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Author(s):
CMS Collaboration; Chatrchyan, Serguei; Bortignon, Pierluigi; Caminada, Lea; Chanon, Nicolas; Chen, Z.; Cittolin, Sergio; Dissertori, Günther; Dittmar, Michael; Eugster, Jürg; Freudenreich, Klaus; Grab, Christoph; Hervé, Alain; Hintz, Wieland; Lecomte, Pierre; Lustermann, Werner; Marchica, Carmelo; Martinez Ruiz del Arbol, Pablo; Meridiani, Paolo; Milenovic, Predrag; Moortgat, Filip; Nägeli, Christoph; Nef, Pascal; Nessi-Tedaldi, Francesca; Pape, Luc; Pauss, Felicitas; Punz, Thomas; Rizzi, A.; Ronga, Frédéric; Rossini, Marco; Sala, Leonardo; Sanchez, Ann-Karin; Sawley, Marie-Christine; Stieger, Benjamin; Tauscher, Ludwig; Thea, Alessandro; Theofilatos, Konstantinos; Treille, Daniel; Urscheler, Christina; Wallny, Rainer; Weber, M.; Wehrli, Lukas; Weng, J.; et al.

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Search for Neutral Minimal Supersymmetric Standard Model Higgs Bosons Decaying to Tau Pairs in pp Collisions at $\sqrt{s} = 7$ TeV

S. Chatrchyan *et al.**
(CMS Collaboration)

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A search for neutral minimal supersymmetric standard model (MSSM) Higgs bosons in pp collisions at the LHC at a center-of-mass energy of 7 TeV is presented. The results are based on a data sample corresponding to an integrated luminosity of 36 pb^{-1} recorded by the CMS experiment. The search uses decays of the Higgs bosons to tau pairs. No excess is observed in the tau-pair invariant-mass spectrum. The resulting upper limits on the Higgs boson production cross section times branching fraction to tau pairs, as a function of the pseudoscalar Higgs boson mass, yield stringent new bounds in the MSSM parameter space.

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The standard model (SM) has been extremely successful in describing a wide range of phenomena in particle physics, and has survived some four decades of experimental testing. However, the only remaining undiscovered particle predicted by the SM, the Higgs boson [1–5], suffers from quadratically divergent self-energy corrections at high energies [6]. Numerous extensions to the SM have been proposed to address these divergences. One such model, supersymmetry [7], a symmetry between fundamental bosons and fermions, results in cancellation of the divergences at tree level. The minimal supersymmetric extension to the standard model (MSSM) requires the presence of two Higgs doublets. This leads to a more complicated scalar sector, with five massive Higgs bosons: a light neutral state (h), two charged states ($H^{\pm}$), a heavy neutral CP-even state (H), and a neutral CP-odd state (A).

The masses of the MSSM Higgs boson states are specified up to radiative corrections mainly by two parameters, usually taken to be the mass of the pseudoscalar state, m_A, and the ratio of the vacuum expectation values of the two Higgs doublets, $\tan\beta$. At large $\tan\beta$ (greater than about 20–30), the couplings of the Higgs bosons to down-type quarks are approximately proportional to $\tan\beta$. As a result, the production cross section for two of the three neutral Higgs bosons can be nearly as large as that for the electroweak gauge bosons W and Z at a proton-proton collider such as the Large Hadron Collider (LHC). Two main production processes contribute to $pp \to \phi + X$, where $\phi = h$, H, or A: gluon fusion through a a b quark loop and direct $b\bar{b}$ annihilation from the b parton density in the beam protons.

The mass relations among the neutral MSSM Higgs bosons are such that if $m_A \lesssim 130$ GeV$/c^2$, at large $\tan\beta$ the masses of the h and A are nearly degenerate, while that of the H is approximately 130 GeV$/c^2$. If $m_A \gtrsim 130$ GeV$/c^2$, then the masses of the A and H are nearly degenerate, while that of the h remains near 130 GeV$/c^2$. The precise value of the crossover point depends predominantly on the nature of the mass mixing in the top-squark states.

This Letter reports a search for MSSM neutral Higgs bosons in pp collisions at $\sqrt{s} = 7$ TeV at the LHC, using a data sample collected in 2010 corresponding to 36 pb^{-1} of integrated luminosity recorded by the Compact Muon Solenoid (CMS) experiment. This search is similar to those performed at the Tevatron [8] and complementary to the MSSM Higgs search at LEP [9].

The tau-pair decays of the neutral Higgs bosons, having a branching fraction of roughly 10%, serve as the best experimental signature for this search. The $b\bar{b}$ mode, though it has a much larger branching fraction, suffers from an overwhelming background from QCD processes. Three final states where one or both taus decay leptonically are used: $e\tau_h$, $\mu\tau_h$, and $e\mu$, where we use the symbol τ_h to indicate a reconstructed hadronic decay of a τ.

The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter and the brass or scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel return yoke. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry. Details of the CMS detector and its performance can be found elsewhere [10].

CMS uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing to the center of the LHC, the y axis pointing up (perpendicular to the LHC plane), and the z axis along the

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anticlockwise-beam direction. The polar angle θ is measured from the positive z axis and the azimuthal angle ϕ is measured in the xy plane. We measure the pseudorapidity η of outgoing particles based on their polar angle according to $\eta \equiv -\ln(\tan\frac{\theta}{2})$.

The triggers used to select the events for this analysis are based on the presence of an electron and/or a muon trigger object [11,12]. With increasing instantaneous luminosity, in order to keep the online transverse momentum thresholds on electrons lower than those used in offline selections, special triggers requiring the presence of both a lepton and a charged track with an accompanying calorimeter pattern consistent with a τ decaying hadronically were adopted for the $e\tau_h$ and $\mu\tau_h$ channels.

