a sample corresponding to an integrated luminosity of 15.2 fb^{-1}. Events are required to have three leptons (electrons or muons), two jets with large pseudorapidity separation and high dijet mass, and missing transverse momentum. The number of events observed in the signal region agrees with the standard model prediction. The first limits on $\sigma_{\mathrm{VBF}}(H^{\pm})\mathcal{B}(H^{\pm} \to WZ)$ at $\sqrt{s} = 13$ TeV are obtained. The results are interpreted in the Georgi-Machacek model for which the most stringent limits to date are derived.

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Smith,[127] V. J. Smith,[127] K. W. Bell,[128] A. Belyaev,[128,mmm] C. Brew,[128] R. M. Brown,[128] L. Calligaris,[128] D. Cieri,[128] D. J. A. Cockerill,[128] J. A. Coughlan,[128] K. Harder,[128] S. Harper,[128] E. Olaiya,[128] D. Petyt,[128] C. H. Shepherd-Themistocleous,[128] A. Thea,[128] I. R. Tomalin,[128] T. Williams,[128] M. Baber,[129] R. Bainbridge,[129] O. Buchmuller,[129] A. Bundock,[129] S. Casasso,[129] M. Citron,[129] D. Colling,[129] L. Corpe,[129] P. Dauncey,[129] G. Davies,[129] A. De Wit,[129] M. Della Negra,[129] R. Di Maria,[129] P. Dunne,[129] A. Elwood,[129] D. Futyan,[129] Y. Haddad,[129] G. Hall,[129] G. Iles,[129] T. James,[129] R. Lane,[129] C. Laner,[129] L. Lyons,[129] A.-M. Magnan,[129] S. Malik,[129] L. Mastrolorenzo,[129] J. Nash,[129] A. Nikitenko,[129,ww] J. Pela,[129] B. Penning,[129] M. Pesaresi,[129] D. M. Raymond,[129] A. Richards,[129] A. Rose,[129] E. Scott,[129] C. Seez,[129] S. Summers,[129] A. Tapper,[129] K. Uchida,[129] M. Vazquez Acosta,[129,nnn] T. Virdee,[129,p] J. Wright,[129] S. C. Zenz,[129] J. E. Cole,[130] P. R. Hobson,[130] A. Khan,[130] P. Kyberd,[130] I. D. Reid,[130] P. Symonds,[130] L. Teodorescu,[130] M. Turner,[130] A. Borzou,[131] K. Call,[131] J. Dittmann,[131] K. Hatakeyama,[131] H. Liu,[131] N. Pastika,[131] R. Bartek,[132] A. Dominguez,[132] A. Buccilli,[133] S. I. Cooper,[133] C. Henderson,[133] P. Rumerio,[133] C. West,[133] D. Arcaro,[134] A. Avetisyan,[134] T. Bose,[134] D. Gastler,[134] D. Rankin,[134] C. Richardson,[134] J. Rohlf,[134] L. Sulak,[134] D. Zou,[134] G. Benelli,[135] D. Cutts,[135] A. Garabedian,[135] J. Hakala,[135] U. Heintz,[135]

J. M. Hogan,[135] O. Jesus,[135] K. H. M. Kwok,[135] E. Laird,[135] G. Landsberg,[135] Z. Mao,[135] M. Narain,[135] S. Piperov,[135] S. Sagir,[135] E. Spencer,[135] R. Syarif,[135] R. Breedon,[136] D. Burns,[136] M. Calderon De La Barca Sanchez,[136] S. Chauhan,[136] M. Chertok,[136] J. Conway,[136] R. Conway,[136] P. T. Cox,[136] R. Erbacher,[136] C. Flores,[136] G. Funk,[136] M. Gardner,[136] W. Ko,[136] R. Lander,[136] C. Mclean,[136] M. Mulhearn,[136] D. Pellett,[136] J. Pilot,[136] S. Shalhout,[136] M. Shi,[136] J. Smith,[136] M. Squires,[136] D. Stolp,[136] K. Tos,[136] M. Tripathi,[136] M. Bachtis,[137] C. Bravo,[137] R. Cousins,[137] A. Dasgupta,[137] A. Florent,[137] J. Hauser,[137] M. Ignatenko,[137] N. Mccoll,[137] D. Saltzberg,[137] C. Schnaible,[137] V. Valuev,[137] M. Weber,[137] E. Bouvier,[138] K. Burt,[138] R. Clare,[138] J. Ellison,[138] J. W. Gary,[138] S. M. A. Ghiasi Shirazi,[138] G. Hanson,[138] J. Heilman,[138] P. Jandir,[138] E. Kennedy,[138] F. Lacroix,[138] O. R. Long,[138] M. Olmedo