Search for Flavor-Changing Neutral Currents in Top-Quark Decays $t \to Zq$ in pp Collisions at $\sqrt{s} = 8$ TeV

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A search for flavor-changing neutral currents in top-quark decays $t \to Zq$ is performed in events produced from the decay chain $t\bar{t} \to Zq + Wb$, where both vector bosons decay leptonically, producing a final state with three leptons (electrons or muons). A data set collected with the CMS detector at the LHC is used, corresponding to an integrated luminosity of 19.7 fb^{-1} of proton-proton collisions at a center-of-mass energy of 8 TeV. No excess is seen in the observed number of events relative to the standard model prediction; thus, no evidence for flavor-changing neutral currents in top-quark decays is found. A combination with a previous search at 7 TeV excludes a $t \to Zq$ branching fraction greater than 0.05% at the 95% confidence level.

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The heaviest known elementary particle, the top quark, decays to a bottom quark and a W boson, $t \to Wb$, with a branching fraction of nearly 100% [1]. Within the standard model (SM), the corresponding flavor-changing neutral current (FCNC) decay to a Z boson and a light up-type quark (u or c), $t \to Zq$, is suppressed by the GIM mechanism [2], occurring only at the quantum loop level, with a branching fraction $\mathcal{B}(t \to Zq)$ at $\mathcal{O}(10^{-14})$ [3]. The detection of FCNC $t \to Zq$ decays at a higher-than-expected rate would thus be clear evidence for physics beyond the SM.

Some extensions of the SM, such as R-parity-violating supersymmetric models [4], top-color-assisted technicolor models [5], and singlet quark models [6] predict enhancements of the FCNC branching fraction that could be as large as $\mathcal{O}(10^{-4})$. These models, however, need to be updated from their earlier parametrizations using the latest Large Hadron Collider (LHC) results. While this is not easily done in general without a detailed analysis, a recent study [7] places $\mathcal{B}(t \to Zq)$ at $\mathcal{O}(10^{-5})$ in warped extra dimension models [8,9]. The rate is very sensitive to the Kaluza-Klein gluon scale m_{KK}, as well as right-handed mixing parameters. The m_{KK} scale is probed directly [10,11] at the LHC, while B physics measurements [12] do not significantly constrain right-handed couplings. In this Letter we report a search for $t \to Zq$ at the LHC, with results that start to complement both the direct search for KK gluons, as well as flavor physics constraints.

The experimental searches on top FCNC have been carried out since LEP and HERA on single top quark production with best limit $\mathcal{B}(t \to Zq) < 4\%$ [13,14]. The current limit by Tevatron on top FCNC decay is $< 3.2\%$ [15]. In a previous search with the Compact Muon Solenoid (CMS) experiment, we reported results from a search for this decay using 5.0 fb^{-1} of proton-proton collisions at a center-of-mass energy $\sqrt{s} = 7$ TeV, resulting in a 95% confidence level (C.L.) upper limit on $\mathcal{B}(t \to Zq)$ of 0.21% [16]. A limit of 0.73% [17] on the branching fraction has also been reported by the ATLAS experiment from an analysis of 2.1 fb^{-1} of 7 TeV data. The analysis described in this Letter uses a data sample corresponding to an integrated luminosity of 19.7 fb^{-1} of pp collisions at $\sqrt{s} = 8$ TeV.

The central feature of the CMS apparatus is a superconducting solenoid, which provides an axial magnetic field of 3.8 T. Within the field volume there are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass or scintillator hadron calorimeter. Charged-particle trajectories are measured by the tracker, covering $0 \le \phi \le 2\pi$ in azimuth and $|\eta| < 2.5$ in pseudorapidity, where η is defined as $-\ln[\tan(\theta/2)]$, and θ is the polar angle of the trajectory of the particle with respect to the counterclockwise proton beam direction. Muons are identified and measured in gas-ionization detectors embedded in the steel flux return yoke outside the solenoid. A more detailed description of the CMS detector can be found in Ref. [18].