The analysis presented here makes use of particle flow techniques which combine the information from all CMS subdetectors to identify and reconstruct individual particles in the event, namely, muons, electrons, photons, and charged and neutral hadrons. The detailed description of the algorithm and its commissioning can be found elsewhere [13,14]. The particle list is given as input to the jet, tau, and missing transverse energy reconstruction.

The main challenge in the identification of hadronic tau decays is overcoming the large background due to hadronic jets from QCD processes. Hadronic tau decays almost always yield one or three charged pions, plus zero to several neutral pions, depending on the decay mode. The algorithm used here starts with a high-transverse-momentum (p_T) reconstructed charged hadron, and combines it with other nearby reconstructed charged hadron and neutral pion candidates. The algorithm considers all possible combinations of these objects and determines which are consistent with the kinematics of tau decay. Among those, it chooses the most isolated in terms of the presence of nearby reconstructed particles. Requirements on the isolation variables, specific to each final state, determine an operating point in the space of tau identification efficiency versus the jet-to-tau misidentification rate. We optimize the full analysis for best sensitivity by choosing the ''loose'' operating point of the HPS algorithm [15].

For the $\mu\tau_h$ and $e\tau_h$ final states, we select events with an isolated muon or electron with $p_T > 15$ GeV/c and $|\eta| < 2.1$, and an oppositely charged τ_h with $p_T > 20$ GeV/c and $|\eta| < 2.3$. The transverse mass of the $\ell = e$, μ with the missing transverse energy E_T, obtained using all reconstructed particles in the event, is defined as $M_T = \sqrt{2p_T^{\ell}E_T(1-\cos\Delta\phi)}$, where $\Delta\phi$ is the difference in azimuth between the e or μ and the $\not{E}_T$ vector. We require $M_T < 40$ GeV/c^2, in order to reduce the background from W + jets events. For the $e\mu$ final state, we select events with an isolated electron with $|\eta| < 2.5$ and an oppositely charged isolated muon with $|\eta| < 2.1$, both with $M_T > 15$ GeV/c and $M_T < 50$ GeV/c^2 (to reject WW and $t\bar{t}$ events), calculated for each lepton separately. We reject events in which there are more than one e or μ. After the above requirements, the trigger requirements have an efficiency of roughly 90% in the three search channels for $Z \to \tau\tau$ events.

The observed number of events in each channel appears in Table I. The largest source of events selected with these requirements comes from $Z \to \tau\tau$. We estimate the contribution from this process using a detailed GEANT4 simulation of the CMS detector, with the events modeled by the POWHEG Monte Carlo generator [16–19]. We determine the normalization for this process based on the number of observed $Z \to \tau\tau$ and $Z \to \mu\mu$ events [20].

A significant source of background arises from QCD multijet events and W + jets events in which a jet is misidentified as τ_h, and there is a real or misidentified e or μ. The rates for these processes are estimated using the number of observed same-charge events, and cross-checked using the jet-to-tau misidentification rate measured in multijet events. Other background processes include $t\bar{t}$ production and $Z \to ee/\mu\mu$ events, particularly in the $e\tau_h$ channel, due to the 2–3% probability for electrons to be misidentified as τ_h [15]. The small fake-lepton background from W + jets and QCD for the $e\mu$ channel is estimated using data. Table I shows the expected number of events for each of the background processes. The event generator PYTHIA6 [21] is used to model the Higgs boson signal and other backgrounds. The TAUOLA [22] package is used for tau decays in all cases.

To distinguish the Higgs boson signal from the background, we reconstruct the tau-pair mass using a likelihood technique. The algorithm estimates the original tau three-momenta by maximizing a likelihood with respect to free parameters corresponding to the missing tau-neutrino momenta, and subject to all applicable kinematic constraints. Other terms in the likelihood take into account the

TABLE I. Number of estimated background events in the selected sample, observed number of events, and overall signal efficiency for $m_A = 200$ GeV/c^2 (including all branching fractions) for each search channel. Uncertainties include statistics and all systematics, except for those on integrated luminosity or energy scales. The QCD multijet background for the $e\tau_h$ final state is the sum of the QCD multijet and γ + jet backgrounds.

Process	$\mu\tau_h$	$e\tau_h$	$e\mu$
$Z \to \tau\tau$	329 ± 77	190 ± 44	88 ± 5
$t\bar{t}$	6 ± 3	2.6 ± 1.3	7.1 ± 1.3
$Z \to \ell\ell$, jet $\to \tau_h$	6.4 ± 2.4	15 ± 6.2	⋯
$Z \to \ell\ell$	12.9 ± 3.5	109 ± 28	2.4 ± 0.3
$Z \to \ell\ell$	54.9 ± 4.8	30.6 ± 3.1	
$W \to \tau\nu$, $\tau \to \ell\nu\bar{\nu}$	14.7 ± 1.3	7.0 ± 0.7	1.5 ± 0.5
QCD multijet and γ + jet	132 ± 14	181 ± 23	
$WW/WZ/ZZ$	1.6 ± 0.8	0.8 ± 0.4	3.0 ± 0.4
Total	557 ± 79	536 ± 57	102 ± 5
Observed	517	540	101
Signal Efficiency	0.0391	0.0245	0.00582

tau-decay phase space and the probability density in the tau transverse momentum, parametrized as a function of the tau-pair mass. This algorithm yields a tau-pair mass with a mean consistent with the true value, and a distribution with a nearly Gaussian shape. The mass resolution is ~21% at a Higgs boson mass of 130 GeV/c^2, to be compared with ~24% for the (non-Gaussian) distribution of the invariant mass reconstructed from the visible tau-decay products. The observed reconstructed tau-pair mass distribution summed over all three channels is shown in Fig. 1.