Negrete,[138] M. I. Paneva,[138] A. Shrinivas,[138] W. Si,[138] H. Wei,[138] S. Wimpenny,[138] B. R. Yates,[138] J. G. Branson,[139] G. B. Cerati,[139] S. Cittolin,[139] M. Derdzinski,[139] R. Gerosa,[139] A. Holzner,[139] D. Klein,[139] V. Krutelyov,[139] J. Letts,[139] I. Macneill,[139] D. Olivito,[139] S. Padhi,[139] M. Pieri,[139] M. Sani,[139] V. Sharma,[139] S. Simon,[139] M. Tadel,[139] A. Vartak,[139] S. Wasserbaech,[139,ooo] C. Welke,[139] J. Wood,[139] F. Würthwein,[139] A. Yagil,[139] G. Zevi Della Porta,[139] N. Amin,[140] R. Bhandari,[140] J. Bradmiller-Feld,[140] C. Campagnari,[140] A. Dishaw,[140] V. Dutta,[140] M. Franco Sevilla,[140] C. George,[140] F. Golf,[140] L. Gouskos,[140] J. Gran,[140] R. Heller,[140] J. Incandela,[140] S. D. Mullin,[140] A. Ovcharova,[140] H. Qu,[140] J. Richman,[140] D. Stuart,[140] I. Suarez,[140] J. Yoo,[140] D. Anderson,[141] J. Bendavid,[141] A. Bornheim,[141] J. Bunn,[141] J. M. Lawhorn,[141] A. Mott,[141] H. B. Newman,[141] C. Pena,[141] M. Spiropulu,[141] J. R. Vlimant,[141] S. Xie,[141] R. Y. Zhu,[141] M. B. Andrews,[142] T. Ferguson,[142] M. Paulini,[142] J. Russ,[142] M. Sun,[142] H. Vogel,[142] I. Vorobiev,[142] M. Weinberg,[142] J. P. Cumalat,[143] W. T. Ford,[143] F. Jensen,[143] A. Johnson,[143] M. Krohn,[143] S. Leontsinis,[143] T. Mulholland,[143] K. Stenson,[143] S. R. Wagner,[143] J. Alexander,[144] J. Chaves,[144] J. Chu,[144] S. Dittmer,[144] K. Mcdermott,[144] N. Mirman,[144] J. R. Patterson,[144] A. Rinkevicius,[144] A. Ryd,[144] L. Skinnari,[144] L. Soffi,[144] S. M. Tan,[144] Z. Tao,[144] J. Thom,[144] J. Tucker,[144] P. Wittich,[144] M. Zientek,[144] D. Winn,[145] S. Abdullin,[146] M. Albrow,[146] G. Apollinari,[146] A. Apresyan,[146] S. Banerjee,[146] L. A. T. Bauerdick,[146] A. Beretvas,[146] J. Berryhill,[146] P. C. Bhat,[146] G. Bolla,[146] K. Burkett,[146] J. N. Butler,[146] H. W. K. Cheung,[146] F. Chlebana,[146] S. Cihangir,[146,a] M. Cremonesi,[146] J. Duarte,[146] V. D. Elvira,[146] I. Fisk,[146] J. Freeman,[146] E. Gottschalk,[146] L. Gray,[146] D. Green,[146] S. Grünendahl,[146] O. Gutsche,[146] R. M. Harris,[146] S. Hasegawa,[146] J. Hirschauer,[146] Z. Hu,[146] B. Jayatilaka,[146] S. Jindariani,[146] M. Johnson,[146] U. Joshi,[146] B. Klima,[146] B. Kreis,[146] S. Lammel,[146] J. Linacre,[146] D. Lincoln,[146] R. Lipton,[146] M. Liu,[146] T. Liu,[146] R. Lopes De Sá,[146] J. Lykken,[146] K. Maeshima,[146] N. Magini,[146] J. M. Marraffino,[146] S. Maruyama,[146] D. Mason,[146] P. McBride,[146] P. Merkel,[146] S. Mrenna,[146] S. Nahn,[146] V. O'Dell,[146] K. Pedro,[146] O. Prokofyev,[146] G. Rakness,[146] L. Ristori,[146] E. Sexton-Kennedy,[146] A. Soha,[146] W. J. Spalding,[146] L. Spiegel,[146] S. Stoynev,[146] J. Strait,[146] N. Strobbe,[146] L. Taylor,[146] S. Tkaczyk,[146] N. V. Tran,[146] L. Uplegger,[146] E. W. Vaandering,[146] C. Vernieri,[146] M. Verzocchi,[146] R. Vidal,[146] M. Wang,[146] H. A. 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A. Hangal,[151] D. J. Hofman,[151] K. Jung,[151] J. Kamin,[151] I. D. Sandoval Gonzalez,[151] H. Trauger,[151] N. Varelas,[151] H. Wang,[151] Z. Wu,[151] J. Zhang,[151] B. Bilki,[152,ppp] W. Clarida,[152] K. Dilsiz,[152] S. Durgut,[152] R. P. Gandrajula,[152] M. Haytmyradov,[152] V. Khristenko,[152] J.