Search for Top-Quark Partners with Charge 5/3 in the Same-Sign Dilepton Final State

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A search for the production of heavy partners of the top quark with charge 5/3 is performed in events with a pair of same-sign leptons. The data sample corresponds to an integrated luminosity of 19.5 fb^{-1} and was collected at $\sqrt{s} = 8$ TeV by the CMS experiment. No significant excess is observed in the data above the expected background, and the existence of top-quark partners with masses below 800 GeV is excluded at a 95% confidence level, assuming they decay exclusively to tW. This is the first limit on these particles from the LHC, and it is significantly more restrictive than previous limits.

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Various extensions of the standard model (SM) address the hierarchy problem, caused by the quadratic divergences in the quantum-loop corrections to the Higgs boson mass, by proposing new heavy particles. Since the largest correction arises from the top-quark loop, a class of these models, based on composite Higgs scenarios [1–4], predicts the existence of heavy partners of the top quark to explain the cancellation of this correction. These "top-quark partners" are expected to have masses close to the electroweak symmetry breaking scale and thus would be accessible at the CERN Large Hadron Collider (LHC), located near Geneva, Switzerland. They may also have exotic charge ($5e/3$, where $-e$ is the charge of the electron) and in this case would not contribute to the coupling of the Higgs boson to gluons [5]. Searches for such top-quark partners explore parameter space that is not excluded by the recent observation of a Higgs boson with properties consistent with those of the SM Higgs particle [6–14]. Theoretical predictions suggest that searches in the mass region from 500 GeV to 1.5 TeV present the greatest potential for discovery at the LHC [2,15].

This Letter presents a search for exotic top-quark partners using LHC pp collision data collected by the Compact Muon Solenoid (CMS) experiment at a center-of-mass energy $\sqrt{s} = 8$ TeV. The analysis is based on a data sample corresponding to an integrated luminosity of 19.5 fb^{-1}. We look for the $T_{5/3}$, an exotic top-quark partner with charge $5e/3$. We assume that the $T_{5/3}$ is pair produced via either gluon fusion or quark annihilation and decays via $T_{5/3} \to tW^+$ followed by $t \to W^+ b$ (charge conjugate modes are implied throughout this Letter). Single $T_{5/3}$ production is not considered because it is more model dependent and presents a different event topology [2].

We focus on the dilepton final state wherein, for one or both of the $T_{5/3}$, its two W bosons both decay into leptons, which will have the same charge. Because of the presence of the two bottom quarks and the possibility of hadronic decays for one of the top-quark partners, this final state also includes significant jet activity. The leptons considered in this analysis are electrons and muons. The presence of leptons with the same electric charge (same-sign leptons) distinguishes this process from $t\bar{t}$, making the contribution of the latter comparable to backgrounds with much smaller cross sections: $t\bar{t}W$, $t\bar{t}WW$, $t\bar{t}Z$, WWW, and same-sign WW. Because of its large cross section, $t\bar{t}$ still contributes to the overall background through instrumental effects such as charge misidentification in dilepton decays, as well as through $t\bar{t}$ events where the W boson from one top quark decays leptonically and the second lepton arises from a b-quark decay. Additional processes that contribute to the expected background include QCD multijets, $W/Z+$jets, and dibosons (WZ and ZZ). A previous search using a signature of same-sign leptons, multiple jets, and missing transverse energy was performed by the CDF experiment and excludes $T_{5/3}$ masses below 365 GeV at the 95% confidence level (C.L.) [16]. The CDF Collaboration also set a limit on the production of exotic quarks with charge $-4e/3$ [17].

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel flux return yoke outside the solenoid. In addition, the CMS detector has extensive forward calorimetry. A more detailed description of the CMS detector can be found elsewhere [18].

Simulation of the pair production of top-quark partners was performed with the MADGRAPH 5.1.1 [19] event generator, and 12 samples corresponding to values of the

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$T_{5/3}$ mass from 350 GeV to 1 TeV were produced. The PYTHIA 6.426 [20] generator was used for parton showering, hadronization, and simulation of the underlying event. The CTEQ6L [21] parton distribution functions were used, and the PYTHIA parameters for the underlying event were set to the $Z2^*$ [22] tune. The detector response was modeled using GEANT4 [23]. The next-to-next-to-leading-order cross section for $T_{5/3}$ pair production was found using TOP++ [24] to vary from 5.3 pb at the mass of 350 GeV to 3.4 fb at the mass of 1 TeV. The uncertainty on the cross section in the mass range used for the analysis is about 5%.

The background processes include $t\bar{t}$, $W(\to \ell\nu)$ + jets, $Z/\gamma^*(\to \ell\ell)$ + jets, and dibosons (WZ and ZZ). Additional low-rate SM processes were also considered: $W^\pm W^\pm$, WWW, $t\bar{t}W$, $t\bar{t}WW$, and $t\bar{t}Z$. These were all simulated by means of MADGRAPH with PYTHIA used for hadronization. Next-to-leading-order or, where available, next-to-next-to-leading-order cross sections were employed [25,26].

For all the simulated samples, the additional proton-proton interactions in each beam crossing (pileup) were modeled by superimposing minimum bias interactions (obtained using PYTHIA with the $Z2^*$ tune) onto simulated events, with the multiplicity distribution matching the one observed in data.

This analysis relies on the reconstruction of three physical objects: electrons, muons, and jets. The events are reconstructed using the CMS "particle-flow" event description algorithm [27,28]. Candidate events are required to have at least two leptons with the same charge that are within the detector acceptance ($|\eta| < 2.4$) and to have passed triggers based on dielectrons, dimuons, or electron-muon combinations. Here, η is the pseudorapidity defined as $\eta \equiv -\ln[\tan(\theta/2)]$, where θ is the polar angle with respect to the counterclockwise beam direction. Candidate events must also have at least one good reconstructed primary vertex matched to the track origins of the two selected leptons. Candidate electrons are reconstructed using energy deposits in the ECAL and a track from the silicon detectors. The shape of the shower in the ECAL must be consistent with that of an electron, and the shower must be well matched to the extrapolated track. Additional requirements are imposed to reject electrons produced by photon conversions. The charge of each electron candidate is measured using three different methods. Two of the measurements are based on two different tracking algorithms: the standard CMS track reconstruction algorithm [29] and the Gaussian sum filter algorithm [30], optimized to take into account the possible emission of bremsstrahlung photons in the silicon tracker. The third measurement is based on the relative position of the calorimeter cluster and the projected track from the pixel detector. All three measurements are required to be consistent with the electron hypothesis. Muon candidates are required to be reconstructed by both the silicon tracker and the muon system, and the combined fit of the track must be of good quality (χ^2 per degree of freedom less than 10).

All selected leptons are required to be isolated. The isolation for each lepton is estimated by first computing the scalar sum of the transverse momenta of all neutral and charged reconstructed particle candidates, except the lepton itself, within a cone of size $\Delta R \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ around the lepton, where ϕ is the azimuthal angle. This sum is then divided by the transverse momentum (p_T) of the lepton to calculate the relative isolation (I_R). The values for the cone size and the maximum allowed I_R are $\Delta R = 0.3(0.4)$ and $I_R = 0.15(0.20)$, respectively, for electrons (muons), as determined by optimization studies for CMS top-quark related analyses. An event-by-event correction is applied to the computation of the lepton isolation in order to account for the effect of pileup. Scale factors to correct for imperfect detector simulation are obtained using the tag-and-probe method [31] for lepton identification and isolation as a function of lepton p_T and η. In addition, we define a category of "loose" leptons with some of the isolation and identification requirements relaxed. The I_R threshold for these leptons is increased from 0.15 to 0.60 for electrons and from 0.20 to 0.40 for muons.

For the range of $T_{5/3}$ masses accessible at $\sqrt{s} = 8$ TeV, the analysis exploits advanced techniques in jet reconstruction for identifying highly boosted top quarks and W bosons that decay hadronically. In particular, if the top quarks are highly boosted ($p_T > 400$ GeV), their decay products are collimated and merged into one jet. We use a "top-quark tagging" algorithm based on identifying jet substructure [32] to reconstruct such merged top-quark jets. Jets are clustered using the Cambridge-Aachen algorithm [33,34], as implemented in FASTJET version 3 [35], with a distance parameter of $R = 0.8$ in η-ϕ space (CA8 jets). The CA8 top-quark jets are required to have $p_T > 400$ GeV and more than two subjets found by the top-quark tagging algorithm. The jet mass must be consistent with the mass of the top quark, and the minimum pairwise mass of the three highest p_T subjets is required to be greater than 50 GeV.