Various imperfectly known or imperfectly simulated effects can alter the shape and normalization of the reconstructed tau-pair invariant-mass spectrum. The main sources of normalization uncertainties include the total integrated luminosity (11%) [23], background normalizations (Table I), Z production cross section (4%), and lepton identification and isolation efficiency (0.2–2.0% depending on lepton type). The tau identification efficiency uncertainty is estimated to be 23% from an independent study [15]. The uncertainty due to trigger efficiencies is 0.2% for the $\mu\tau_h$ and $e\mu$ channels, and 2.0% for the $e\tau_h$ channel. Uncertainties that contribute to mass-spectrum shape variations include the tau (3%), muon (1%), and electron (2%) energy scales, and uncertainties on the E_T scale that is used for the tau-pair invariant-mass reconstruction [24]. The E_T scale uncertainties contribute via the jet-energy scale (3%) and unclustered energy scale (10%), where the unclustered energy is defined as the energy remaining after vectorially subtracting leptons and objects clustered in jets with $p_T > 10$ GeV/c.

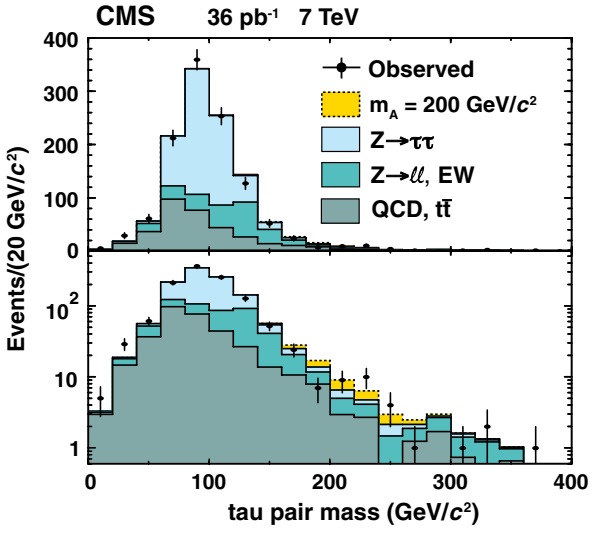

FIG. 1 (color online). The reconstructed tau-pair invariant-mass distribution on linear (above) and logarithmic (below) scales, for the sum of the $e\tau_h$, $\mu\tau_h$, and $e\mu$ final states, comparing the observed distributions (points with error bars) to the sum of the expected backgrounds (shaded histograms). The contribution from a Higgs boson signal (m_A = 200 GeV/c^2) is also shown, with normalization corresponding to the 95% upper bound on $\sigma_\phi B_{\tau\tau}$.

To search for the presence of a Higgs boson signal in the selected events, we perform a maximum likelihood fit to the tau-pair invariant-mass spectrum. Systematic uncertainties are represented by nuisance parameters, which we remove by marginalization, assuming a log normal prior for normalization parameters, and Gaussian priors for mass-spectrum shape uncertainties. The uncertainties that affect the shape of the mass spectrum, mainly those corresponding to the energy scales, are represented by nuisance parameters whose variation results in a continuous modification of the spectrum shape [25].

The parameter representing the tau identification uncertainty affects taus from the Higgs boson signal and the main background, $Z \to \tau\tau$, equally. This effectively allows the observed $Z \to \tau\tau$ events to provide an *in situ* calibration of this efficiency, except for Higgs boson masses near that of the Z. Near the Z mass, the tau identification efficiency uncertainty dominates in the $e\tau_h$ and $\mu\tau_h$ channels, and the $e\mu$ channel thus provides the greatest sensitivity.

The mass spectra show no evidence for the presence of a Higgs boson signal, and we set 95% CL (confidence level) upper bounds on the Higgs boson cross section times the tau-pair branching fraction (denoted by $\sigma_\phi B_{\tau\tau}$) using a Bayesian method assuming a uniform prior in $\sigma_\phi B_{\tau\tau}$. The invariant-mass spectrum in Fig. 1 shows the result of a fit with a Higgs boson signal corresponding to $m_A = 200$ GeV/c^2 present, for $\sigma_\phi B_{\tau\tau} = 8.71$ pb, the value above which we exclude at 95% CL.

Figure 2 shows the observed upper bound on $\sigma_\phi B_{\tau\tau}$ as a function of m_A, where we use as the signal acceptance model the combined mass spectra from the gg and $b\bar{b}$ production processes for h, A, and H, and assuming $\tan\beta = 30$ [26]. The plot also shows the one- and two-standard-deviation range of expected upper limits for various potential experimental outcomes. The observed limits

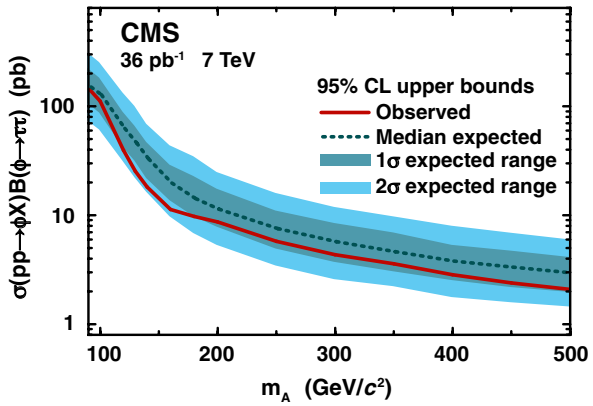

FIG. 2 (color online). The expected one- and two-standard-deviation ranges and observed 95% CL upper limits on $\sigma_\phi B_{\tau\tau}$ as a function of m_A. The signal acceptance is based on the MSSM model described in the text, assuming $\tan\beta = 30$.