-P. Merlo,[152] H. Mermerkaya,[152,qqq] A. Mestvirishvili,[152] A. Moeller,[152] J. Nachtman,[152] H. Ogul,[152] Y. Onel,[152] F. Ozok,[152,rrr] A. Penzo,[152] C. Snyder,[152] E. Tiras,[152] J. Wetzel,[152] K. Yi,[152] B. Blumenfeld,[153] A. Cocoros,[153] N. Eminizer,[153] D. Fehling,[153] L. Feng,[153] A. V. Gritsan,[153] P. Maksimovic,[153] J. Roskes,[153] U. Sarica,[153] M. Swartz,[153] M. Xiao,[153] C. You,[153] A. Al-bataineh,[154] P. Baringer,[154] A. Bean,[154] S. Boren,[154] J. Bowen,[154] J. Castle,[154] L. Forthomme,[154] S. Khalil,[154] A. Kropivnitskaya,[154] D. Majumder,[154] W. Mcbrayer,[154] M. Murray,[154] S. Sanders,[154] R. Stringer,[154] J. D. Tapia Takaki,[154] Q. Wang,[154] A. Ivanov,[155] K. Kaadze,[155] Y. Maravin,[155] A. Mohammadi,[155] L. K. Saini,[155] N. Skhirtladze,[155] S. Toda,[155] F. Rebassoo,[156] D. Wright,[156] C. Anelli,[157] A. Baden,[157] O. Baron,[157] A. Belloni,[157] B. Calvert,[157] S. C. Eno,[157] C. Ferraioli,[157] N. J. Hadley,[157] S. Jabeen,[157] G. Y. Jeng,[157] R. G. Kellogg,[157] J. Kunkle,[157] A. C. Mignerey,[157] F. Ricci-Tam,[157] Y. H. Shin,[157] A. Skuja,[157] M. B. Tonjes,[157] S. C. Tonwar,[157] D. Abercrombie,[158] B. Allen,[158] A. Apyan,[158] V. Azzolini,[158] R. Barbieri,[158] A. Baty,[158] R. Bi,[158] K. Bierwagen,[158] S. Brandt,[158] W. Busza,[158] I. A. Cali,[158] M. D'Alfonso,[158] Z. Demiragli,[158]

G. Gomez Ceballos,[158] M. Goncharov,[158] D. Hsu,[158] Y. Iiyama,[158] G. M. Innocenti,[158] M. Klute,[158] D. Kovalskyi,[158] K. Krajczar,[158] Y. S. Lai,[158] Y.-J. Lee,[158] A. Levin,[158] P. D. Luckey,[158] B. Maier,[158] A. C. Marini,[158] C. Mcginn,[158] C. Mironov,[158] S. Narayanan,[158] X. Niu,[158] C. Paus,[158] C. Roland,[158] G. Roland,[158] J. Salfeld-Nebgen,[158] G. S. F. Stephans,[158] K. Tatar,[158] D. Velicanu,[158] J. Wang,[158] T. W. Wang,[158] B. Wyslouch,[158] A. C. Benvenuti,[159] R. M. Chatterjee,[159] A. Evans,[159] P. Hansen,[159] S. Kalafut,[159] S. C. Kao,[159] Y. Kubota,[159] Z. Lesko,[159] J. Mans,[159] S. Nourbakhsh,[159] N. Ruckstuhl,[159] R. Rusack,[159] N. Tambe,[159] J. Turkewitz,[159] J. G. Acosta,[160] S. Oliveros,[160] E. Avdeeva,[161] K. Bloom,[161] D. R. Claes,[161] C. Fangmeier,[161] R. Gonzalez Suarez,[161] R. Kamalieddin,[161] I. Kravchenko,[161] A. Malta Rodrigues,[161] J. Monroy,[161] J. E. Siado,[161] G. R. Snow,[161] B. Stieger,[161] M. Alyari,[162] J. Dolen,[162] A. Godshalk,[162] C. Harrington,[162] I. Iashvili,[162] D. Nguyen,[162] A. Parker,[162] S. Rappoccio,[162] B. Roozbahani,[162] G. Alverson,[163] E. Barberis,[163] A. Hortiangtham,[163] A. Massironi,[163] D. M. Morse,[163] D. Nash,[163] T. Orimoto,[163] R. Teixeira De Lima,[163] D. Trocino,[163] R.-J. Wang,[163] D. Wood,[163] S. Bhattacharya,[164] O. Charaf,[164] K. A. Hahn,[164] N. Mucia,[164] N. Odell,[164] B. Pollack,[164] M. H. Schmitt,[164] K. Sung,[164] M. Trovato,[164] M. Velasco,[164] N. Dev,[165] M. Hildreth,[165] K. Hurtado Anampa,[165] C. Jessop,[165] D. J. Karmgard,[165] N. Kellams,[165] K. Lannon,[165] N. Marinelli,[165] F. Meng,[165] C. Mueller,[165] Y. Musienko,[165,jj] M. Planer,[165] A. Reinsvold,[165] R. Ruchti,[165] N. Rupprecht,[165] G. Smith,[165] S. Taroni,[165] M. Wayne,[165] M. Wolf,[165] A. Woodard,[165] J. Alimena,[166] L. Antonelli,[166] B. Bylsma,[166] L. S. Durkin,[166] S. Flowers,[166] B. Francis,[166] A. Hart,[166] C. Hill,[166] W. Ji,[166] B. Liu,[166] W. Luo,[166] D. Puigh,[166] B. L. Winer,[166] H. W. Wulsin,[166] S. Cooperstein,[167] O. Driga,[167] P. Elmer,[167] J. Hardenbrook,[167] P. Hebda,[167] D. Lange,[167] J. Luo,[167] D. Marlow,[167] T. Medvedeva,[167] K. Mei,[167] I. Ojalvo,[167] J. Olsen,[167] C. Palmer,[167] P. Piroué,[167] D. Stickland,[167] A. Svyatkovskiy,[167] C. Tully,[167] S. Malik,[168] A. Barker,[169] V. E. Barnes,[169] S. Folgueras,[169] L. Gutay,[169] M. K. Jha,[169] M. Jones,[169] A. W. Jung,[169] A. Khatiwada,[169] D. H. Miller,[169] N. Neumeister,[169] J. F. Schulte,[169] J. Sun,[169] F. Wang,[169] W. Xie,[169] N. Parashar,[170] J. Stupak,[170] A. Adair,[171] B. Akgun,[171] Z. Chen,[171] K. M. Ecklund,[171] F. J. M. Geurts,[171] M. Guilbaud,[171] W. Li,[171] B. Michlin,[171] M. Northup,[171] B. P. Padley,[171] J. Roberts,[171] J. Rorie,[171] Z. Tu,[171] J. Zabel,[171] B. Betchart,[172] A. Bodek,[172] P. de