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Search for a W' or Techni-ρ Decaying into WZ in pp Collisions at $\sqrt{s} = 7$ TeV

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A search is performed in pp collisions at $\sqrt{s} = 7$ TeV for exotic particles decaying via WZ to final states with electrons and muons. The data sample corresponds to an integrated luminosity of approximately 5 fb^{-1}. No significant excess is observed in the data above the expected standard model background. Upper bounds at 95% confidence level are set on the production cross section of the W' boson described by the sequential standard model and on the $W'WZ$ coupling. W' bosons with masses below 1143 GeV are excluded. Limits are also set in the context of low-scale technicolor models, under a range of assumptions concerning the model parameters.

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The standard model (SM) of particle physics has passed many rigorous tests, and its predictions have often been matched by experimental data with amazing precision. However, it is widely accepted that the SM cannot be the ultimate theory of fundamental particles and their interactions since it has a number of shortcomings; e.g., it fails to incorporate gravity and has no explanation for the dominance of matter over antimatter in the Universe. Various extensions of the SM have been proposed to address these problems and to explain the mechanism of electroweak symmetry breaking. Many of these models predict the existence of a new heavy charged gauge boson, generically known as W', that decays into a pair of W and Z bosons [1–6]. Previous W' searches have typically interpreted their results in terms of the sequential standard model (SSM) [7–12], a simple extension of the SM in which the couplings of the W' to fermions are identical to those of the W. Many of these searches have been conducted in leptonic final states and assume that the $W' \to WZ$ decay mode is suppressed. Searches for exotic particles that decay into WZ pairs are thus complementary to searches in the leptonic channels. Moreover, there are other models in which the W' couplings to SM fermions are suppressed, giving rise to a fermiophobic W' with an enhanced coupling to W and Z bosons [13,14]. It is therefore important to search for W' bosons also in the WZ final state.

Another model predicting a new heavy boson decaying into WZ is technicolor (TC): a gauge theory modeled on QCD with no elementary scalar particles [15,16]. TC provides a dynamical explanation of electroweak symmetry breaking by generating masses of the W and Z bosons through the binding energy of techni-fermions. Furthermore, it predicts a series of techni-hadrons that are bound states of the new strong interaction. By analogy with QCD, the techni-hadrons with $I^G(J^{PC}) = 1^-(0^{-+})$, $1^+(1^{--})$, and $1^-(1^{++})$ are called π_{TC}, ρ_{TC}, and a_{TC}, respectively. In low-scale technicolor (LSTC) [17,18], the lightest techni-hadrons are expected to have masses below 700 GeV, with the charged ρ_{TC} and a_{TC} able to decay to WZ boson pairs. Since these two states are expected to be nearly mass-degenerate [18], they would appear as a single feature in the WZ invariant mass spectrum, and we hereafter refer to them collectively as ρ_{TC}. The relationship between the masses of ρ_{TC} and π_{TC}, $M(\rho_{\text{TC}})$ and $M(\pi_{\text{TC}})$, significantly affects the ρ_{TC} branching fractions [19]. If $M(\rho_{\text{TC}}) < 2M(\pi_{\text{TC}})$, the decay $\rho_{\text{TC}} \to \pi_{\text{TC}} + W$ dominates, such that the branching fraction $\mathcal{B}(\rho_{\text{TC}} \to WZ) < 10\%$. However, if this decay is kinematically inaccessible, $\mathcal{B}(\rho_{\text{TC}} \to WZ)$ approaches 100%.

This Letter presents a search for new particles decaying via a WZ pair with $W \to \ell\nu$ and $Z \to \ell\ell$ in the final state, where $\ell = e, \mu$. The results are interpreted in the context of a SSM W' boson and a LSTC ρ_{TC} particle. A previous search in this channel performed by the D0 experiment excludes W' bosons with masses between 188 and 520 GeV at 95% confidence level (C.L.) [9]. Their result also excludes ρ_{TC} between 208 and 409 GeV at 95% C.L., under the assumption that $M(\rho_{\text{TC}}) < M(\pi_{\text{TC}}) + M(W)$. The analysis presented here considers the case where the relations between parameters are those of Ref. [19], $M(\pi_{\text{TC}}) = \frac{3}{4}M(\rho_{\text{TC}}) - 25$ GeV, and also investigates the results of varying the ρ_{TC} and π_{TC} masses.