The decay products of W bosons from the $T_{5/3}$ decay or from a highly boosted top quark, for which the b quark is reconstructed independently, may also merge into a single jet. We use a "jet pruning" algorithm [36] to identify the hadronic decay of such W bosons. This algorithm also uses CA8 jets as inputs with the pruning parameters taken from the original theoretical papers [37,38]. CA8 W-boson jets are required to have $p_T > 200$ GeV, exactly two subjets, and their mass must be consistent with that of the W boson [39].

To account for W bosons and top quarks that are not highly boosted, jets are also reconstructed using the anti-k_T algorithm [40] with a distance parameter of 0.5 (AK5). These jets are required to have $p_T > 30$ GeV. If an AK5 jet overlaps with a top-quark jet or a W-boson jet ($\Delta R < 0.8$), the AK5 jet is discarded.

All of the above categories of jets are required to have $|\eta| < 2.4$ and particle-flow jet identification [41]. Jet energy corrections are applied to account for residual nonuniformity and nonlinearity of the detector response. Jet energies are also corrected by subtracting the average contribution of particles from pileup [42,43]. For the simulated samples, additional smearing is applied to the jet p_T (~7%–19% depending on η) in order to reproduce the jet energy resolution observed in data. All jets must be $\Delta R \geq 0.3$ away from the selected leptons and, as mentioned above, $\Delta R \geq 0.8$ away from any other jet. A correction to account for differences in the identification efficiency of W-boson and top-quark jets between data and simulation is applied [44].

The signal selection, optimized to yield the best signal sensitivity, requires the following. (i) At least two isolated same-sign leptons as defined above with $p_T > 30$ GeV. Between each lepton and every top-quark jet, we require $\Delta R > 0.8$. (ii) Dilepton Z-boson veto: $M(ee) < 76$ GeV or $M(ee) > 106$ GeV. This selection applies only to the dielectron channel. If the muon charge is mismeasured, its momentum will also be mismeasured, so a selected muon pair from a Z boson will not fall within this invariant mass range. (iii) Trilepton Z-boson veto: $M(\ell\ell) < 76$ GeV or $M(\ell\ell) > 106$ GeV, where $M(\ell\ell)$ is the invariant mass of either one of the selected leptons and any other same-flavor opposite-sign lepton in the event with $p_T > 15$ GeV that satisfies the loose lepton criteria. (iv) $N_c \geq 7$, where N_c is the number of constituents identified in the event. For the purpose of this selection, each AK5 jet and each lepton count as one constituent. Since a W-boson jet is assumed to correspond to a W boson, each such jet counts as two constituents, corresponding to the W-boson decay products. Likewise, each top-quark jet represents a top quark and counts as three constituents. (v) $H_T > 900$ GeV, where H_T is the scalar sum of the p_T of all selected jets and leptons in the event. With these criteria, the signal efficiency is 10%–13% for $T_{5/3}$ masses between 750 and 1000 GeV.

The backgrounds associated with this analysis fall into three main categories. First, they may originate from SM processes leading to prompt, same-sign dilepton signatures, including diboson production (WZ and ZZ), $t\bar{t}W$, $t\bar{t}WW$, $t\bar{t}Z$, $W^{\pm}W^{\pm}$, and WWW. The contribution of these backgrounds is obtained from simulation.

The second category consists of events from processes with prompt, opposite-sign leptons, such as $t\bar{t}$ and Drell-Yan production, in which one of the leptons is misreconstructed with the wrong charge, leading to a same-sign dilepton final state. For muons in the p_T range typical of the dominant backgrounds, the charge misidentification rate is extremely small (of order 10^{-4}) and its contribution to the background is negligible [45]. For electrons, the charge misidentification probability (~10^{-3}) is derived from a data sample dominated by Drell-Yan events obtained by selecting dileptons with an invariant mass consistent with originating from the Z boson, using the ratio of same-sign Z-boson candidates to the total number of candidates. The number of expected same-sign events due to charge misidentification is then estimated by considering the total number of events passing the full selection but having oppositely charged leptons. These events are weighted by the charge misidentification probability parametrized as a function of the electron p_T and η to obtain the contribution of this background type.

The third category consists of events with one or more "nonprompt leptons." This is the primary instrumental background arising from jets being misidentified as leptons and nonprompt leptons passing tight isolation selection criteria. This contribution is estimated using the "tight-loose" method described in Ref. [46]. "Tight" leptons have the same definition as those used in the analysis, whereas "loose" leptons are defined earlier. The background is estimated by using events with one or more loose leptons weighted by the ratios of the numbers of tight leptons to the numbers of loose leptons expected for prompt and nonprompt leptons. The ratio for prompt leptons is determined from Drell-Yan events where the invariant mass of the leptons is within 10 GeV of the Z-boson mass. The nonprompt ratio is determined from a sample enriched in background by requiring exactly one lepton, low missing transverse energy ($E_T^{\text{miss}} < 25$ GeV), low transverse mass ($M_T < 25$ GeV), and at least one jet (the "away jet") with $p_T > 40$ GeV and $\Delta R > 1.0$ with respect to the lepton. The transverse mass is defined as $M_T \equiv \sqrt{2 p_T^{\ell} E_T^{\text{miss}}(1 - \cos\Delta\phi)}$, where $\Delta\phi$ is the angle between the lepton transverse momentum (p_T^{ℓ}) and the direction associated with E_T^{miss}.

The systematic uncertainties that affect the signal and background acceptance include uncertainties in the efficiency of the trigger (1%), lepton reconstruction and identification efficiency (1% per lepton), pileup, and the jet energy scale (JES). The uncertainties due to the JES and pileup are obtained by varying the respective quantities in simulation. For the signal, the JES and pileup uncertainties in the acceptance correspond to 2% and 3%, respectively. For the simulated backgrounds, they range from 3% to 6%, depending on the sample. In addition, we assign a constant 3% uncertainty due to the JES of CA8 jets for all simulated samples [44]. The dominant uncertainty in the expected event yields due to backgrounds derived from simulation is the overall normalization uncertainty. The ZZ (5.1%), WZ (17%), and $t\bar{t}W$ (32%) normalization uncertainties are taken from Refs. [26,47,48], respectively. For the other rare backgrounds, we assume a conservative normalization uncertainty of 50% [49]. An uncertainty of 20% is assigned to the background contribution from charge misidentification, based on the difference in the charge misidentification rate between Drell-Yan data and $t\bar{t}$ simulation. Following Ref. [45], we also assign a conservative additional systematic uncertainty of 50% in the estimation of backgrounds due to nonprompt leptons. This uncertainty is

TABLE I. Summary table of expected and observed numbers of events for all channels. The background is composed of the same-sign component, the contribution due to charge misidentification, and that due to misreconstructed leptons. All systematic uncertainties are included. Also shown is the expected contribution from a $T_{5/3}$ with mass of 800 GeV.

Channel	ee	$e\mu$	$\mu\mu$	All
Same sign	0.8 ± 0.2	1.9 ± 0.4	1.3 ± 0.3	4.0 ± 0.8
Charge misidentification	0.06 ± 0.02	0.04 ± 0.01	...	0.11 ± 0.02
Nonprompt	1.9 ± 1.2	0.6 ± 0.9	0.3 ± 0.6	2.8 ± 1.9
Total background	2.7 ± 1.3	2.5 ± 1.0	1.6 ± 0.7	6.8 ± 2.1
Observed events	0	6	3	9
$T_{5/3}$	2.1 ± 0.1	4.7 ± 0.3	2.8 ± 0.2	9.7 ± 0.5

based on closure tests using $t\bar{t}$ and $W+$jets simulated samples and takes into account variations due to the away jet p_T and the flavor composition of the background, thus also accounting for any potential dependence on kinematic parameters that alter the background composition (such as H_T). We also include a 2.6% uncertainty due to the luminosity [50] for all event yields that are derived from simulation.

The final numbers of observed and expected events are reported in Table I for each of the three lepton channels (ee, $e\mu$, and $\mu\mu$) and their combination. Figure 1 shows the H_T distribution for all channels combined.