TABLE II. Expected range and observed 95% CL upper limits for $\sigma_\phi \cdot B_{\tau\tau}$ as functions of m_A, and 95% CL upper bound on $\tan\beta$ in the $m_h^{\max}$ scenario described in the text. No bounds on $\tan\beta$ above 60 are quoted.

	95% CL Upper Limit				
m_A	Expected $\sigma_\phi B_{\tau\tau}$ (pb)			Observed	
(GeV/c^2)	-1σ	Median	$+1\sigma$	$\sigma_\phi B_{\tau\tau}$	$\tan\beta$
90	107.75	153.30	227.10	147.74	27.4
100	88.61	127.09	184.17	112.30	29.2
120	42.72	62.48	90.24	39.61	25.2
130	31.97	45.96	67.11	25.40	22.6
140	22.14	32.81	47.30	18.20	23.6
160	13.83	19.70	29.27	11.37	23.8
180	9.95	14.16	23.13	9.78	28.1
200	7.90	11.36	17.61	8.71	33.0
250	5.01	7.54	11.15	5.77	43.4
300	3.77	5.71	8.58	4.36	56.6
350	3.09	4.64	7.04	3.60	...
400	2.57	3.79	5.39	2.86	...
450	2.21	3.34	4.77	2.41	...
500	2.00	2.95	4.18	2.10	...

are well within the expected range assuming no signal. The observed and expected upper limits are shown in Table II.

We can interpret the upper limits on $\sigma_\phi B_{\tau\tau}$ in the MSSM parameter space of $\tan\beta$ versus m_A for an example scenario. We use here the $m_h^{\max}$ [27,28] benchmark scenario in which $M_{\rm SUSY} = 1$ TeV/c^2, $X_t = 2M_{\rm SUSY}$, $\mu = 200$ GeV/c^2, $M_{\tilde{g}} = 800$ GeV/c^2, $M_2 = 200$ GeV/c^2, and $A_b = A_t$, where $M_{\rm SUSY}$ denotes the common soft-SUSY-breaking squark mass of the third generation; $X_t = A_t - /\tan\beta$ the stop mixing parameter; A_t and A_b the stop and sbottom trilinear couplings, respectively; μ the Higgsino mass parameter; $M_{\tilde{g}}$ the gluino mass; and M_2 the SU(2)-gaugino mass parameter. The value of M_1 is fixed via the GUT relation $M_1 = (5/3)M_2 \sin\theta_W/\cos\theta_W$. In determining these bounds on $\tan\beta$, shown in Table II and in Fig. 3, we have used the central values of the Higgs boson cross sections as a function of $\tan\beta$ reported by the LHC Higgs Cross Section Working Group [26]. The cross sections have been obtained from the GGH@NNLO [29,30] and HIGLU [31] programs for the gluon-fusion process and from the BBH@NNLO [32] program for the $b\bar{b} \to \phi$ process in the five-flavor scheme, rescaling the corresponding Yukawa couplings by the MSSM factors calculated with FeynHiggs [33]. The $gg \to \phi$ cross-section calculations combine the full quark mass-dependent NLO QCD corrections [34] and NNLO corrections in the heavy-top-quark limit [29,35,36]. The effect of the theoretical uncertainties is illustrated in Fig. 3. We do not quote limits above $\tan\beta = 60$ as the theoretical relation between cross section and $\tan\beta$ becomes unreliable.

The present results exclude a region in $\tan\beta$ down to values smaller than those excluded by the Tevatron experiments [8] for $m_A \lesssim 140$ GeV/c^2, and significantly extend the excluded region of MSSM parameter space at larger values of m_A. Figure 3 also shows the region excluded by the LEP experiments [9].

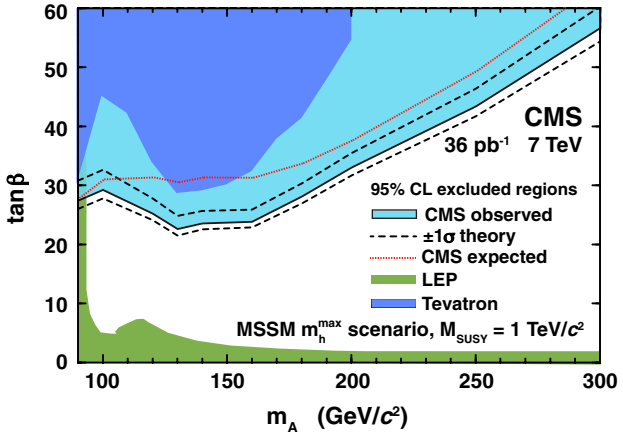

FIG. 3 (color online). Region in the parameter space of $\tan\beta$ versus m_A excluded at 95% CL in the context of the MSSM $m_h^{\max}$ scenario, with the effect of $\pm 1\sigma$ theoretical uncertainties shown. The other shaded regions show the 95% CL excluded regions from the LEP and Tevatron experiments.

In conclusion, we have performed a search for neutral MSSM Higgs bosons, using the first sample of CMS data from proton-proton collisions at a center-of-mass energy of 7 TeV at the LHC, corresponding to an integrated luminosity of 36 pb^{-1}. The tau-pair decay mode in final states with one e or μ plus a hadronic decay of a tau, and the $e\mu$ final state were used. The observed tau-pair mass spectrum reveals no evidence for neutral Higgs boson production, and we determine an upper bound on the product of the Higgs boson cross section and tau-pair branching fraction as a function of m_A. These results, interpreted in the MSSM parameter space of $\tan\beta$ versus m_A, in the $m_h^{\max}$ scenario, exclude a previously unexplored region reaching as low as $\tan\beta = 23$ at $m_A = 130$ GeV/c^2.