Barbaro,[172] R. Demina,[172] Y. t. Duh,[172] T. Ferbel,[172] M. Galanti,[172] A. Garcia-Bellido,[172] J. Han,[172] O. Hindrichs,[172] A. Khukhunaishvili,[172] K. H. Lo,[172] P. Tan,[172] M. Verzetti,[172] A. Agapitos,[173] J. P. Chou,[173] Y. Gershtein,[173] T. A. Gómez Espinosa,[173] E. Halkiadakis,[173] M. Heindl,[173] E. Hughes,[173] S. Kaplan,[173] R. Kunnawalkam Elayavalli,[173] S. Kyriacou,[173] A. Lath,[173] R. Montalvo,[173] K. Nash,[173] M. Osherson,[173] H. Saka,[173] S. Salur,[173] S. Schnetzer,[173] D. Sheffield,[173] S. Somalwar,[173] R. Stone,[173] S. Thomas,[173] P. Thomassen,[173] M. Walker,[173] A. G. Delannoy,[174] M. Foerster,[174] J. Heideman,[174] G. Riley,[174] K. Rose,[174] S. Spanier,[174] K. Thapa,[174] O. Bouhali,[175,sss] A. Celik,[175] M. Dalchenko,[175] M. De Mattia,[175] A. Delgado,[175] S. Dildick,[175] R. Eusebi,[175] J. Gilmore,[175] T. Huang,[175] E. Juska,[175] T. Kamon,[175,ttt] R. Mueller,[175] Y. Pakhotin,[175] R. Patel,[175] A. Perloff,[175] L. Perniè,[175] D. Rathjens,[175] A. Safonov,[175] A. Tatarinov,[175] K. A. Ulmer,[175] N. Akchurin,[176] J. Damgov,[176] F. De Guio,[176] C. Dragoiu,[176] P. R. Dudero,[176] J. Faulkner,[176] E. Gurpinar,[176] S. Kunori,[176] K. Lamichhane,[176] S. W. Lee,[176] T. Libeiro,[176] T. Peltola,[176] S. Undleeb,[176] I. Volobouev,[176] Z. Wang,[176] S. Greene,[177] A. Gurrola,[177] R. Janjam,[177] W. Johns,[177] C. Maguire,[177] A. Melo,[177] H. Ni,[177] P. Sheldon,[177] S. Tuo,[177] J. Velkovska,[177] Q. Xu,[177] M. W. Arenton,[178] P. Barria,[178] B. Cox,[178] R. Hirosky,[178] A. Ledovskoy,[178] H. Li,[178] C. Neu,[178] T. Sinthuprasith,[178] X. Sun,[178] Y. Wang,[178] E. Wolfe,[178] F. Xia,[178] C. Clarke,[179] R. Harr,[179] P. E. Karchin,[179] J. Sturdy,[179] S. Zaleski,[179] D. A. Belknap,[180] J. Buchanan,[180] C. Caillol,[180] S. Dasu,[180] L. Dodd,[180] S. Duric,[180] B. Gomber,[180] M. Grothe,[180] M. Herndon,[180] A. Hervé,[180] U. Hussain,[180] P. Klabbers,[180] A. Lanaro,[180] A. Levine,[180] K. Long,[180] R. Loveless,[180] G. A. Pierro,[180] G. Polese,[180] T. Ruggles,[180] A. Savin,[180] N. Smith,[180] W. H. Smith,[180] D. Taylor,[180] and N. Woods[180]

(CMS Collaboration)

[1]*Yerevan Physics Institute, Yerevan, Armenia*
[2]*Institut für Hochenergiephysik, Wien, Austria*
[3]*Institute for Nuclear Problems, Minsk, Belarus*
[4]*National Centre for Particle and High Energy Physics, Minsk, Belarus*
[5]*Universiteit Antwerpen, Antwerpen, Belgium*
[6]*Vrije Universiteit Brussel, Brussel, Belgium*
[7]*Université Libre de Bruxelles, Bruxelles, Belgium*
[8]*Ghent University, Ghent, Belgium*

[9]*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*
[10]*Université de Mons, Mons, Belgium*
[11]*Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil*
[12]*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
[13a]*Universidade Estadual Paulista, São Paulo, Brazil*
[13b]*Universidade Federal do ABC, São Paulo, Brazil*
[14]*Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria*
[15]*University of Sofia, Sofia, Bulgaria*