No significant excess is observed. Exclusion limits are computed at 95% C.L. by using the ROOSTATS implementation [51] of the Bayesian approach. We use a cut-and-count method and compare the numbers of observed events with the numbers of expected signal and background events. A flat prior is used for the signal production cross section. The event yields from all lepton channels are combined when setting the limits. Upper bounds are set on the production cross section of heavy top-quark partners, assuming a 100% branching fraction (BF) for the decay $T_{5/3} \to tW$. The resulting expected and observed limits are shown in Fig. 2. The expected lower limit on the mass of the $T_{5/3}$ is 830 GeV, and the observed limit is 800 GeV.

The use of recently developed jet substructure techniques in this analysis for identifying boosted top quarks and W bosons enables us to probe cross sections of $T_{5/3}$ pair production that are between 10%–20% lower than would otherwise be possible for $T_{5/3}$ masses in the range 800–1000 GeV. The reconstruction of the $T_{5/3}$ mass benefits as well, and this can, in the event of a discovery in the future,

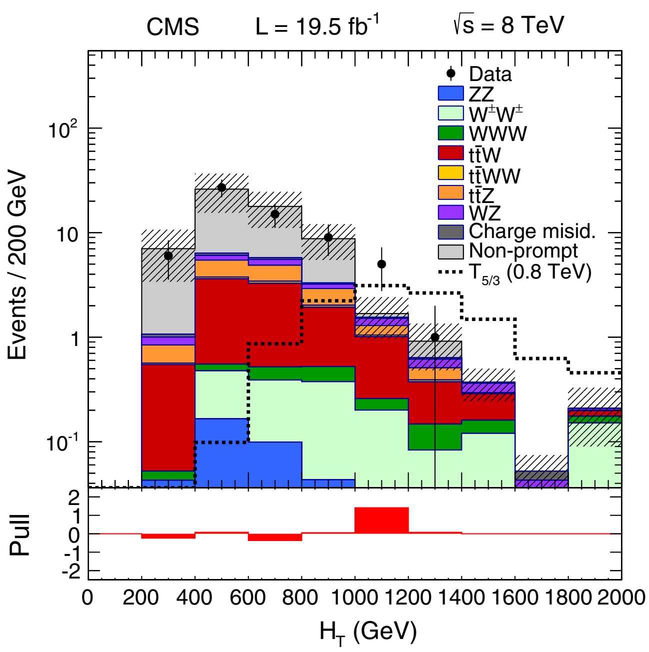

FIG. 1 (color online). The distribution of H_T for all channels combined after the full selection except for the H_T requirement itself. The shaded band represents the total uncertainty in the predicted backgrounds. The final bin includes all overflow events. The pull is defined as the difference between the observed and expected values divided by the total uncertainty.

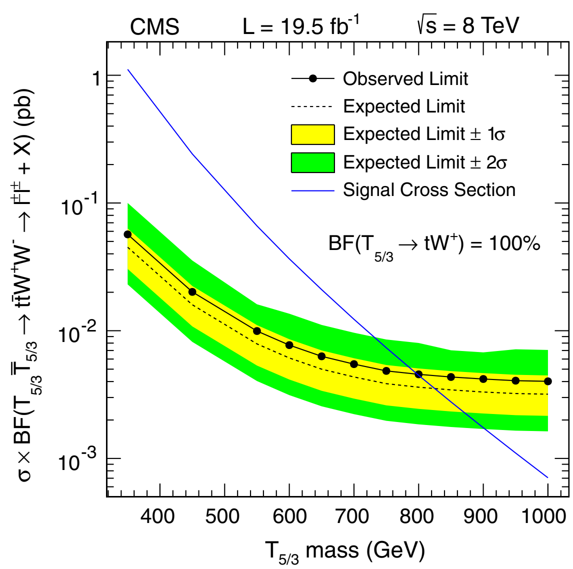

FIG. 2 (color online). Expected and observed 95% C.L. limits on the $T_{5/3}$ production cross section times the branching fraction for decay to same-sign dileptons. The 1σ and 2σ combined statistical and systematic expected variations are shown as yellow (light) and green (dark) bands, respectively.

be used to distinguish a $T_{5/3}$ from other exotic particles which decay in a similar manner [52].

In summary, a search for an exotic top partner with charge 5/3 in same-sign dileptonic events has been performed using 19.5 fb^{-1} of data collected by the CMS experiment at $\sqrt{s} = 8$ TeV. No significant excess is observed in the data above the expected standard model background. An upper bound at the 95% confidence level is set on the production cross section of heavy top-quark partners, assuming a 100% branching fraction for the decay $T_{5/3} \to tW$, and masses below 800 GeV are excluded. This is the first limit on $T_{5/3}$ production from the LHC, and it is significantly more restrictive than the 365 GeV limit set by previous searches.

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[52] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.112.171801 for figures illustrating the agreement of data with background predictions and showing the reconstructed top partner mass.

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Quertenmont,[8] M. Selvaggi,[8] M. Vidal Marono,[8] J. M. Vizan Garcia,[8] N. Beliy,[9] T. Caebergs,[9] E. Daubie,[9] G. H. Hammad,[9] G. A. Alves,[10] M. Correa Martins Junior,[10] T. Martins,[10] M. E. Pol,[10] M. H. G. Souza,[10] W. L. Aldá Júnior,[11] W. Carvalho,[11] J. Chinellato,[11,g] A. Custódio,[11] E. M. Da Costa,[11] D. De Jesus Damiao,[11] C. De Oliveira Martins,[11] S. Fonseca De Souza,[11] H. Malbouisson,[11] M. Malek,[11] D. Matos Figueiredo,[11] L. Mundim,[11] H. Nogima,[11] W. L. Prado Da Silva,[11] J. Santaolalla,[11] A. Santoro,[11] A. Sznajder,[11] E. J. Tonelli Manganote,[11,g] A. Vilela Pereira,[11] C. A. Bernardes,[12b] F. A. Dias,[12a,h] T. R. Fernandez Perez Tomei,[12a] E. M. Gregores,[12b] C. Lagana,[12a] P. G. Mercadante,[12b] S. F. Novaes,[12a] Sandra S. Padula,[12a] V. Genchev,[13,c] P. Iaydjiev,[13,c] A. Marinov,[13] S. Piperov,[13] M. Rodozov,[13] G. Sultanov,[13] M. Vutova,[13] A. Dimitrov,[14] I. Glushkov,[14] R. Hadjiiska,[14] V. Kozhuharov,[14] L. Litov,[14] B. Pavlov,[14] P. Petkov,[14] J. G. Bian,[15] G. M. Chen,[15] H. S. Chen,[15] M. Chen,[15] R. Du,[15] C. H. Jiang,[15] D. Liang,[15] S. Liang,[15] X. Meng,[15] R. Plestina,[15,i] J. Tao,[15] X. Wang,[15] Z. Wang,[15] C. Asawatangtrakuldee,[16] Y. Ban,[16] Y. Guo,[16] Q. Li,[16] W. Li,[16] S. Liu,[16] Y. Mao,[16] S. J. Qian,[16] D. Wang,[16] L. Zhang,[16] W. Zou,[16] C. Avila,[17] C. A. Carrillo Montoya,[17] L. F. Chaparro Sierra,[17] C. Florez,[17] J. P. Gomez,[17] B. Gomez Moreno,[17] J. C. Sanabria,[17] N. Godinovic,[18] D. Lelas,[18] D. Polic,[18] I. Puljak,[18] Z. Antunovic,[19] M. Kovac,[19] V. Brigljevic,[20] K. Kadija,[20] J. Luetic,[20] D. Mekterovic,[20] S. Morovic,[20] L. Tikvica,[20] A. Attikis,[21] G. Mavromanolakis,[21] J. Mousa,[21] C. Nicolaou,[21] F. Ptochos,[21] P. A. Razis,[21] M. Finger,[22] M. Finger Jr.,[22] A. A. Abdelalim,[23,j] Y. Assran,[23,k] S. Elgammal,[23,j] A. Ellithi Kamel,[23,l] M. A. Mahmoud,[23,m] A. Radi,[23,n,o] M. Kadastik,[24] M. Müntel,[24] M. Murumaa,[24] M. Raidal,[24] L. Rebane,[24] A. Tiko,[24] P. Eerola,[25] G. Fedi,[25] M. Voutilainen,[25] J. Härkönen,[26] V. Karimäki,[26] R. Kinnunen,[26] M. J. Kortelainen,[26] T. Lampén,[26] K. Lassila-Perini,[26] S. Lehti,[26] T. Lindén,[26] P. Luukka,[26] T. Mäenpää,[26] T. Peltola,[26] E. Tuominen,[26] J. Tuominiemi,[26] E. Tuovinen,[26] L. Wendland,[26] T. Tuuva,[27] M. Besancon,[28] F. Couderc,[28] M. Dejardin,[28] D. Denegri,[28] B. Fabbro,[28] J. L. Faure,[28] F. Ferri,[28] S. Ganjour,[28] A. Givernaud,[28] P. Gras,[28] G. Hamel de Monchenault,[28] P. Jarry,[28] E. Locci,[28] J. Malcles,[28] A. Nayak,[28] J. Rander,[28] A. Rosowsky,[28] M. Titov,[28] S. Baffioni,[29] F. Beaudette,[29] P. Busson,[29] C. Charlot,[29] N. Daci,[29] T. Dahms,[29] M. Dalchenko,[29] L. Dobrzynski,[29] A. Florent,[29] R. Granier de Cassagnac,[29] M. Haguenauer,[29] P. Miné,[29] C. Mironov,[29] I. N. Naranjo,[29] M. Nguyen,[29] C. Ochando,[29] P. Paganini,[29] D. Sabes,[29] R. Salerno,[29] Y. Sirois,[29] C. Veelken,[29] Y. Yilmaz,[29] A. Zabi,[29] J.-L. Agram,[30,p] J. Andrea,[30]