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Mestvirishvili,[130] A. Moeller,[130] J. Nachtman,[130] C. R. Newsom,[130] E. Norbeck,[130] J. Olson,[130] Y. Onel,[130] F. Ozok,[130] S. Sen,[130] J. Wetzel,[130] T. Yetkin,[130] K. Yi,[130] B. A. Barnett,[131] B. Blumenfeld,[131] A. Bonato,[131] C. Eskew,[131] D. Fehling,[131] G. Giurgiu,[131] A. V. Gritsan,[131] Z. J. Guo,[131] G. Hu,[131] P. Maksimovic,[131] S. Rappoccio,[131] M. Swartz,[131] N. V. Tran,[131] A. Whitbeck,[131] P. Baringer,[132] A. Bean,[132] G. Benelli,[132] O. Grachov,[132] R. P. Kenny Iii,[132] M. Murray,[132] D. Noonan,[132] S. Sanders,[132] J. S. Wood,[132] V. Zhukova,[132] A. f. Barfuss,[133] T. Bolton,[133] I. Chakaberia,[133] A. Ivanov,[133] S. Khalil,[133] M. Makouski,[133] Y. Maravin,[133] S. Shrestha,[133] I. Svintradze,[133] Z. Wan,[133] J. Gronberg,[134] D. Lange,[134] D. Wright,[134] A. Baden,[135] M. Boutemeur,[135] S. C. Eno,[135] D. Ferencek,[135] J. A. Gomez,[135] N. J. Hadley,[135] R. G. Kellogg,[135] M. Kirn,[135] Y. Lu,[135] A. C. Mignerey,[135] K. Rossato,[135] P. Rumerio,[135] F. Santanastasio,[135] A. Skuja,[135] J. Temple,[135] M. B. Tonjes,[135] S. C. Tonwar,[135] E. Twedt,[135] B. Alver,[136] G. Bauer,[136] J. Bendavid,[136] W. Busza,[136] E. Butz,[136] I. A. Cali,[136] M. Chan,[136] V. Dutta,[136] P. Everaerts,[136] G. Gomez Ceballos,[136] M. Goncharov,[136] K. A. Hahn,[136] P. Harris,[136] Y. Kim,[136] M. Klute,[136] Y.-J. Lee,[136] W. Li,[136] C. Loizides,[136] P. D. Luckey,[136] T. Ma,[136] S. Nahn,[136] C. Paus,[136] D. Ralph,[136] C. Roland,[136] G. Roland,[136] M. Rudolph,[136] G. S. F. Stephans,[136] F. Stöckli,[136] K. Sumorok,[136] K. Sung,[136] E. A. Wenger,[136] S. Xie,[136] M. Yang,[136] Y. Yilmaz,[136] A. S. Yoon,[136] M. Zanetti,[136] S. I. Cooper,[137] P. Cushman,[137] B. Dahmes,[137] A. De Benedetti,[137] P. R. Dudero,[137] G. Franzoni,[137] J. Haupt,[137] K. Klapoetke,[137] Y. Kubota,[137] J. Mans,[137] V. Rekovic,[137] R. Rusack,[137] M. Sasseville,[137] A. Singovsky,[137] L. M. Cremaldi,[138] R. Godang,[138] R. Kroeger,[138] L. Perera,[138] R. Rahmat,[138] D. A. Sanders,[138] D. Summers,[138] K. Bloom,[139] S. Bose,[139] J. Butt,[139] D. R. Claes,[139] A. Dominguez,[139] M. Eads,[139] J. Keller,[139] T. Kelly,[139] I. Kravchenko,[139] J. Lazo-Flores,[139] H. Malbouisson,[139] S. Malik,[139] G. R. Snow,[139] U. Baur,[140] A. Godshalk,[140] I. Iashvili,[140] S. Jain,[140] A. Kharchilava,[140] A. Kumar,[140] S. P. Shipkowski,[140] K. Smith,[140] G. Alverson,[141] E. Barberis,[141] D. Baumgartel,[141] O. Boeriu,[141] M. Chasco,[141] S. Reucroft,[141] J. Swain,[141] D. Trocino,[141] D. Wood,[141] J. Zhang,[141] A. Anastassov,[142] A. Kubik,[142] N. Odell,[142] R. A. Ofierzynski,[142] B. Pollack,[142] A. Pozdnyakov,[142] M. Schmitt,[142] S. Stoynev,[142] M. Velasco,[142] S. Won,[142] L. Antonelli,[143] D. Berry,[143] M. Hildreth,[143] C. Jessop,[143] D. J. Karmgard,[143] J. Kolb,[143] T. Kolberg,[143] K. Lannon,[143] W. Luo,[143] S. Lynch,[143] N. Marinelli,[143] D. M. Morse,[143] T. Pearson,[143] R. Ruchti,[143] J. Slaunwhite,[143] N. Valls,[143] M. Wayne,[143] J. Ziegler,[143] B. Bylsma,[144] L. S. Durkin,[144] J. Gu,[144] C. Hill,[144] P. Killewald,[144] K. Kotov,[144] T. Y. Ling,[144] M. Rodenburg,[144] G. Williams,[144] N. Adam,[145] E. Berry,[145] P. Elmer,[145] D. Gerbaudo,[145] V. Halyo,[145] P. Hebda,[145]