Monte Carlo (MC) samples of Drell-Yan events, SM $t\bar{t}$, $Zt\bar{t}$, $Wt\bar{t}$, tbZ, and diboson (WW, WZ, and ZZ) events are simulated using MADGRAPH [19], while single-top-quark events are generated using POWHEG [20–22]. The signal sample $pp \to t\bar{t} \to Zq + Wb \to \ell^+\ell^- q + \ell'^{\pm}\nu b(\ell, \ell' = e, \mu, \tau)$ is generated with MADGRAPH. One of the top quarks of the pair is forced to decay as $t \to Zq$, where q stands for a u or c quark with equal probability, while the other decays to Wb. The ratio between the dimension-four vector and the

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axial-vector couplings of the $t \to Zq$ FCNC model is assumed to be SM-like [23]. In all cases, hadronization and showering are simulated with PYTHIA 6 [24], while τ decays are simulated with TAUOLA [25]. The set of parton distribution functions (PDFs) used is CTEQ6L [26]. The CMS detector response for all MC samples is simulated using a GEANT4-based [27] model, and the events are reconstructed and analyzed using the same software used to process collision data. The simulated events are weighted so that the trigger efficiencies, reconstruction efficiencies, and the distribution of reconstructed vertices observed in data are reproduced.

The search is performed by looking for $t\bar{t}$ events where one top quark decays into Zq and the other decays into Wb with both vector bosons decaying leptonically, which provide a very clear signature. The analysis follows closely the search performed at 7 TeV [16]. Several of the event selection requirements have been reoptimized before the complete data set was collected, based on the expected signal and background yields at 8 TeV with $\mathcal{B}(t \to Zq) = 0.1\%$.

Events are required to pass at least one of the ee or $\mu\mu$ high transverse momenta (p_T) dilepton triggers. Events with two opposite-sign, same-flavor, isolated leptons (e or μ) having an invariant mass between 78 and 102 GeV, consistent with a Z-boson decay, and one extra charged lepton (e or μ) are selected. When there is more than one lepton pair forming a Z candidate, the pair with invariant mass closest to the nominal value is taken. All three leptons must satisfy the following kinematic requirements: $p_T > 20$ GeV and $|\eta| < 2.5$ for electrons and $|\eta| < 2.4$ for muons. The lepton selection efficiencies (reconstruction, identification, and isolation) mean values and their dependence with p_T and $|\eta|$ are consistent between the data and the simulation [28,29].

Multiple simultaneous interactions per bunch crossing (pileup) were observed in data. Events are required to have at least one good primary vertex candidate [30]. In events with more than one candidate, the vertex with highest $\Sigma p_T{}^2$ of its associated tracks is selected. The leptons and all charged particle tracks that are associated with jets are required to be consistent with originating from the primary vertex.

Since the leptons are expected to originate from the decays of W and Z bosons, they are required to be isolated as defined in Ref. [31]. Events with a fourth isolated lepton are rejected. Neutrinos from W-boson decays escape detection and produce a significant momentum imbalance in the detector in the plane transverse to the beams. The missing transverse momentum ($-\Sigma\vec{p}_T$) and its magnitude ($\not{E}_T$) are reconstructed using the CMS particle-flow technique [32], and we require the $\not{E}_T$ to be larger than 30 GeV. The W-boson candidates are constructed from the momentum of the extra lepton and the missing transverse momentum (assumed to originate from an undetected neutrino), by constraining the resulting invariant mass to be equal to the W-boson mass [1].

The requirements described above, namely events with dilepton-triggers, a Z boson candidate, an extra lepton, no fourth lepton, and the requirement of $\not{E}_T$, will be referred to as the "basic event selection". The observed number of events after the basic event selection is 1424, in agreement with the MC expectation of 1455 ± 16 events, including 1229 ± 4 events from WZ and 86.3 ± 0.2 events from ZZ production, where the uncertainty quoted is statistical only.