D. Bloch,[30] J.-M. Brom,[30] E. C. Chabert,[30] C. Collard,[30] E. Conte,[30,p] F. Drouhin,[30,p] J.-C. Fontaine,[30,p] D. Gelé,[30] U. Goerlach,[30] C. Goetzmann,[30] P. Juillot,[30] A.-C. Le Bihan,[30] P. Van Hove,[30] S. Gadrat,[31] S. Beauceron,[32] N. Beaupere,[32] G. Boudoul,[32] S. Brochet,[32] J. Chasserat,[32] R. Chierici,[32] D. Contardo,[32] P. Depasse,[32] H. El Mamouni,[32] J. Fan,[32] J. Fay,[32] S. Gascon,[32] M. Gouzevitch,[32] B. Ille,[32] T. Kurca,[32] M. Lethuillier,[32] L. Mirabito,[32] S. Perries,[32] J. D. Ruiz Alvarez,[32] L. Sgandurra,[32] V. Sordini,[32] M. Vander Donckt,[32] P. Verdier,[32] S. Viret,[32] H. Xiao,[32] Z. Tsamalaidze,[33,q] C. Autermann,[34] S. Beranek,[34] M. Bontenackels,[34] B. Calpas,[34] M. Edelhoff,[34] L. Feld,[34] O. Hindrichs,[34] K. Klein,[34] A. Ostapchuk,[34] A. Perieanu,[34] F. Raupach,[34] J. Sammet,[34] S. Schael,[34] D. Sprenger,[34] H. Weber,[34] B. Wittmer,[34] V. Zhukov,[34,f] M. Ata,[35] J. Caudron,[35] E. Dietz-Laursonn,[35] D. Duchardt,[35] M. Erdmann,[35] R. Fischer,[35] A. Güth,[35] T. Hebbeker,[35] C. Heidemann,[35] K. Hoepfner,[35] D. Klingebiel,[35] S. Knutzen,[35] P. Kreuzer,[35] M. Merschmeyer,[35] A. Meyer,[35] M. Olschewski,[35] K. Padeken,[35] P. Papacz,[35] H. Reithler,[35] S. A. Schmitz,[35] L. Sonnenschein,[35] D. Teyssier,[35] S. Thüer,[35] M. Weber,[35] V. Cherepanov,[36] Y. Erdogan,[36] G. Flügge,[36] H. Geenen,[36] M. Geisler,[36] W. Haj Ahmad,[36] F. Hoehle,[36] B. Kargoll,[36] T. Kress,[36] Y. Kuessel,[36] J. Lingemann,[36,c] A. Nowack,[36] I. M. Nugent,[36] L. Perchalla,[36] O. Pooth,[36] A. Stahl,[36] I. Asin,[37] N. Bartosik,[37] J. Behr,[37] W. Behrenhoff,[37] U. Behrens,[37] A. J. Bell,[37] M. Bergholz,[37,r] A. Bethani,[37] K. Borras,[37] A. Burgmeier,[37] A. Cakir,[37] L. Calligaris,[37] A. Campbell,[37] S. Choudhury,[37] F. Costanza,[37] C. Diez Pardos,[37] S. Dooling,[37] T. Dorland,[37] G. Eckerlin,[37] D. Eckstein,[37] T. Eichhorn,[37] G. Flucke,[37] A. Geiser,[37] A. Grebenyuk,[37] P. Gunnellini,[37] S. Habib,[37] J. Hauk,[37] G. Hellwig,[37] M. Hempel,[37] D. Horton,[37] H. Jung,[37] M. Kasemann,[37] P. Katsas,[37] C. Kleinwort,[37] M. Krämer,[37] D. Krücker,[37] W. Lange,[37] J. Leonard,[37] K. Lipka,[37] W. Lohmann,[37,r] B. Lutz,[37] R. Mankel,[37] I. Marfin,[37] I.-A. Melzer-Pellmann,[37] A. B. Meyer,[37] J. Mnich,[37] A. Mussgiller,[37] S. Naumann-Emme,[37] O. Novgorodova,[37] F. Nowak,[37] H. Perrey,[37] A. Petrukhin,[37] D. Pitzl,[37] R. Placakyte,[37] A. Raspereza,[37] P. M. Ribeiro Cipriano,[37] C. Riedl,[37] E. Ron,[37] M. Ö. Sahin,[37] J. Salfeld-Nebgen,[37] R. Schmidt,[37,r] T. Schoerner-Sadenius,[37] M. Schröder,[37] M. Stein,[37] A. D. R. Vargas Trevino,[37] R. Walsh,[37] C. Wissing,[37] M. Aldaya Martin,[38] V. Blobel,[38] H. Enderle,[38] J. Erfle,[38] E. Garutti,[38] M. Görner,[38] M. Gosselink,[38] J. Haller,[38] K. Heine,[38] R. S. Höing,[38] H. Kirschenmann,[38] R. Klanner,[38] R. Kogler,[38] J. Lange,[38] I. Marchesini,[38] J. Ott,[38] T. Peiffer,[38] N. Pietsch,[38] D. Rathjens,[38] C. Sander,[38] H. Schettler,[38] P. Schleper,[38] E. Schlieckau,[38] A. Schmidt,[38] M. Seidel,[38] J. Sibille,[38,s] V. Sola,[38] H. Stadie,[38] G. Steinbrück,[38] D. Troendle,[38] E. Usai,[38] L. Vanelderen,[38] C. Barth,[39] C. Baus,[39] J. Berger,[39] C. Böser,[39] E. Butz,[39] T. Chwalek,[39] W. De Boer,[39] A. Descroix,[39] A. Dierlamm,[39] M. Feindt,[39] M. Guthoff,[39,c] F. Hartmann,[39,c] T. Hauth,[39,c] H. Held,[39] K. H. Hoffmann,[39] U. Husemann,[39] I. Katkov,[39,f] A. Kornmayer,[39,c] E. Kuznetsova,[39] P. Lobelle Pardo,[39] D. Martschei,[39] M. U. Mozer,[39] Th. Müller,[39] M. Niegel,[39] A. Nürnberg,[39] O. Oberst,[39] G. Quast,[39] K. Rabbertz,[39] F. Ratnikov,[39] S. Röcker,[39] F.-P. Schilling,[39] G. Schott,[39] H. J. Simonis,[39] F. M. Stober,[39] R. Ulrich,[39] J. Wagner-Kuhr,[39] S. Wayand,[39] T. Weiler,[39] R. Wolf,[39] M. Zeise,[39] G. Anagnostou,[40] G. Daskalakis,[40] T. 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Banerjee,[49] S. Bhattacharya,[49] K. Chatterjee,[49] S. Dutta,[49] B. Gomber,[49] Sa. Jain,[49] Sh. Jain,[49] R. Khurana,[49] A. Modak,[49] S. Mukherjee,[49] D. Roy,[49] S. Sarkar,[49] M. Sharan,[49] A. P. Singh,[49] A. Abdulsalam,[50] D. Dutta,[50] S. Kailas,[50] V. Kumar,[50] A. K. Mohanty,[50,c] L. M. Pant,[50] P. Shukla,[50] A. Topkar,[50] T. Aziz,[51] R. M. Chatterjee,[51] S. Ganguly,[51] S. Ghosh,[51] M. Guchait,[51,w] A. Gurtu,[51,x] G. Kole,[51] S. Kumar,[51] M. Maity,[51,y] G. Majumder,[51] K. Mazumdar,[51] G. B. Mohanty,[51] B. Parida,[51] K. Sudhakar,[51] N. Wickramage,[51,z] S. Banerjee,[52] S. Dugad,[52] H. Arfaei,[53] H. Bakhshiansohi,[53] H. Behnamian,[53] S. M. Etesami,[53,aa] A. Fahim,[53,bb] A. Jafari,[53] M. Khakzad,[53] M. Mohammadi Najafabadi,[53] M. Naseri,[53] S. Paktinat Mehdiabadi,[53] B. Safarzadeh,[53,cc] M. Zeinali,[53] M. Grunewald,[54] M. Abbrescia,[55a,55b] L. Barbone,[55a,55b] C. Calabria,[55a,55b] S. S. Chhibra,[55a,55b] A. Colaleo,[55a] D. Creanza,[55a,55c] N. De Filippis,[55a,55c] M. De Palma,[55a,55b] L. Fiore,[55a] G. Iaselli,[55a,55c] G. Maggi,[55a,55c] M. Maggi,[55a] B. Marangelli,[55a,55b] S. My,[55a,55c] S. Nuzzo,[55a,55b] N. Pacifico,[55a] A. Pompili,[55a,55b] G. Pugliese,[55a,55c] R. Radogna,[55a,55b] G. Selvaggi,[55a,55b] L. Silvestris,[55a] G. Singh,[55a,55b] R. Venditti,[55a,55b] P. Verwilligen,[55a] G. Zito,[55a] G. Abbiendi,[56a] A. C. Benvenuti,[56a] D. Bonacorsi,[56a,56b] S. Braibant-Giacomelli,[56a,56b] L. Brigliadori,[56a,56b] R. Campanini,[56a,56b] P. Capiluppi,[56a,56b] A. Castro,[56a,56b] F. R. Cavallo,[56a] G. Codispoti,[56a,56b] M. Cuffiani,[56a,56b] G. M. Dallavalle,[56a] F. Fabbri,[56a] A. Fanfani,[56a,56b]