A. Hunt,[145] J. Jones,[145] E. Laird,[145] D. Lopes Pegna,[145] D. Marlow,[145] T. Medvedeva,[145] M. Mooney,[145] J. Olsen,[145] P. Piroué,[145] X. Quan,[145] H. Saka,[145] D. Stickland,[145] C. Tully,[145] J. S. Werner,[145] A. Zuranski,[145] J. G. Acosta,[146] X. T. Huang,[146] A. Lopez,[146] H. Mendez,[146] S. Oliveros,[146] J. E. Ramirez Vargas,[146] A. Zatserklyaniy,[146] E. Alagoz,[147] V. E. Barnes,[147] G. Bolla,[147] L. Borrello,[147] D. Bortoletto,[147] A. Everett,[147] A. F. Garfinkel,[147] L. Gutay,[147] Z. Hu,[147] M. Jones,[147] O. Koybasi,[147] M. Kress,[147] A. T. Laasanen,[147] N. Leonardo,[147] C. Liu,[147] V. Maroussov,[147] P. Merkel,[147] D. H. Miller,[147] N. Neumeister,[147] I. Shipsey,[147] D. Silvers,[147] A. Svyatkovskiy,[147] H. D. Yoo,[147] J. Zablocki,[147] Y. Zheng,[147] P. Jindal,[148] N. Parashar,[148] C. Boulahouache,[149] V. Cuplov,[149] K. M. Ecklund,[149] F. J. M. Geurts,[149] B. P. Padley,[149] R. Redjimi,[149] J. Roberts,[149] J. Zabel,[149] B. Betchart,[150] A. Bodek,[150] Y. S. Chung,[150] R. Covarelli,[150] P. de Barbaro,[150] R. Demina,[150] Y. Eshaq,[150] H. Flacher,[150] A. Garcia-Bellido,[150] P. Goldenzweig,[150] Y. Gotra,[150] J. Han,[150] A. Harel,[150] D. C. Miner,[150] D. Orbaker,[150] G. Petrillo,[150] D. Vishnevskiy,[150] M. Zielinski,[150] A. Bhatti,[151] R. Ciesielski,[151] L. Demortier,[151] K. Goulianos,[151] G. Lungu,[151] S. Malik,[151] C. Mesropian,[151] M. Yan,[151] O. Atramentov,[152] A. Barker,[152] D. Duggan,[152] Y. Gershtein,[152] R. Gray,[152] E. Halkiadakis,[152] D. Hidas,[152] D. Hits,[152] A. Lath,[152] S. Panwalkar,[152] R. Patel,[152] A. Richards,[152] K. Rose,[152] S. Schnetzer,[152] S. Somalwar,[152] R. Stone,[152] S. Thomas,[152] G. Cerizza,[153] M. Hollingsworth,[153] S. Spanier,[153] Z. C. Yang,[153] A. York,[153] J. Asaadi,[154] R. Eusebi,[154] J. Gilmore,[154] A. Gurrola,[154] T. Kamon,[154] V. Khotilovich,[154] R. Montalvo,[154] C. N. Nguyen,[154] I. Osipenkov,[154] Y. Pakhotin,[154] J. Pivarski,[154] A. Safonov,[154] S. Sengupta,[154] A. Tatarinov,[154] D. Toback,[154] M. Weinberger,[154] N. Akchurin,[155] C. Bardak,[155] J. Damgov,[155] C. Jeong,[155] K. Kovitanggoon,[155] S. W. Lee,[155] Y. Roh,[155] A. Sill,[155] I. Volobouev,[155] R. Wigmans,[155] E. Yazgan,[155] E. Appelt,[156] E. Brownson,[156] D. Engh,[156] C. Florez,[156] W. Gabella,[156] M. Issah,[156] W. Johns,[156] P. Kurt,[156] C. Maguire,[156] A. Melo,[156] P. Sheldon,[156] B. Snook,[156] S. Tuo,[156] J. Velkovska,[156] M. W. Arenton,[157] M. Balazs,[157] S. Boutle,[157] B. Cox,[157] B. Francis,[157] R. Hirosky,[157] A. Ledovskoy,[157] C. Lin,[157] C. Neu,[157] R. Yohay,[157] S. Gollapinni,[158] R. Harr,[158] P. E. Karchin,[158] P. Lamichhane,[158] M. Mattson,[158] C. Milstène,[158] A. Sakharov,[158] M. Anderson,[159] M. Bachtis,[159] J. N. Bellinger,[159] D. Carlsmith,[159] S. Dasu,[159] J. Efron,[159] K. Flood,[159] L. Gray,[159] K. S. Grogg,[159] M. Grothe,[159] R. Hall-Wilton,[159] M. Herndon,[159] P. Klabbers,[159] J. Klukas,[159] A. Lanaro,[159] C. Lazaridis,[159] J. Leonard,[159] R. Loveless,[159] A. Mohapatra,[159] F. Palmonari,[159] D. Reeder,[159] I. Ross,[159] A. Savin,[159] W. H. Smith,[159] J. Swanson,[159] and M. Weinberg[159]

(CMS Collaboration)