This study uses data corresponding to an integrated luminosity of 4.98 ± 0.11 fb^{-1} of proton-proton collisions at $\sqrt{s} = 7$ TeV, recorded by the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC) in 2011. The central feature of the apparatus is a superconducting solenoid, of 6 m internal diameter, providing a field of 3.8 T. Inside the magnet coil are the silicon pixel and strip tracker, the lead tungstate crystal electromagnetic calorimeter, and the brass-scintillator hadron calorimeter.

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Muons are measured in gas-ionization detectors embedded in the steel return yoke. In addition to the barrel and end cap detectors, CMS has extensive forward calorimetry. The trigger system, composed of a custom hardware layer feeding into a commercial processor farm, reduces the event rate to approximately 300 Hz for storage and further analysis. A detailed description of the CMS apparatus may be found elsewhere [20].

The $WZ \to 3\ell\nu$ decay under study is characterized by a pair of same-flavor, opposite-charge, isolated leptons with high transverse momentum (p_T), having an invariant mass consistent with that of the Z boson, along with a third, high-p_T, isolated lepton, and missing transverse energy (E_T^{miss}) associated with the escaping neutrino. Other sources of events with three leptons, genuine or misidentified, constitute the background, and can be grouped into the following classes: (1) The irreducible SM WZ background. (2) Nonresonant events with no genuine Z boson in the final state, including top pair ($t\bar{t}$), multijet, $W + \text{jet}$, $W\gamma$, and $WW + \text{jet}$ production. Only the first of these makes a significant background contribution, and the others are therefore not considered in this analysis. (3) Events with a genuine Z boson decaying to leptons and a third misidentified or nonisolated lepton that is reconstructed as isolated. These events include $Z + \text{jets}$ (both light and heavy flavor) and $Z\gamma$ processes. (4) Events with a genuine Z boson decaying to leptons and a third genuine isolated lepton, dominated by $ZZ \to 4\ell$ decays in which one of the four leptons is undetected. Although irreducible, this contribution is small because of the low ZZ production cross section and dilepton decay branching fraction.

The background was modeled using samples produced with a full GEANT4 [21] simulation of the CMS detector. The primary SM background arises from the $WZ \to 3\ell\nu$ process, which was generated using the MADGRAPH5.1 [22] generator, interfaced to PYTHIA 6.4.22 [23] for parton showering, hadronization, and simulation of the underlying event. The CTEQ6L1 [24] parton distribution functions (PDFs) were used with PYTHIA tune Z2 [25]. Higher-order effects were estimated using next-to-leading-order (NLO) K-factor corrections, obtained using MCFM 6.1 [26]. The other background processes were also generated with MADGRAPH in combination with PYTHIA, with the exception of the ZZ process, which was generated using POWHEG 1.1 [27]. The signal was simulated using PYTHIA 6.4.22 with mass-dependent next-to-next-to-leading-order cross sections obtained using the simulation code FEWZ 2.0 [28]. Characteristic signal widths are in the range 50–150 GeV for the W' and 50–70 GeV for the ρ_{TC} masses examined. These are dominated by the detector resolution, as the natural widths are approximately 10 and 2 GeV, respectively.

Candidate events were triggered using a double-electron or double-muon requirement, with p_T thresholds of 17 and 8 GeV, respectively, for the highest-p_T and second-highest-p_T leptons. In the offline selection, events were required to have at least three reconstructed leptons within the tracking acceptance of $|\eta| < 2.5$ (2.4) for electrons (muons), where $\eta \equiv -\ln[\tan(\theta/2)]$, and θ is the polar angle with respect to the counterclockwise proton beam. To reduce background from jets misidentified as leptons, all lepton candidates were required to satisfy a series of identification and isolation criteria. In calculating isolation variables, the track momenta and energy deposits, excluding those associated with the lepton itself, were summed in a cone of $\Delta R < 0.3$ around the lepton direction, where $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$, and divided by the lepton transverse momentum. These sums were corrected for additional proton-proton interactions in each bunch crossing (pileup) using the fast jet energy density technique [29,30]. For simulated samples, pileup was modeled by superimposing generated minimum-bias interactions onto simulated events, weighted such that the interaction multiplicity agreed with the luminosity profile of the data set used. An additional scale factor (equal to one within 5%) derived from "tag-and-probe" [31] studies was applied to simulated events to correct for differences in lepton