[16]*Beihang University, Beijing, China*
[17]*Institute of High Energy Physics, Beijing, China*
[18]*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
[19]*Universidad de Los Andes, Bogota, Colombia*
[20]*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia*
[21]*University of Split, Faculty of Science, Split, Croatia*
[22]*Institute Rudjer Boskovic, Zagreb, Croatia*
[23]*University of Cyprus, Nicosia, Cyprus*
[24]*Charles University, Prague, Czech Republic*
[25]*Universidad San Francisco de Quito, Quito, Ecuador*
[26]*Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt*
[27]*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*
[28]*Department of Physics, University of Helsinki, Helsinki, Finland*
[29]*Helsinki Institute of Physics, Helsinki, Finland*
[30]*Lappeenranta University of Technology, Lappeenranta, Finland*
[31]*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
[32]*Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France*
[33]*Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France*
[34]*Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France*
[35]*Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France*
[36]*Georgian Technical University, Tbilisi, Georgia*
[37]*Tbilisi State University, Tbilisi, Georgia*
[38]*RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*
[39]*RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
[40]*RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*
[41]*Deutsches Elektronen-Synchrotron, Hamburg, Germany*
[42]*University of Hamburg, Hamburg, Germany*
[43]*Institut für Experimentelle Kernphysik, Karlsruhe, Germany*
[44]*Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece*
[45]*National and Kapodistrian University of Athens, Athens, Greece*
[46]*National Technical University of Athens, Athens, Greece*
[47]*University of Ioánnina, Ioánnina, Greece*
[48]*MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary*
[49]*Wigner Research Centre for Physics, Budapest, Hungary*
[50]*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*
[51]*Institute of Physics, University of Debrecen, Debrecen, Hungary*
[52]*Indian Institute of Science (IISc), Bangalore, India*
[53]*National Institute of Science Education and Research, Bhubaneswar, India*
[54]*Panjab University, Chandigarh, India*
[55]*University of Delhi, Delhi, India*
[56]*Saha Institute of Nuclear Physics, Kolkata, India*
[57]*Indian Institute of Technology Madras, Madras, India*
[58]*Bhabha Atomic Research Centre, Mumbai, India*
[59]*Tata Institute of Fundamental Research-A, Mumbai, India*
[60]*Tata Institute of Fundamental Research-B, Mumbai, India*
[61]*Indian Institute of Science Education and Research (IISER), Pune, India*
[62]*Institute for Research in Fundamental Sciences (IPM), Tehran, Iran*
[63]*University College Dublin, Dublin, Ireland*
[64a]*INFN Sezione di Bari, Bari, Italy*
[64b]*Università di Bari, Bari, Italy*
[64c]*Politecnico di Bari, Bari, Italy*

[65a]*INFN Sezione di Bologna, Bologna, Italy*
[65b]*Università di Bologna, Bologna, Italy*
[66a]*INFN Sezione di Catania, Catania, Italy*
[66b]*Università di Catania, Catania, Italy*
[67a]*INFN Sezione di Firenze, Firenze, Italy*
[67b]*Università di Firenze, Firenze, Italy*
[68]*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
[69a]*INFN Sezione di Genova, Genova, Italy*
[69b]*Università di Genova, Genova, Italy*
[70a]*INFN Sezione di Milano-Bicocca, Milano, Italy*
[70b]*Università di Milano-Bicocca, Milano, Italy*