Figure 1 shows the distributions for data and simulated events of the $\not{E}_T$ and transverse mass (m_T) of the W-boson candidate after the basic event selection. The transverse mass is calculated using the transverse

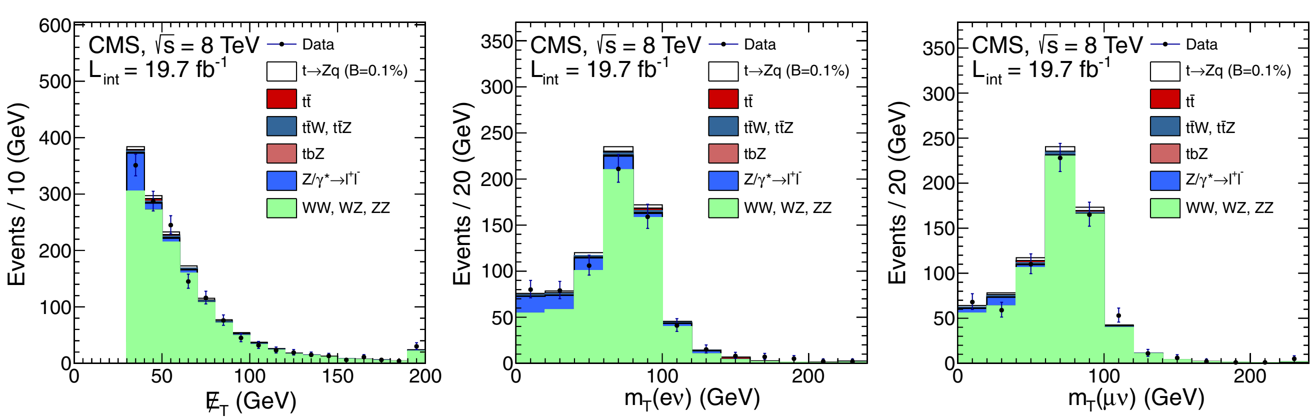

FIG. 1 (color online). Comparison between data and simulated events for an integrated luminosity of 19.7 fb^{-1}, after the basic event selection, for the $\not{E}_T$ distribution (left), the reconstructed $e\nu$ transverse mass (middle) of the W-boson candidate, and the reconstructed $\mu\nu$ transverse mass (right) of the W-boson candidate. The data are represented by the points with error bars, and the open histogram shows the expected signal assuming $\mathcal{B}(t \to Zq)$ is equal to 0.1%. Stacked solid histograms represent the dominant backgrounds, with statistical uncertainties on these backgrounds at the few percent level (not shown).

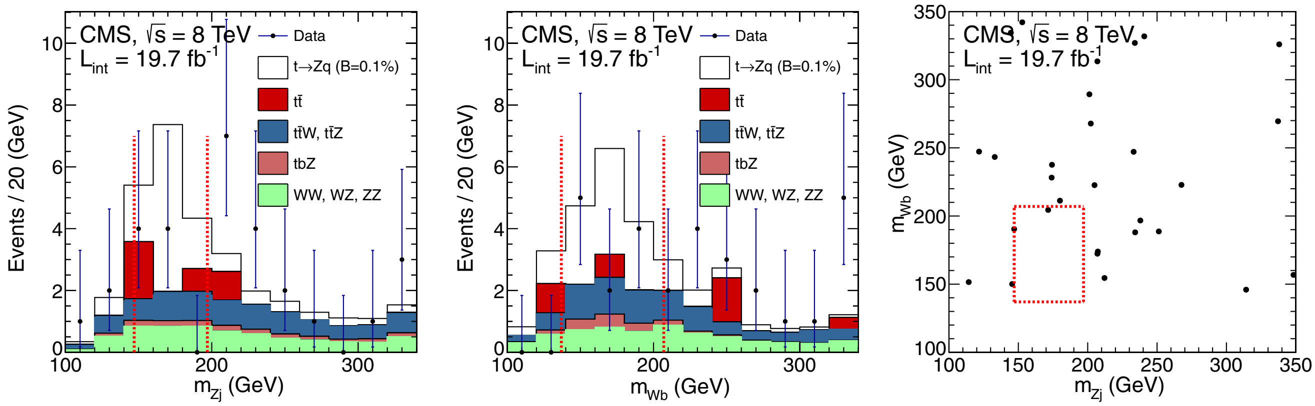

FIG. 2 (color online). Comparison between data and simulated events of the m_{Zj} (left), m_{Wb} (middle), and two-dimensional scatter (right) distributions after the event selection prior to the top-quark mass requirements, which are shown as the dotted vertical lines (left, middle) and box (right). The data, corresponding to an integrated luminosity of 19.7 fb^{-1}, are represented by the points with error bars and the open histogram is the expected signal. The stacked solid histograms represent the dominant backgrounds. The statistical uncertainties are not drawn. The last bin in each of the left two plots contains all the overflow events.

momentum of the extra lepton (p_T^ℓ), the $\not{E}_T$, and the azimuthal angle difference ($\Delta\phi$) between the two, as $m_T = \sqrt{2 p_T^\ell \not{E}_T (1 - \cos(\Delta\phi))}$.