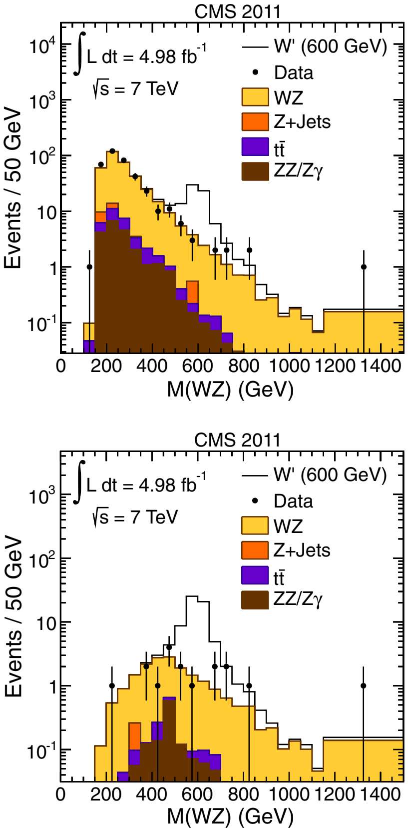

FIG. 1 (color online). Distribution of the WZ invariant mass (top) before application of the L_T requirement and (bottom) after applying the L_T requirement ($L_T > 290$ GeV) for the W' mass point at 600 GeV.

selection efficiency measured in recorded and simulated event samples.

Z boson candidates were reconstructed from pairs of opposite-sign, same-flavor leptons with the highest and second-highest lepton p_T greater than 20 and 10 GeV, respectively, and with an invariant mass between 60 and 120 GeV. In events where more than one such pair was found, the one with invariant mass closest to the nominal Z mass was selected. If four leptons compatible with two distinct Z candidates were present, the event was rejected in order to suppress ZZ background. The candidate for the W boson decay product was required to pass tighter isolation and identification requirements. If multiple lepton candidates existed, the highest-p_T remaining lepton, with p_T greater than 20 GeV, was chosen. Finally, candidate events were required to have $E_T^{\text{miss}} > 30$ GeV, as measured with a particle-flow algorithm [32], in order to discriminate against $Z +$ jets events with high-p_T jets misidentified as leptons and against $Z\gamma$ events with converted photons.

As the momentum component of the neutrino along the beam direction is unknown, the invariant mass of WZ candidates cannot be uniquely determined. However, by assuming the W to have its nominal mass, the value of the neutrino longitudinal momentum is constrained to one of the two solutions of a quadratic equation. Owing to detector resolution effects, the reconstructed transverse mass was found to lie above the invariant W mass, $M(W)$, in 20% of events, leading to complex solutions for the neutrino longitudinal momentum. In these cases, a real solution was recovered by setting $M(W)$ equal to the measured transverse mass. This results in two identical solutions for the neutrino longitudinal momentum. In simulated events with two unique solutions, the smaller-magnitude solution was found to be correct in approximately 75% of the cases, and this solution was therefore chosen for all events. The observed invariant mass distribution of WZ candidates, $M(WZ)$, is shown on the upper panel of Fig. 1.

In order to optimize the expected upper limit on the signal cross section, an additional selection requirement was applied on the scalar sum of the transverse momenta of the charged leptons coming from the W and Z bosons (L_T). For each W'/ρ_{TC} mass hypothesis considered, an optimized WZ mass search window and a minimum L_T requirement were jointly determined to give the best expected limit. The chosen L_T and mass-window requirements are listed in Table I, and the WZ invariant mass after applying the L_T requirement for the W' mass point at 600 GeV is shown on the lower panel of Fig. 1. There is no excess observed in the data above the expected standard model background.

As a cross-check of the simulation, the $Z +$ jets and $t\bar{t}$ backgrounds were estimated from the data by measuring the efficiencies for genuine and misidentified leptons to pass the isolation criteria and applying those efficiencies to a sample of events passing all requirements except for isolation. The total background result agrees with the numbers from simulation, and the uncertainties assigned to the $Z +$ jets and $t\bar{t}$ contributions when determining limits were based on the uncertainties in the estimates from data.

Systematic uncertainties affecting the product of acceptance, reconstruction, and identification efficiencies for the final-state objects were determined from simulation. These include uncertainties stemming from lepton and E_T^{miss} energy scales and resolutions, NLO effects, and pileup simulation. Following the recommendations of the PDF4LHC group [33], PDF and α_s variations of the MSTW2008 [34], CTEQ6.6 [35], and NNPDF2.0 [36] PDF sets were taken

TABLE I. Minimum L_T requirements and search windows for each $W'/(\rho_{TC})$ mass point along with the number of expected background events, observed events, and signal efficiency. Indicated uncertainties are statistical and systematic combined in quadrature.