D. Fasanella,[56a,56b] P. Giacomelli,[56a] C. Grandi,[56a] L. Guiducci,[56a,56b] S. Marcellini,[56a] G. Masetti,[56a] M. Meneghelli,[56a,56b] A. Montanari,[56a] F. L. Navarria,[56a,56b] F. Odorici,[56a] A. Perrotta,[56a] F. Primavera,[56a,56b] A. M. Rossi,[56a,56b] T. Rovelli,[56a,56b] G. P. Siroli,[56a,56b] N. Tosi,[56a,56b] R. Travaglini,[56a,56b] S. Albergo,[57a,57b] G. Cappello,[57a] M. Chiorboli,[57a,57b] S. Costa,[57a,57b] F. Giordano,[57a,c] R. Potenza,[57a,57b] A. Tricomi,[57a,57b] C. Tuve,[57a,57b] G. Barbagli,[58a] V. Ciulli,[58a,58b] C. Civinini,[58a] R. D'Alessandro,[58a,58b] E. Focardi,[58a,58b] E. Gallo,[58a] S. Gonzi,[58a,58b] V. Gori,[58a,58b] P. Lenzi,[58a,58b] M. Meschini,[58a] S. Paoletti,[58a] G. Sguazzoni,[58a] A. Tropiano,[58a,58b] L. Benussi,[59] S. Bianco,[59] F. Fabbri,[59] D. Piccolo,[59] P. Fabbricatore,[60a] R. Ferretti,[60a,60b] F. Ferro,[60a] M. Lo Vetere,[60a,60b] R. Musenich,[60a] E. Robutti,[60a] S. Tosi,[60a,60b] A. Benaglia,[61a] M. E. Dinardo,[61a,61b] S. Fiorendi,[61a,61b,c] S. Gennai,[61a] A. Ghezzi,[61a,61b] P. Govoni,[61a,61b] M. T. Lucchini,[61a,61b,c] S. Malvezzi,[61a] R. A. Manzoni,[61a,61b,c] A. Martelli,[61a,61b,c] D. Menasce,[61a] L. Moroni,[61a] M. Paganoni,[61a,61b] D. Pedrini,[61a] S. Ragazzi,[61a,61b] N. Redaelli,[61a] T. Tabarelli de Fatis,[61a,61b] S. Buontempo,[62a] N. Cavallo,[62a,62c] F. Fabozzi,[62a,62c] A. O. M. Iorio,[62a,62b] L. Lista,[62a] S. Meola,[62a,62d,c] M. Merola,[62a] P. Paolucci,[62a,c] P. Azzi,[63a] N. Bacchetta,[63a] D. Bisello,[63a,63b] A. Branca,[63a,63b] R. Carlin,[63a,63b] P. Checchia,[63a] T. Dorigo,[63a] U. Dosselli,[63a] M. Galanti,[63a,63b,c] F. Gasparini,[63a,63b] U. Gasparini,[63a,63b] P. Giubilato,[63a,63b] A. Gozzelino,[63a] K. Kanishchev,[63a,63c] S. Lacaprara,[63a] I. Lazzizzera,[63a,63c] M. Margoni,[63a,63b] A. T. Meneguzzo,[63a,63b] M. Nespolo,[63a] M. Passaseo,[63a] J. Pazzini,[63a,63b] M. Pegoraro,[63a] N. Pozzobon,[63a,63b] P. Ronchese,[63a,63b] F. Simonetto,[63a,63b] E. Torassa,[63a] M. Tosi,[63a,63b] P. Zotto,[63a,63b] A. Zucchetta,[63a,63b] G. Zumerle,[63a,63b] M. Gabusi,[64a,64b] S. P. Ratti,[64a,64b] C. Riccardi,[64a,64b] P. Vitulo,[64a,64b] M. Biasini,[65a,65b] G. M. Bilei,[65a] L. Fanò,[65a,65b] P. Lariccia,[65a,65b] G. Mantovani,[65a,65b] M. Menichelli,[65a] A. Nappi,[65a,65b,a] F. Romeo,[65a,65b] A. Saha,[65a] A. Santocchia,[65a,65b] A. Spiezia,[65a,65b] K. Androsov,[66a,dd] P. Azzurri,[66a] G. Bagliesi,[66a] J. Bernardini,[66a] T. Boccali,[66a] G. Broccolo,[66a,66c] R. Castaldi,[66a] M. A. Ciocci,[66a,dd] R. Dell'Orso,[66a] F. Fiori,[66a,66c] L. Foà,[66a,66c] A. Giassi,[66a] M. T. Grippo,[66a,dd] A. Kraan,[66a] F. Ligabue,[66a,66c] T. Lomtadze,[66a] L. Martini,[66a,66b] A. Messineo,[66a,66b] C. S. Moon,[66a,ee] F. Palla,[66a] A. Rizzi,[66a,66b] A. Savoy-Navarro,[66a,ff] A. T. Serban,[66a] P. Spagnolo,[66a] P. Squillacioti,[66a,dd] R. Tenchini,[66a] G. Tonelli,[66a,66b] A. Venturi,[66a] P. G. Verdini,[66a] C. Vernieri,[66a,66c] L. Barone,[67a,67b] F. Cavallari,[67a] D. Del