To reduce the background from diboson events we require at least two jets, reconstructed also using a particle-flow technique [32], each with $p_T > 30$ GeV and $|\eta| < 2.4$. Exactly one of these jets should be identified (tagged) as a b-quark jet. These requirements further reduce the observed event yields from 1424 after the basic event selection to 29. The b-jet identification is performed using the combined secondary vertex b-tagging algorithm described in Ref. [33]. This tagging method has an identification efficiency of 62% for b jets with transverse momentum between 30 and 100 GeV and a misidentification rate of about 18% for c jets and below 1.5% for other jets.

The invariant mass of the W boson and the b-tagged jet, m_{Wb}, is required to be within 35 GeV of the top-quark mass, which is set to 172.5 GeV in the simulation. A non-b jet is combined with the Z candidate to form a second top-quark candidate. By examining all possible pairings, the top-quark candidate which has the largest separation in azimuthal angle to the first top quark is selected, and the reconstructed top-quark mass, m_{Zj}, is required to be within 25 GeV of the assumed value of 172.5 GeV . The mass requirements are the same as in the 7 TeV analysis [16]. Figure 2 shows the comparison of the m_{Zj} and m_{Wb} distributions in data and simulation, while Table I summarizes the signal efficiencies determined from simulated events.

According to simulations, the dominant backgrounds arise from diboson and $t\bar{t} + X$ production. These processes can be categorized into three groups based on the number of b quarks present: (a) diboson and Drell-Yan events with almost no b quarks, (b) events from top-quark FCNC decay with only one b quark, (c) $t\bar{t}$, tbZ, $t\bar{t}W$, and $t\bar{t}Z$ processes with at least two b quarks. Events passing the basic event selection, with two jets to be paired with W and Z bosons are divided into three samples: (a) events with no b-tagged jets, (b) events with exactly one b-tagged jet, and (c) the rest of the events. The numbers of events in those three samples can be related to the yields of the three groups based on the b-tagging efficiencies for b jets, c jets, or other jets, which are measured using data. The numbers of events in the three groups are then turned into an estimate of the corresponding yields via a linear 3×3 system of equations to be solved before the top-quark mass requirements. The corresponding acceptances of the mass requirements are obtained from MC simulations. The overall contribution from WZ plus ZZ and Drell-Yan backgrounds is estimated to be $1.4 \pm 0.1(\mathrm{stat}) \pm 0.3(\mathrm{syst})$ events. The expected yield from $t\bar{t}W$, $t\bar{t}Z$, tbZ, and $t\bar{t}$ backgrounds is $1.7 \pm 0.8(\mathrm{stat}) \pm 0.4(\mathrm{syst})$ events. The uncertainty of the b-tagging efficiency, measured in control data samples, and the uncertainty on the top-quark mass requirement, estimated with MC simulation, contribute to the systematic uncertainty. The estimated background yields are summarized in Table II and show a good agreement with those obtained

TABLE I. Signal selection efficiency, in percent, for each dilepton channels with respect to events from all channels. The efficiency is calculated as the fraction of events with leptonically (e, μ, τ) decaying W and Z bosons passing the selection. Only MC statistical uncertainties are shown.

Channel	Efficiencies [%]
eee	0.49 ± 0.01
$ee\mu$	0.52 ± 0.01
$\mu\mu e$	0.55 ± 0.01
$\mu\mu\mu$	0.55 ± 0.01
All	2.12 ± 0.03

TABLE II. Expected number of signal $t \to Zq$ events, background composition, and observed events corresponding to an integrated luminosity of 19.7 fb^{-1} for all dilepton channels; background estimates included. The uncertainties in the background estimation include the statistical and systematic components shown separately, in that order.