[71a]*INFN Sezione di Napoli, Roma, Italy*
[71b]*Università di Napoli 'Federico II', Roma, Italy*
[71c]*Università della Basilicata, Roma, Italy*
[71d]*Università G. Marconi, Roma, Italy*
[72a]*INFN Sezione di Padova, Padova, Italy*
[72b]*Università di Padova, Padova, Italy*
[72c]*Università di Trento, Trento, Italy*
[73a]*INFN Sezione di Pavia, Pavia, Italy*
[73b]*Università di Pavia, Pavia, Italy*
[74a]*INFN Sezione di Perugia, Perugia, Italy*
[74b]*Università di Perugia, Perugia, Italy*
[75a]*INFN Sezione di Pisa, Pisa, Italy*
[75b]*Università di Pisa, Pisa, Italy*
[75c]*Scuola Normale Superiore di Pisa, Pisa, Italy*
[76a]*INFN Sezione di Roma, Roma, Italy*
[76b]*Sapienza Università di Roma, Roma, Italy*
[77a]*INFN Sezione di Torino, Torino, Italy*
[77b]*Università di Torino, Torino, Italy*
[77c]*Università del Piemonte Orientale, Novara, Italy*
[78a]*INFN Sezione di Trieste, Trieste, Italy*
[78b]*Università di Trieste, Trieste, Italy*
[79]*Kyungpook National University, Daegu, Korea*
[80]*Chonbuk National University, Jeonju, Korea*
[81]*Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea*
[82]*Hanyang University, Seoul, Korea*
[83]*Korea University, Seoul, Korea*
[84]*Seoul National University, Seoul, Korea*
[85]*University of Seoul, Seoul, Korea*
[86]*Sungkyunkwan University, Suwon, Korea*
[87]*Vilnius University, Vilnius, Lithuania*
[88]*National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia*
[89]*Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico*
[90]*Universidad Iberoamericana, Mexico City, Mexico*
[91]*Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*
[92]*Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico*
[93]*University of Auckland, Auckland, New Zealand*
[94]*University of Canterbury, Christchurch, New Zealand*
[95]*National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*
[96]*National Centre for Nuclear Research, Swierk, Poland*
[97]*Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*
[98]*Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal*
[99]*Joint Institute for Nuclear Research, Dubna, Russia*
[100]*Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia*
[101]*Institute for Nuclear Research, Moscow, Russia*
[102]*Institute for Theoretical and Experimental Physics, Moscow, Russia*
[103]*Moscow Institute of Physics and Technology, Moscow, Russia*
[104]*National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia*
[105]*P.N. Lebedev Physical Institute, Moscow, Russia*
[106]*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*

[107]*Novosibirsk State University (NSU), Novosibirsk, Russia*
[108]*State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia*
[109]*University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia*
[110]*Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*
[111]*Universidad Autónoma de Madrid, Madrid, Spain*
[112]*Universidad de Oviedo, Oviedo, Spain*
[113]*Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain*
[114]*CERN, European Organization for Nuclear Research, Geneva, Switzerland*
[115]*Paul Scherrer Institut, Villigen, Switzerland*
[116]*Institute for Particle Physics, ETH Zurich, Zurich, Switzerland*
[117]*Universität Zürich, Zurich, Switzerland*
[118]*National Central University, Chung-Li, Taiwan*
[119]*National Taiwan University (NTU), Taipei, Taiwan*
[120]*Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand*
[121]*Cukurova University, Physics Department, Science and Art Faculty, Adana, Turkey*