Re,[67a,67b] M. Diemoz,[67a] M. Grassi,[67a,67b] C. Jorda,[67a] E. Longo,[67a,67b] F. Margaroli,[67a,67b] P. Meridiani,[67a] F. Micheli,[67a,67b] S. Nourbakhsh,[67a,67b] G. Organtini,[67a,67b] R. Paramatti,[67a] S. Rahatlou,[67a,67b] C. Rovelli,[67a] L. Soffi,[67a,67b] P. Traczyk,[67a,67b] N. Amapane,[68a,68b] R. Arcidiacono,[68a,68c] S. Argiro,[68a,68b] M. Arneodo,[68a,68c] R. Bellan,[68a,68b] C. Biino,[68a] N. Cartiglia,[68a] S. Casasso,[68a,68b] M. Costa,[68a,68b] A. Degano,[68a,68b] N. Demaria,[68a] C. Mariotti,[68a] S. Maselli,[68a] E. Migliore,[68a,68b] V. Monaco,[68a,68b] M. Musich,[68a] M. M. Obertino,[68a,68c] G. Ortona,[68a,68b] L. Pacher,[68a,68b] N. Pastrone,[68a] M. Pelliccioni,[68a,c] A. Potenza,[68a,68b] A. Romero,[68a,68b] M. Ruspa,[68a,68c] R. Sacchi,[68a,68b] A. Solano,[68a,68b] A. Staiano,[68a] U. Tamponi,[68a] S. Belforte,[69a] V. Candelise,[69a,69b] M. Casarsa,[69a] F. Cossutti,[69a,c] G. Della Ricca,[69a,69b] B. Gobbo,[69a] C. La Licata,[69a,69b] M. Marone,[69a,69b] D. Montanino,[69a,69b] A. Penzo,[69a] A. Schizzi,[69a,69b] T. Umer,[69a,69b] A. Zanetti,[69a] S. Chang,[70] T. Y. Kim,[70] S. K. Nam,[70] D. H. Kim,[71] G. N. Kim,[71] J. E. Kim,[71] D. J. Kong,[71] S. Lee,[71] Y. D. Oh,[71] H. Park,[71] D. C. Son,[71] J. Y. Kim,[72] Zero J. Kim,[72] S. Song,[72] S. Choi,[73] D. Gyun,[73] B. Hong,[73] M. Jo,[73] H. Kim,[73] Y. Kim,[73] K. S. Lee,[73] S. K. Park,[73] Y. Roh,[73] M. Choi,[74] J. H. Kim,[74] C. Park,[74] I. C. Park,[74] S. Park,[74] G. Ryu,[74] Y. Choi,[75] Y. K. Choi,[75] J. Goh,[75] M. S. Kim,[75] E. Kwon,[75] B. Lee,[75] J. Lee,[75] S. Lee,[75] H. Seo,[75] I. Yu,[75] A. Juodagalvis,[76] H. Castilla-Valdez,[77] E. De La Cruz-Burelo,[77] I. Heredia-de La Cruz,[77,gg] R. Lopez-Fernandez,[77] J. Martínez-Ortega,[77] A. Sanchez-Hernandez,[77] L. M. Villasenor-Cendejas,[77] S. Carrillo Moreno,[78] F. Vazquez Valencia,[78] H. A. Salazar Ibarguen,[79] E. Casimiro Linares,[80] A. Morelos Pineda,[80] D. Krofcheck,[81] P. H. Butler,[82] R. Doesburg,[82] S. Reucroft,[82] H. Silverwood,[82] M. Ahmad,[83] M. I. Asghar,[83] J. Butt,[83] H. R. Hoorani,[83] S. Khalid,[83] W. A. Khan,[83] T. Khurshid,[83] S. Qazi,[83] M. A. Shah,[83] M. Shoaib,[83] H. Bialkowska,[84] M. Bluj,[84,hh] B. Boimska,[84] T. Frueboes,[84] M. Górski,[84] M. Kazana,[84] K. Nawrocki,[84] K. Romanowska-Rybinska,[84] M. Szleper,[84] G. Wrochna,[84] P. Zalewski,[84] G. Brona,[85] K. Bunkowski,[85] M. Cwiok,[85] W. Dominik,[85] K. Doroba,[85] A. Kalinowski,[85] M. Konecki,[85] J. Krolikowski,[85] M. Misiura,[85] W. Wolszczak,[85] P. Bargassa,[86] C. Beirão Da Cruz E Silva,[86] P. Faccioli,[86] P. G. Ferreira Parracho,[86] M. Gallinaro,[86] F. Nguyen,[86] J. Rodrigues Antunes,[86] J. Seixas,[86,c] J. Varela,[86] P. Vischia,[86] S. Afanasiev,[87] P. Bunin,[87] I. Golutvin,[87] I. Gorbunov,[87] V. Karjavin,[87] V. Konoplyanikov,[87] G. Kozlov,[87] A. Lanev,[87] A. Malakhov,[87] V. Matveev,[87] P. Moisenz,[87] V. Palichik,[87] V. Perelygin,[87] M. Savina,[87] S. Shmatov,[87] N. Skatchkov,[87] V. Smirnov,[87] A. Zarubin,[87] V. Golovtsov,[88] Y. Ivanov,[88] V. Kim,[88] P. Levchenko,[88] V. Murzin,[88] V. Oreshkin,[88] I. Smirnov,[88] V. Sulimov,[88] L. Uvarov,[88] S. Vavilov,[88] A. Vorobyev,[88] An. Vorobyev,[88] Yu. Andreev,[89] A. Dermenev,[89] S. Gninenko,[89] N. Golubev,[89] M. Kirsanov,[89] N. Krasnikov,[89] A. Pashenkov,[89] D. Tlisov,[89] A. Toropin,[89] V. Epshteyn,[90] V. Gavrilov,[90] N. Lychkovskaya,[90] V. Popov,[90] G. Safronov,[90] S. Semenov,[90] A. Spiridonov,[90] V. Stolin,[90] E. Vlasov,[90] A. Zhokin,[90] V. Andreev,[91] M. Azarkin,[91] I. Dremin,[91]