Process	Estimation from data	MC prediction
$t \to Zq$ ($\mathcal{B} = 0.1\%$)	...	$6.4 \pm 0.1 \pm 1.3$
WZ		$0.9 \pm 0.1 \pm 0.3$
ZZ	$1.4 \pm 0.1 \pm 0.3$	< 0.1
Drell–Yan		< 0.1
$t\bar{t}$		$0.7^{+1.1}_{-0.4} \pm 1.2$
$t\bar{t}Z$		$1.1 \pm 0.1 \pm 0.8$
	$1.7 \pm 0.8 \pm 0.4$	
$t\bar{t}W$		$0.1 \pm 0.1 \pm 0.1$
tbZ		$0.3 \pm 0.1 \pm 0.2$
Total background	$3.1 \pm 0.8 \pm 0.8$	$3.2 \pm 1.2 \pm 1.5$
Observed events	1	...

from MC simulation. The background estimations from data are used for the final results.

To calculate the expected upper limits, the systematic uncertainties from the dilepton trigger efficiency, lepton selection efficiency [28], pileup modeling [34], b-jet tagging efficiency [33], jet energy scale and missing transverse energy resolution [35] are included, with the b-jet tagging efficiency being the dominant one for the background estimation. Additionally, several sources of uncertainties in the signal yield are evaluated: the choice of PDFs, generator parameters, and uncertainty in the $t\bar{t}$ cross section. The major contributions come from the PDFs and the generator parameters of the signal MC simulation. The prescription given in Ref. [36] is used to determine the uncertainty from the CTEQ66 PDF error sets [37]. The uncertainty from the generator parametrization is evaluated using CMS fast simulation [38] samples with different top-quark mass assumptions (± 2 GeV), different parton-jet matching thresholds (30 GeV and 60 GeV), and different event renormalization and factorization scales (varied between $1/4$ and $4\times$ from their nominal value). In addition, there is a 2.6% uncertainty on the luminosity measurement [39]. All these sources, summarized in Table III, are combined in quadrature to give a 20% relative uncertainty in the signal selection acceptance. The systematic uncertainties in the background estimation are listed with the total background prediction given in Table II.

After applying all the criteria and adding all four channels, 3.1 ± 1.1 events are expected from SM background processes and 1 event is observed in data. A 95% C.L. upper limit on the branching fraction of the $t \to Zq$ decay is determined using the modified frequentist approach (CL_s method [40,41]). A summary of the observed and predicted yields and limits is presented in Tables II and IV. The observed and expected 95% C.L. upper limits on the branching fraction $\mathcal{B}(t \to Zq)$ are 0.06% and 0.10%, respectively.

TABLE III. Summary of the systematic uncertainties for the signal selection acceptance.

Source	Uncertainty %
Renormalization/factorization scales	12
Parton distribution functions	7
$t\bar{t}$ cross section	7
Parton matching threshold	6
Lepton selection	6
Trigger efficiency	5
b-tagging	5
Top-quark mass	4
Jet energy scale	4
Missing transverse energy resolution	3
Pileup modeling	3
Total	20

These results are combined with the statistically independent results of our previous search [16]. The systematic uncertainties on the signal efficiency estimation and the luminosity measurements are taken as fully correlated. Since the background estimations are based on independent samples, their systematic uncertainties are treated as uncorrelated, except for the uncertainties on the top mass selection requirement due to the choice of PDF, which are also taken as fully correlated. The combination with the 7 TeV b-tag analysis [16] gives a slightly lower expected limit and hence is chosen as the reference result. The observed upper limit on $\mathcal{B}(t \to Zq)$ is 0.05%, with a median expectation of 0.09%, and with 1σ and 2σ ranges which are 0.06–0.13% and 0.05–0.18%, respectively. The derived limits and their uncertainties are shown in Table IV.

In summary, a search for FCNC events in top-quark decays in $t\bar{t}$ events produced in proton-proton collisions at $\sqrt{s} = 8$ TeV is presented. A sample of events with three leptons (e or μ) in the final state and compatible with leptonic decays of a Z and Wb boson is selected from data recorded with the CMS detector and corresponding to an integrated luminosity of 19.7 fb^{-1}. No excess of events above the background is observed. Combining this result with a previous search corresponding to an integrated luminosity of 5.0 fb^{-1} t $\sqrt{s} = 7$ TeV, excludes a $t \to Zq$

TABLE IV. Upper limits at a 95% C.L. for $\mathcal{B}(t \to Zq)$, as obtained using the 8 TeV data with an integrated luminosity of 19.7 fb^{-1}, and from the combination with previous CMS 7 TeV (5.0 fb^{-1}) data.