[1]*Yerevan Physics Institute, Yerevan, Armenia*
[2]*Institut für Hochenergiephysik der OeAW, Wien, Austria*
[3]*National Centre for Particle and High Energy Physics, Minsk, Belarus*
[4]*Universiteit Antwerpen, Antwerpen, Belgium*
[5]*Vrije Universiteit Brussel, Brussel, Belgium*
[6]*Université Libre de Bruxelles, Bruxelles, Belgium*
[7]*Ghent University, Ghent, Belgium*
[8]*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*
[9]*Université de Mons, Mons, Belgium*
[10]*Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil*
[11]*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
[12]*Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil*
[13]*Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria*
[14]*University of Sofia, Sofia, Bulgaria*
[15]*Institute of High Energy Physics, Beijing, China*
[16]*State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China*
[17]*Universidad de Los Andes, Bogota, Colombia*
[18]*Technical University of Split, Split, Croatia*
[19]*University of Split, Split, Croatia*
[20]*Institute Rudjer Boskovic, Zagreb, Croatia*
[21]*University of Cyprus, Nicosia, Cyprus*
[22]*Charles University, Prague, Czech Republic*
[23]*Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt*
[24]*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*
[25]*Department of Physics, University of Helsinki, Helsinki, Finland*

[26]Helsinki Institute of Physics, Helsinki, Finland
[27]Lappeenranta University of Technology, Lappeenranta, Finland
[28]Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
[29]DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
[30]Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
[31]Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
[32]Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules (IN2P3), Villeurbanne, France
[33]Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
[34]Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
[35]RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
[36]RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
[37]RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
[38]Deutsches Elektronen-Synchrotron, Hamburg, Germany
[39]University of Hamburg, Hamburg, Germany
[40]Institut für Experimentelle Kernphysik, Karlsruhe, Germany
[41]Institute of Nuclear Physics "Demokritos", Aghia Paraskevi, Greece
[42]University of Athens, Athens, Greece
[43]University of Ioánnina, Ioánnina, Greece
[44]KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
[45]Institute of Nuclear Research ATOMKI, Debrecen, Hungary
[46]University of Debrecen, Debrecen, Hungary
[47]Panjab University, Chandigarh, India
[48]University of Delhi, Delhi, India
[49]Bhabha Atomic Research Centre, Mumbai, India
[50]Tata Institute of Fundamental Research-EHEP, Mumbai, India
[51]Tata Institute of Fundamental Research-HECR, Mumbai, India
[52]Institute for Research and Fundamental Sciences (IPM), Tehran, Iran
[53a]INFN Sezione di Bari, Bari, Italy
[53b]Università di Bari, Bari, Italy
[53c]Politecnico di Bari, Bari, Italy
[54a]INFN Sezione di Bologna, Bologna, Italy
[54b]Università di Bologna, Bologna, Italy
[55a]INFN Sezione di Catania, Catania, Italy
[55b]Università di Catania, Catania, Italy
[56a]INFN Sezione di Firenze, Firenze, Italy
[56b]Università di Firenze, Firenze, Italy
[57]INFN Laboratori Nazionali di Frascati, Frascati, Italy
[58]INFN Sezione di Genova, Genova, Italy
[59a]INFN Sezione di Milano-Bicocca, Milano, Italy
[59b]Università di Milano-Bicocca, Milano, Italy
[60a]INFN Sezione di Napoli, Napoli, Italy
[60b]Università di Napoli "Federico II", Napoli, Italy
[61a]INFN Sezione di Padova, Padova, Italy
[61b]Università di Padova, Padova, Italy
[61c]Università di Trento (Trento), Padova, Italy
[62a]INFN Sezione di Pavia, Pavia, Italy
[62b]Università di Pavia, Pavia, Italy
[63a]INFN Sezione di Perugia, Perugia, Italy
[63b]Università di Perugia, Perugia, Italy
[64a]INFN Sezione di Pisa, Pisa, Italy
[64b]Università di Pisa, Pisa, Italy
[64c]Scuola Normale Superiore di Pisa, Pisa, Italy
[65a]INFN Sezione di Roma, Roma, Italy
[65b]Università di Roma "La Sapienza", Roma, Italy
[66a]INFN Sezione di Torino, Torino, Italy
[66b]Università di Torino, Torino, Italy
[66c]Università del Piemonte Orientale (Novara), Torino, Italy
[67a]INFN Sezione di Trieste, Trieste, Italy
[67b]Università di Trieste, Trieste, Italy
[68]Kangwon National University, Chunchon, Korea

[69]Kyungpook National University, Daegu, Korea
[70]Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
[71]Korea University, Seoul, Korea
[72]University of Seoul, Seoul, Korea
[73]Sungkyunkwan University, Suwon, Korea
[74]Vilnius University, Vilnius, Lithuania
[75]Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
[76]Universidad Iberoamericana, Mexico City, Mexico
[77]Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
[78]Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
[79]University of Auckland, Auckland, New Zealand
[80]University of Canterbury, Christchurch, New Zealand
[81]National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
[82]Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
[83]Soltan Institute for Nuclear Studies, Warsaw, Poland
[84]Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
[85]Joint Institute for Nuclear Research, Dubna, Russia
[86]Petersburg Nuclear Physics Institute, Gatchina (St Petersburg), Russia
[87]Institute for Nuclear Research, Moscow, Russia
[88]Institute for Theoretical and Experimental Physics, Moscow, Russia
[89]Moscow State University, Moscow, Russia
[90]P.N. Lebedev Physical Institute, Moscow, Russia
[91]State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
[92]University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
[93]Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
[94]Universidad Autónoma de Madrid, Madrid, Spain
[95] Universidad de Oviedo, Oviedo, Spain
[96]Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
[97]CERN, European Organization for Nuclear Research, Geneva, Switzerland
[98]Paul Scherrer Institut, Villigen, Switzerland
[99]Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
[100]Universität Zürich, Zurich, Switzerland
[101]National Central University, Chung-Li, Taiwan
[102]National Taiwan University (NTU), Taipei, Taiwan
[103]Cukurova University, Adana, Turkey
[104]Middle East Technical University, Physics Department, Ankara, Turkey
[105]Bogazici University, Istanbul, Turkey
[106]National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
[107]University of Bristol, Bristol, United Kingdom
[108]Rutherford Appleton Laboratory, Didcot, United Kingdom
[109]Imperial College, London, United Kingdom
[110]Brunel University, Uxbridge, United Kingdom
[111]Baylor University, Waco, USA
[112]Boston University, Boston, USA
[113]Brown University, Providence, USA
[114]University of California, Davis, Davis, USA
[115]University of California, Los Angeles, Los Angeles, USA
[116]University of California, Riverside, Riverside, USA
[117]University of California, San Diego, La Jolla, USA
[118]University of California, Santa Barbara, Santa Barbara, USA
[119]California Institute of Technology, Pasadena, USA
[120]Carnegie Mellon University, Pittsburgh, USA
[121]University of Colorado at Boulder, Boulder, USA
[122]Cornell University, Ithaca, USA
[123]Fairfield University, Fairfield, USA
[124]Fermi National Accelerator Laboratory, Batavia, USA
[125]University of Florida, Gainesville, USA
[126]Florida International University, Miami, USA
[127]Florida State University, Tallahassee, USA
[128]Florida Institute of Technology, Melbourne, USA
[129]University of Illinois at Chicago (UIC), Chicago, USA