M. Kirakosyan,[91] A. Leonidov,[91] G. Mesyats,[91] S. V. Rusakov,[91] A. Vinogradov,[91] A. Belyaev,[92] E. Boos,[92] V. Bunichev,[92] M. Dubinin,[92,h] L. Dudko,[92] A. Ershov,[92] V. Klyukhin,[92] O. Kodolova,[92] I. Lokhtin,[92] A. Markina,[92] S. Obraztsov,[92] S. Petrushanko,[92] V. Savrin,[92] A. Snigirev,[92] I. Azhgirey,[93] I. Bayshev,[93] S. Bitioukov,[93] V. Kachanov,[93] A. Kalinin,[93] D. Konstantinov,[93] V. Krychkine,[93] V. Petrov,[93] R. Ryutin,[93] A. Sobol,[93] L. Tourtchanovitch,[93] S. Troshin,[93] N. Tyurin,[93] A. Uzunian,[93] A. Volkov,[93] P. Adzic,[94,ii] M. Djordjevic,[94] M. Ekmedzic,[94] J. Milosevic,[94] M. Aguilar-Benitez,[95] J. Alcaraz Maestre,[95] C. Battilana,[95] E. Calvo,[95] M. Cerrada,[95] M. Chamizo Llatas,[95,c] N. Colino,[95] B. De La Cruz,[95] A. Delgado Peris,[95] D. Domínguez Vázquez,[95] C. Fernandez Bedoya,[95] J. P. Fernández Ramos,[95] A. Ferrando,[95] J. Flix,[95] M. C. Fouz,[95] P. Garcia-Abia,[95] O. Gonzalez Lopez,[95] S. Goy Lopez,[95] J. M. Hernandez,[95] M. I. Josa,[95] G. Merino,[95] E. Navarro De Martino,[95] J. Puerta Pelayo,[95] A. Quintario Olmeda,[95] I. Redondo,[95] L. Romero,[95] M. S. Soares,[95] C. Willmott,[95] C. Albajar,[96] J. F. de Trocóniz,[96] H. Brun,[97] J. Cuevas,[97] J. Fernandez Menendez,[97] S. Folgueras,[97] I. Gonzalez Caballero,[97] L. Lloret Iglesias,[97] J. A. Brochero Cifuentes,[98] I. J. Cabrillo,[98] A. Calderon,[98] S. H. Chuang,[98] J. Duarte Campderros,[98] M. Fernandez,[98] G. Gomez,[98] J. Gonzalez Sanchez,[98] A. Graziano,[98] A. Lopez Virto,[98] J. Marco,[98] R. Marco,[98] C. Martinez Rivero,[98] F. Matorras,[98] F. J. Munoz Sanchez,[98] J. Piedra Gomez,[98] T. Rodrigo,[98] A. Y. Rodríguez-Marrero,[98] A. Ruiz-Jimeno,[98] L. Scodellaro,[98] I. Vila,[98] R. Vilar Cortabitarte,[98] D. Abbaneo,[99] E. Auffray,[99] G. Auzinger,[99] M. Bachtis,[99] P. Baillon,[99] A. H. Ball,[99] D. Barney,[99] J. Bendavid,[99] L. Benhabib,[99] J. F. Benitez,[99] C. Bernet,[99,i] G. Bianchi,[99] P. Bloch,[99] A. Bocci,[99] A. Bonato,[99] O. Bondu,[99] C. Botta,[99] H. Breuker,[99] T. Camporesi,[99] G. Cerminara,[99] T. Christiansen,[99] J. A. Coarasa Perez,[99] S. Colafranceschi,[99,jj] M. D'Alfonso,[99] D. d'Enterria,[99] A. Dabrowski,[99] A. David,[99] F. De Guio,[99] A. De Roeck,[99] S. De Visscher,[99] S. Di Guida,[99] M. Dobson,[99] N. Dupont-Sagorin,[99] A. Elliott-Peisert,[99] J. Eugster,[99] G. Franzoni,[99] W. Funk,[99] M. Giffels,[99] D. Gigi,[99] K. Gill,[99] M. Girone,[99] M. Giunta,[99] F. Glege,[99] R. Gomez-Reino Garrido,[99] S. Gowdy,[99] R. Guida,[99] J. Hammer,[99] M. Hansen,[99] P. Harris,[99] A. Hinzmann,[99] V. Innocente,[99] P. Janot,[99] E. Karavakis,[99] K. Kousouris,[99] K. Krajczar,[99] P. Lecoq,[99] C. Lourenço,[99] N. Magini,[99] L. Malgeri,[99] M. Mannelli,[99] L. Masetti,[99] F. Meijers,[99] S. Mersi,[99] E. Meschi,[99] F. Moortgat,[99] M. Mulders,[99] P. Musella,[99] L. Orsini,[99] E. Palencia Cortezon,[99] E. Perez,[99] L. Perrozzi,[99] A. Petrilli,[99] G. Petrucciani,[99] A. Pfeiffer,[99] M. Pierini,[99] M. Pimiä,[99] D. Piparo,[99] M. Plagge,[99] A. Racz,[99] W. Reece,[99] G. Rolandi,[99,kk] M. Rovere,[99] H. Sakulin,[99] F. Santanastasio,[99] C. Schäfer,[99] C. Schwick,[99] S. Sekmen,[99] A. Sharma,[99] P. Siegrist,[99] P. Silva,[99] M. Simon,[99] P. Sphicas,[99,ll] J. Steggemann,[99] B. Stieger,[99] M. Stoye,[99] A. Tsirou,[99] G. I. Veres,[99,u] J. R. Vlimant,[99] H. K. Wöhri,[99] W. D. Zeuner,[99] W. Bertl,[100] K. Deiters,[100] W. Erdmann,[100] K. Gabathuler,[100] R. Horisberger,[100] Q. Ingram,[100] H. C. Kaestli,[100] S. König,[100] D. Kotlinski,[100] U. Langenegger,[100] D. Renker,[100] T. Rohe,[100] F. Bachmair,[101] L. Bäni,[101] L. Bianchini,[101] P. Bortignon,[101] M. A. Buchmann,[101] B. Casal,[101] N. Chanon,[101] A. Deisher,[101] G. Dissertori,[101] M. Dittmar,[101] M. Donegà,[101] M. Dünser,[101] P. Eller,[101] C. Grab,[101] D. Hits,[101] W. Lustermann,[101] B. Mangano,[101] A. C. Marini,[101] P. Martinez Ruiz del Arbol,[101] D. Meister,[101] N. Mohr,[101] C. Nägeli,[101,mm] P. Nef,[101] F. Nessi-Tedaldi,[101] F. Pandolfi,[101] L. Pape,[101] F. Pauss,[101] M. Peruzzi,[101] M. Quittnat,[101] F. J. Ronga,[101] M. Rossini,[101] A. Starodumov,[101,nn] M. Takahashi,[101] L. Tauscher,[101,a] K. Theofilatos,[101] D. Treille,[101] R. Wallny,[101] H. A. Weber,[101] C. Amsler,[102,oo] V. Chiochia,[102] A. De Cosa,[102] C. Favaro,[102] M. Ivova Rikova,[102] B. Kilminster,[102] B. Millan Mejias,[102] J. Ngadiuba,[102] P. Robmann,[102] H. Snoek,[102] S. Taroni,[102] M. Verzetti,[102] Y. Yang,[102] M. Cardaci,[103] K. H. Chen,[103] C. Ferro,[103] C. M. Kuo,[103] S. W. Li,[103] W. Lin,[103] Y. J. Lu,[103] R. Volpe,[103] S. S. Yu,[103] P. Bartalini,[104] P. Chang,[104] Y. H. Chang,[104] Y. W. Chang,[104] Y. Chao,[104] K. F. Chen,[104] P. H. Chen,[104] C. Dietz,[104] U. Grundler,[104] W.-S. Hou,[104] Y. Hsiung,[104] K. Y. Kao,[104] Y. J. Lei,[104] Y. F. Liu,[104] R.-S. Lu,[104] D. Majumder,[104] E. Petrakou,[104] X. Shi,[104] J. G. Shiu,[104] Y. M. Tzeng,[104] M. Wang,[104] R. Wilken,[104] B. Asavapibhop,[105] N. Suwonjandee,[105] A. Adiguzel,[106] M. N. Bakirci,[106,pp] S. Cerci,[106,qq] C. Dozen,[106] I. Dumanoglu,[106] E. Eskut,[106] S. Girgis,[106] G. Gokbulut,[106] E. Gurpinar,[106] I. Hos,[106] E. E. Kangal,[106] A. Kayis Topaksu,[106] G. Onengut,[106,rr] K. Ozdemir,[106] S. Ozturk,[106,pp] A. Polatoz,[106] K. Sogut,[106,ss] D. Sunar Cerci,[106,qq] B. Tali,[106,qq] H. Topakli,[106,pp] M. Vergili,[106] I. V. Akin,[107] T. Aliev,[107] B. Bilin,[107] S. Bilmis,[107] M. Deniz,[107] H. Gamsizkan,[107] A. M. Guler,[107] G. Karapinar,[107,tt] K. Ocalan,[107] A. Ozpineci,[107] M. Serin,[107] R. Sever,[107] U. E. Surat,[107] M. Yalvac,[107] M. Zeyrek,[107] E. Gülmez,[108] B. Isildak,[108,uu] M. Kaya,[108,vv] O. Kaya,[108,vv] S. Ozkorucuklu,[108,ww] N. Sonmez,[108,xx] H. Bahtiyar,[109,yy] E. Barlas,[109] K. Cankocak,[109] Y. O. Günaydin,[109,zz] F. I. Vardarlı,[109] M. Yücel,[109] L. Levchuk,[110] P. Sorokin,[110] J. J. Brooke,[111] E. Clement,[111] D. Cussans,[111] H. Flacher,[111] R. Frazier,[111] J. Goldstein,[111] M. Grimes,[111] G. P. Heath,[111] H. F. Heath,[111] J. Jacob,[111] L. Kreczko,[111] C. Lucas,[111] Z. Meng,[111] D. M. Newbold,[111,aaa] S. Paramesvaran,[111] A. Poll,[111] S. Senkin,[111] V. J. Smith,[111] T. Williams,[111] K. W. Bell,[112] A. Belyaev,[112,bbb] C. Brew,[112] R. M. Brown,[112] D. J. A. Cockerill,[112] J. A. Coughlan,[112] K. Harder,[112] S. Harper,[112] J. Ilic,[112] E. Olaiya,[112] D. Petyt,[112]