$\mathcal{B}(t \to Zq)$	8 TeV	7 + 8 TeV
Expected upper limit	$< 0.10\%$	$< 0.09\%$
Observed upper limit	$< 0.06\%$	$< 0.05\%$
1σ boundary	0.06–0.13%	0.06–0.13%
2σ boundary	0.05–0.20%	0.05–0.18%

branching fraction greater than 0.05% at a confidence level of 95%. This new limit, about four times better than our previous one, has been achieved with a better background estimation, increased cross section at higher energy and increased integrated luminosity. This new result starts to probe the enhanced FCNC branching fraction predicted by certain SM extensions, such as warped extra dimensions. Our limit can be translated into a constraint on the KK gluon to be heavier than 1.1 TeV [9].

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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 PerezTomei,[12a] E. M. Gregores,[12b] C. Lagana,[12a] P. G. Mercadante,[12b] S. F. Novaes,[12a] S. 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] R. Hadjiiska,[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,j] 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. O. 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] T. 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. Geralis,[40] S. Kesisoglou,[40] A. Kyriakis,[40] D. Loukas,[40] A. Markou,[40] C. Markou,[40] E. Ntomari,[40] I. Topsis-giotis,[40] L. Gouskos,[41] A. Panagiotou,[41] N. Saoulidou,[41] E. Stiliaris,[41] X. Aslanoglou,[42] I. Evangelou,[42] G. Flouris,[42] C. Foudas,[42] P. Kokkas,[42] N. Manthos,[42] I. Papadopoulos,[42] E. Paradas,[42] G. Bencze,[43] C. Hajdu,[43] P. Hidas,[43] D. Horvath,[43,t] F. Sikler,[43] V. Veszpremi,[43] G. Vesztergombi,[43,u] A. J. Zsigmond,[43] N. Beni,[44] S. Czellar,[44] J. Molnar,[44] J. Palinkas,[44] Z. Szillasi,[44] J. Karancsi,[45] P. Raics,[45] Z. L. Trocsanyi,[45] B. Ujvari,[45] S. K. Swain,[46,v] S. B. Beri,[47] V. Bhatnagar,[47] N. Dhingra,[47] R. Gupta,[47] M. Kaur,[47] M. Z. Mehta,[47] M. Mittal,[47] N. Nishu,[47] A. Sharma,[47] J. B. Singh,[47] A. Kumar,[48] A. Kumar,[48] S. Ahuja,[48] A. Bhardwaj,[48] B. C. Choudhary,[48] A. Kumar,[48] S. Malhotra,[48] M. Naimuddin,[48] K. Ranjan,[48] P. Saxena,[48] V. Sharma,[48] R. K. Shivpuri,[48] S. Banerjee,[49] S. Bhattacharya,[49] K. Chatterjee,[49] S. Dutta,[49] B. Gomber,[49] S. Jain,[49] S. 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,57c,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] F. Fanzago,[63a] M. Galanti,[63a,63b,c] F. Gasparini,[63a,63b]

U. Gasparini,[63a,63b] P. Giubilato,[63a,63b] F. Gonella,[63a] A. Gozzelino,[63a] K. Kanishchev,[63a,63c] S. Lacaprara,[63a] I. Lazzizzera,[63a,63c] M. Margoni,[63a,63b] A. T. Meneguzzo,[63a,63b] F. Montecassiano,[63a] J. Pazzini,[63a,63b] N. Pozzobon,[63a,63b] P. Ronchese,[63a,63b] F. Simonetto,[63a,63b] E. Torassa,[63a] M. Tosi,[63a,63b] S. Vanini,[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] Z. 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] A. Kamenev,[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] 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] A. Vorobyev,[88] Y. 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. Gribushin,[92] V. Klyukhin,[92] O. Kodolova,[92] I. Lokhtin,[92] A. Markina,[92] S. Obraztsov,[92] M. Perfilov,[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. 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