[122]*Middle East Technical University, Physics Department, Ankara, Turkey*
[123]*Bogazici University, Istanbul, Turkey*
[124]*Istanbul Technical University, Istanbul, Turkey*
[125]*Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine*
[126]*National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine*
[127]*University of Bristol, Bristol, United Kingdom*
[128]*Rutherford Appleton Laboratory, Didcot, United Kingdom*
[129]*Imperial College, London, United Kingdom*
[130]*Brunel University, Uxbridge, United Kingdom*
[131]*Baylor University, Waco, Texas, USA*
[132]*Catholic University of America, Washington DC, USA*
[133]*The University of Alabama, Tuscaloosa, Alabama, USA*
[134]*Boston University, Boston, Massachusetts, USA*
[135]*Brown University, Providence, Rhode Island, USA*
[136]*University of California, Davis, Davis, California, USA*
[137]*University of California, Los Angeles, California, USA*
[138]*University of California, Riverside, Riverside, Riverside, USA*
[139]*University of California, San Diego, La Jolla, USA*
[140]*University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA*
[141]*California Institute of Technology, Pasadena, California, USA*
[142]*Carnegie Mellon University, Pittsburgh, Pennsylvania, USA*
[143]*University of Colorado Boulder, Boulder, Colorado, USA*
[144]*Cornell University, Ithaca, New York, USA*
[145]*Fairfield University, Fairfield, Connecticut, USA*
[146]*Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
[147]*University of Florida, Gainesville, Florida, USA*
[148]*Florida International University, Miami, Florida, USA*
[149]*Florida State University, Tallahassee, Florida, USA*
[150]*Florida Institute of Technology, Melbourne, Florida, USA*
[151]*University of Illinois at Chicago (UIC), Chicago, Illinois, USA*
[152]*The University of Iowa, Iowa City, Iowa, USA*
[153]*Johns Hopkins University, Baltimore, Maryland, USA*
[154]*The University of Kansas, Lawrence, Kansas, USA*
[155]*Kansas State University, Manhattan, Kansas, USA*
[156]*Lawrence Livermore National Laboratory, Livermore, California, USA*
[157]*University of Maryland, College Park, Maryland, USA*
[158]*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
[159]*University of Minnesota, Minneapolis, Minnesota, USA*
[160]*University of Mississippi, Oxford, Mississippi, USA*
[161]*University of Nebraska-Lincoln, Lincoln, Nebraska, USA*
[162]*State University of New York at Buffalo, Buffalo, New York, USA*
[163]*Northeastern University, Boston, Massachusetts, USA*
[164]*Northwestern University, Evanston, Illinois, USA*
[165]*University of Notre Dame, Notre Dame, Indiana, USA*
[166]*The Ohio State University, Columbus, Ohio, USA*

[167]*Princeton University, Princeton, New Jersey, USA*
[168]*University of Puerto Rico, Mayaguez, Puerto Rico, USA*
[169]*Purdue University, West Lafayette, Indiana, USA*
[170]*Purdue University Northwest, Hammond, Indiana, USA*
[171]*Rice University, Houston, Texas, USA*
[172]*University of Rochester, Rochester, New York, USA*
[173]*Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA*
[174]*University of Tennessee, Knoxville, Tennessee, USA*
[175]*Texas A&M University, College Station, Texas, USA*
[176]*Texas Tech University, Lubbock, Texas, USA*
[177]*Vanderbilt University, Nashville, Tennessee, USA*
[178]*University of Virginia, Charlottesville, Virginia, USA*
[179]*Wayne State University, Detroit, Michigan, USA*
[180]*University of Wisconsin - Madison, Madison, Wisconsin, USA*

[a] Deceased.