[130]*The University of Iowa, Iowa City, USA*
[131]*Johns Hopkins University, Baltimore, USA*
[132]*The University of Kansas, Lawrence, USA*
[133]*Kansas State University, Manhattan, USA*
[134]*Lawrence Livermore National Laboratory, Livermore, USA*
[135]*University of Maryland, College Park, USA*
[136]*Massachusetts Institute of Technology, Cambridge, USA*
[137]*University of Minnesota, Minneapolis, USA*
[138]*University of Mississippi, University, USA*
[139]*University of Nebraska-Lincoln, Lincoln, USA*
[140]*State University of New York at Buffalo, Buffalo, USA*
[141]*Northeastern University, Boston, USA*
[142]*Northwestern University, Evanston, USA*
[143]*University of Notre Dame, Notre Dame, USA*
[144]*The Ohio State University, Columbus, USA*
[145]*Princeton University, Princeton, USA*
[146]*University of Puerto Rico, Mayaguez, USA*
[147]*Purdue University, West Lafayette, USA*
[148]*Purdue University Calumet, Hammond, USA*
[149]*Rice University, Houston, USA*
[150]*University of Rochester, Rochester, USA*
[151]*The Rockefeller University, New York, USA*
[152]*Rutgers, the State University of New Jersey, Piscataway, USA*
[153]*University of Tennessee, Knoxville, USA*
[154]*Texas A&M University, College Station, USA*
[155]*Texas Tech University, Lubbock, USA*
[156]*Vanderbilt University, Nashville, USA*
[157]*University of Virginia, Charlottesville, USA*
[158]*Wayne State University, Detroit, USA*
[159]*University of Wisconsin, Madison, USA*

[a]Deceased.
[b]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[c]Also at Universidade Federal do ABC, Santo Andre, Brazil.
[d]Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France., USA
[e]Also at Suez Canal University, Suez, Egypt.
[f]Also at British University, Cairo, Egypt.
[g]Also at Fayoum University, El-Fayoum, Egypt.
[h]Also at Soltan Institute for Nuclear Studies, Warsaw, Poland.
[i]Also at Massachusetts Institute of Technology, Cambridge, USA.
[j]Also at Université de Haute-Alsace, Mulhouse, France.
[k]Also at Brandenburg University of Technology, Cottbus, Germany.
[l]Also at Moscow State University, Moscow, Russia.
[m]Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[n]Also at Eötvös Loránd University, Budapest, Hungary.
[o]Also at Tata Institute of Fundamental Research-HECR, Mumbai, India.
[p]Also at University of Visva-Bharati, Santiniketan, India.
[q]Also at Sharif University of Technology, Tehran, Iran.
[r]Also at Shiraz University, Shiraz, Iran.
[s]Also at Isfahan University of Technology, Isfahan, Iran.
[t]Also at Facoltà Ingegneria Università di Roma ''La Sapienza'', Roma, Italy.
[u]Also at Università della Basilicata, Potenza, Italy.
[v]Also at Università degli studi di Siena, Siena, Italy.
[w]Also at California Institute of Technology, Pasadena, USA.
[x]Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia.
[y]Also at University of California, Los Angeles, Los Angeles, USA.
[z]Also at University of Florida, Gainesville, USA.
[aa]Also at Université de Genève, Geneva, Switzerland.

[bb]Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy.
[cc]Also at INFN Sezione di Roma, Università di Roma ''La Sapienza'', Roma, Italy.
[dd]Also at University of Athens, Athens, Greece.
[ee]Also at The University of Kansas, Lawrence, USA.
[ff]Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
[gg]Also at Paul Scherrer Institut, Villigen, Switzerland.
[hh]Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
[ii]Also at Gaziosmanpasa University, Tokat, Turkey.
[jj]Also at Adiyaman University, Adiyaman, Turkey.
[kk]Also at Mersin University, Mersin, Turkey.
[ll]Also at Izmir Institute of Technology, Izmir, Turkey.
[mm]Also at Kafkas University, Kars, Turkey.
[nn]Also at Suleyman Demirel University, Isparta, Turkey.
[oo]Also at Ege University, Izmir, Turkey.
[pp]Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
[qq]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[rr]Also at INFN Sezione di Perugia, Università di Perugia, Perugia, Italy.
[ss]Also at Utah Valley University, Orem, USA.
[tt]Also at Institute for Nuclear Research, Moscow, Russia.
[uu]Also at Erzincan University, Erzincan, Turkey.