C. H. Shepherd-Themistocleous,[112] A. Thea,[112] I. R. Tomalin,[112] W. J. Womersley,[112] S. D. Worm,[112] M. Baber,[113] R. Bainbridge,[113] O. Buchmuller,[113] D. Burton,[113] D. Colling,[113] N. Cripps,[113] M. Cutajar,[113] P. Dauncey,[113] G. Davies,[113] M. Della Negra,[113] W. Ferguson,[113] J. Fulcher,[113] D. Futyan,[113] A. Gilbert,[113] A. Guneratne Bryer,[113] G. Hall,[113] Z. Hatherell,[113] J. Hays,[113] G. Iles,[113] M. Jarvis,[113] G. Karapostoli,[113] M. Kenzie,[113] R. Lane,[113] R. Lucas,[113,aaa] L. Lyons,[113] A.-M. Magnan,[113] J. Marrouche,[113] B. Mathias,[113] R. Nandi,[113] J. Nash,[113] A. Nikitenko,[113,nn] J. Pela,[113] M. Pesaresi,[113] K. Petridis,[113] M. Pioppi,[113,ccc] D. M. Raymond,[113] S. Rogerson,[113] A. Rose,[113] C. Seez,[113] P. Sharp,[113,a] A. Sparrow,[113] A. Tapper,[113] M. Vazquez Acosta,[113] T. Virdee,[113] S. Wakefield,[113] N. Wardle,[113] J. E. Cole,[114] P. R. Hobson,[114] A. Khan,[114] P. Kyberd,[114] D. Leggat,[114] D. Leslie,[114] W. Martin,[114] I. D. Reid,[114] P. Symonds,[114] L. Teodorescu,[114] M. Turner,[114] J. Dittmann,[115] K. Hatakeyama,[115] A. Kasmi,[115] H. Liu,[115] T. Scarborough,[115] O. Charaf,[116] S. I. Cooper,[116] C. Henderson,[116] P. Rumerio,[116] A. Avetisyan,[117] T. Bose,[117] C. Fantasia,[117] A. Heister,[117] P. Lawson,[117] D. Lazic,[117] J. Rohlf,[117] D. Sperka,[117] J. St. John,[117] L. Sulak,[117] J. Alimena,[118] S. Bhattacharya,[118] G. Christopher,[118] D. Cutts,[118] Z. Demiragli,[118] A. Ferapontov,[118] A. Garabedian,[118] U. Heintz,[118] S. Jabeen,[118] G. Kukartsev,[118] E. Laird,[118] G. Landsberg,[118] M. Luk,[118] M. Narain,[118] M. Segala,[118] T. Sinthuprasith,[118] T. Speer,[118] J. Swanson,[118] R. Breedon,[119] G. Breto,[119] M. Calderon De La Barca Sanchez,[119] S. Chauhan,[119] M. Chertok,[119] J. Conway,[119] R. Conway,[119] P. T. Cox,[119] R. Erbacher,[119] M. Gardner,[119] W. Ko,[119] A. Kopecky,[119] R. Lander,[119] T. Miceli,[119] D. Pellett,[119] J. Pilot,[119] F. Ricci-Tam,[119] B. Rutherford,[119] M. Searle,[119] S. Shalhout,[119] J. Smith,[119] M. Squires,[119] M. Tripathi,[119] S. Wilbur,[119] R. Yohay,[119] V. Andreev,[120] D. Cline,[120] R. Cousins,[120] S. Erhan,[120] P. Everaerts,[120] C. Farrell,[120] M. Felcini,[120] J. Hauser,[120] M. Ignatenko,[120] C. Jarvis,[120] G. Rakness,[120] P. Schlein,[120,a] E. Takasugi,[120] V. Valuev,[120] M. Weber,[120] J. Babb,[121] R. Clare,[121] J. Ellison,[121] J. W. Gary,[121] G. Hanson,[121] J. Heilman,[121] P. Jandir,[121] F. Lacroix,[121] H. Liu,[121] O. R. Long,[121] A. Luthra,[121] M. Malberti,[121] H. Nguyen,[121] A. Shrinivas,[121] J. Sturdy,[121] S. Sumowidagdo,[121] S. Wimpenny,[121] W. Andrews,[122] J. G. Branson,[122] G. B. Cerati,[122] S. Cittolin,[122] R. T. D'Agnolo,[122] D. Evans,[122] A. Holzner,[122] R. Kelley,[122] D. Kovalskyi,[122] M. Lebourgeois,[122] J. Letts,[122] I. Macneill,[122] S. Padhi,[122] C. Palmer,[122] M. Pieri,[122] M. Sani,[122] V. Sharma,[122] S. Simon,[122] E. Sudano,[122] M. Tadel,[122] Y. Tu,[122] A. Vartak,[122] S. Wasserbaech,[122,ddd] F. Würthwein,[122] A. Yagil,[122] J. Yoo,[122] D. Barge,[123] C. Campagnari,[123] T. Danielson,[123] K. Flowers,[123] P. Geffert,[123] C. George,[123] F. Golf,[123] J. Incandela,[123] C. Justus,[123] R. Magaña Villalba,[123] N. Mccoll,[123] V. Pavlunin,[123] J. Richman,[123] R. Rossin,[123] D. Stuart,[123] W. To,[123] C. West,[123] A. Apresyan,[124] A. Bornheim,[124] J. Bunn,[124] Y. Chen,[124] E. Di Marco,[124] J. Duarte,[124] D. Kcira,[124] A. Mott,[124] H. B. Newman,[124] C. Pena,[124] C. Rogan,[124] M. Spiropulu,[124] V. Timciuc,[124] R. Wilkinson,[124] S. Xie,[124] R. Y. Zhu,[124] V. Azzolini,[125] A. Calamba,[125] R. Carroll,[125] T. Ferguson,[125] Y. Iiyama,[125] D. W. Jang,[125] M. Paulini,[125] J. Russ,[125] H. Vogel,[125] I. Vorobiev,[125] J. P. Cumalat,[126] B. R. Drell,[126] W. T. Ford,[126] A. Gaz,[126] E. Luiggi Lopez,[126] U. Nauenberg,[126] J. G. Smith,[126] K. Stenson,[126] K. A. Ulmer,[126] S. R. Wagner,[126] J. Alexander,[127] A. Chatterjee,[127] N. Eggert,[127] L. K. Gibbons,[127] W. Hopkins,[127] A. Khukhunaishvili,[127] B. Kreis,[127] N. Mirman,[127] G. Nicolas Kaufman,[127] J. R. Patterson,[127] A. Ryd,[127] E. Salvati,[127] W. Sun,[127] W. D. Teo,[127] J. Thom,[127] J. Thompson,[127] J. Tucker,[127] Y. Weng,[127] L. Winstrom,[127] P. Wittich,[127] D. Winn,[128] S. Abdullin,[129] M. Albrow,[129] J. Anderson,[129] G. Apollinari,[129] L. A. T. Bauerdick,[129] A. Beretvas,[129] J. Berryhill,[129] P. C. Bhat,[129] K. Burkett,[129] J. N. Butler,[129] V. Chetluru,[129] H. W. K. Cheung,[129] F. Chlebana,[129] S. Cihangir,[129] V. D. Elvira,[129] I. Fisk,[129] J. Freeman,[129] Y. Gao,[129] E. Gottschalk,[129] L. Gray,[129] D. Green,[129] O. Gutsche,[129] D. Hare,[129] R. M. Harris,[129] J. Hirschauer,[129] B. Hooberman,[129] S. Jindariani,[129] M. Johnson,[129] U. Joshi,[129] K. Kaadze,[129] B. Klima,[129] S. Kwan,[129] J. Linacre,[129] D. Lincoln,[129] R. Lipton,[129] J. Lykken,[129] K. Maeshima,[129] J. M. Marraffino,[129] V. I. Martinez Outschoorn,[129] S. Maruyama,[129] D. Mason,[129] P. McBride,[129] K. Mishra,[129] S. Mrenna,[129] Y. Musienko,[129,eee] S. Nahn,[129] C. Newman-Holmes,[129] V. O'Dell,[129] O. Prokofyev,[129] N. Ratnikova,[129] E. Sexton-Kennedy,[129] S. Sharma,[129] W. J. Spalding,[129] L. Spiegel,[129] L. Taylor,[129] S. Tkaczyk,[129] N. V. Tran,[129] L. Uplegger,[129] E. W. Vaandering,[129] R. Vidal,[129] J. Whitmore,[129] W. Wu,[129] F. Yang,[129] J. C. Yun,[129] D. Acosta,[130] P. Avery,[130] D. Bourilkov,[130] T. Cheng,[130] S. Das,[130] M. De Gruttola,[130] G. P. Di Giovanni,[130] D. Dobur,[130] R. D. Field,[130] M. Fisher,[130] Y. Fu,[130] I. K. Furic,[130] J. Hugon,[130] B. Kim,[130] J. Konigsberg,[130] A. Korytov,[130] A. Kropivnitskaya,[130] T. Kypreos,[130] J. F. Low,[130] K. Matchev,[130] P. Milenovic,[130,fff] G. Mitselmakher,[130] L. Muniz,[130] A. Rinkevicius,[130] L. 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