[b] Also at Vienna University of Technology, Vienna, Austria.
[c] Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.
[d] Also at Universidade Estadual de Campinas, Campinas, Brazil.
[e] Also at Universidade Federal de Pelotas, Pelotas, Brazil.
[f] Also at Université Libre de Bruxelles, Bruxelles, Belgium.
[g] Also at Universidad de Antioquia, Medellin, Colombia.
[h] Also at Joint Institute for Nuclear Research, Dubna, Russia.
[i] Also at Helwan University, Cairo, Egypt.
[j] Also at Zewail City of Science and Technology, Zewail, Egypt.
[k] Also at Fayoum University, El-Fayoum, Egypt.
[l] Also at British University in Egypt, Cairo, Egypt.
[m] Also at Ain Shams University, Cairo, Egypt.
[n] Also at Université de Haute Alsace, Mulhouse, France.
[o] Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
[p] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[q] Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[r] Also at University of Hamburg, Hamburg, Germany.
[s] Also at Brandenburg University of Technology, Cottbus, Germany.
[t] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[u] Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
[v] Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
[w] Also at IIT Bhubaneswar, Bhubaneswar, India.
[x] Also at University of Visva-Bharati, Santiniketan, India.
[y] Also at Institute of Physics, Bhubaneswar, India.
[z] Also at University of Ruhuna, Matara, Sri Lanka.
[aa] Also at Isfahan University of Technology, Isfahan, Iran.
[bb] Also at Yazd University, Yazd, Iran.
[cc] Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
[dd] Also at Università degli Studi di Siena, Siena, Italy.
[ee] Also at Purdue University, West Lafayette, USA.
[ff] Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
[gg] Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
[hh] Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.
[ii] Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
[jj] Also at Institute for Nuclear Research, Moscow, Russia.
[kk] Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
[ll] Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
[mm] Also at University of Florida, Gainesville, USA.
[nn] Also at P.N. Lebedev Physical Institute, Moscow, Russia.
[oo] Also at California Institute of Technology, Pasadena, USA.
[pp] Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
[qq] Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
[rr] Also at INFN Sezione di Roma, Sapienza Università di Roma, Rome, Italy.
[ss] Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.

[tt] Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
[uu] Also at National and Kapodistrian University of Athens, Athens, Greece.
[vv] Also at Riga Technical University, Riga, Latvia.
[ww] Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
[xx] Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
[yy] Also at Adiyaman University, Adiyaman, Turkey.
[zz] Also at Istanbul Aydin University, Istanbul, Turkey.
[aaa] Also at Mersin University, Mersin, Turkey.
[bbb] Also at Cag University, Mersin, Turkey.
[ccc] Also at Piri Reis University, Istanbul, Turkey.
[ddd] Also at Gaziosmanpasa University, Tokat, Turkey.
[eee] Also at Ozyegin University, Istanbul, Turkey.
[fff] Also at Izmir Institute of Technology, Izmir, Turkey.
[ggg] Also at Marmara University, Istanbul, Turkey.
[hhh] Also at Kafkas University, Kars, Turkey.
[iii] Also at Istanbul Bilgi University, Istanbul, Turkey.
[jjj] Also at Yildiz Technical University, Istanbul, Turkey.
[kkk] Also at Hacettepe University, Ankara, Turkey.
[lll] Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
[mmm] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[nnn] Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.
[ooo] Also at Utah Valley University, Orem, USA.
[ppp] Also at Beykent University.
[qqq] Also at Erzincan University, Erzincan, Turkey.
[rrr] Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
[sss] Also at Texas A&M University at Qatar, Doha, Qatar.
[ttt] Also at Kyungpook National University, Daegu, Korea.