$M(W'/\rho_{TC})$ (GeV)	L_T (GeV)	WZ Mass-Window (GeV)	$N_{\text{Bkg}}^{\text{MC}}$	Data	ϵ_{Sig} (%)
200	0	190–210	50 ± 9	52	8.0 ± 0.4
250	150	230–270	34 ± 6	40	8.8 ± 0.4
300	160	280–320	24 ± 5	23	18 ± 1
400	220	360–440	13 ± 2	7	29 ± 1
500	230	450–550	8 ± 2	9	41 ± 1
600	290	540–660	3.4 ± 0.7	2	45 ± 1
700	360	620–780	1.8 ± 0.4	2	48 ± 1
800	400	710–890	1.0 ± 0.2	1	52 ± 2
900	400	760–1040	1.0 ± 0.2	0	61 ± 2
1000	400	820–1180	0.8 ± 0.2	0	65 ± 2
1100	400	890–1310	0.6 ± 0.1	0	63 ± 1
1200	400	940–1460	0.4 ± 0.1	0	58 ± 1
1300	400	1020–1580	0.3 ± 0.1	0	50 ± 1
1400	400	1110–1690	0.18 ± 0.05	0	36 ± 1
1500	400	1200–1800	0.13 ± 0.04	0	30 ± 1

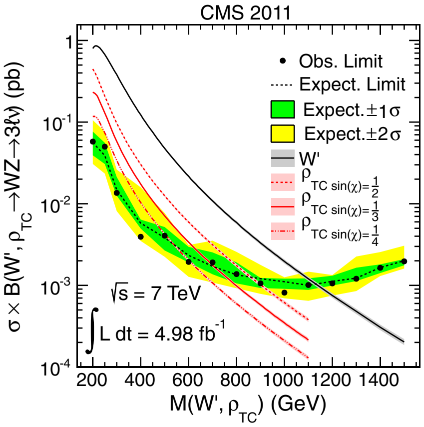

FIG. 2 (color online). Expected and observed 95% C.L. upper limits on $\sigma \times \mathcal{B}(W'/\rho_{TC} \to 3\ell\nu)$ as a function of the resonance mass for W' or ρ_{TC}, along with the 1σ and 2σ combined statistical and systematic expected variation shown as green (dark) and yellow (light) bands, respectively. The theoretical cross sections, with PDF uncertainties, include a mass-dependent next-to-next-to-leading-order K factor. The LSTC cross sections assume the relationship $M(\pi_{TC}) = \frac{3}{4}M(\rho_{TC}) - 25$ GeV.

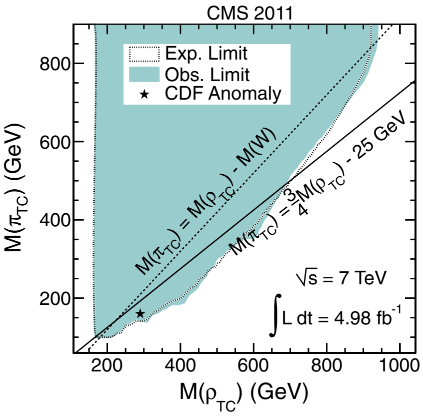

FIG. 3 (color online). Exclusion region at 95% C.L. for LSTC as a function of the ρ_{TC} and π_{TC} masses.

into account and their impact on the signal cross sections estimated.

The uncertainty on the background simulation is dominated by the 10% uncertainty due to NLO K-factor corrections for the WZ component. Cross section uncertainties of 7.5% for ZZ [26], 13% for $Z\gamma$ [37], and 17% for WZ [38] were also taken into account, along with a 2.2% uncertainty on the integrated luminosity [39].

Exclusion limits on the production cross section $\sigma(pp \to W'/\rho_{TC} \to WZ) \times \mathcal{B}(WZ \to 3\ell\nu)$ were determined by comparing the number of observed events with the numbers of expected signal and background events in each search window. The calculations were performed using the ROOSTATS implementation [40] of the CL$_s$ statistic. The event counts and efficiencies are shown in Table I. We note that the efficiency drops at high W' mass because of the isolation requirement as the leptons from the boosted Z boson become more collimated. We interpolate between mass points where we have simulated the signal to establish mass limits for each model.

In the SSM, these limits allow the exclusion of W' bosons with masses below 1143 GeV (Fig. 2). For LSTC, with the chosen parameters $M(\pi_{TC}) = \frac{3}{4}M(\rho_{TC}) - 25$ GeV, ρ_{TC} hadrons with masses between 167 and 687 GeV are excluded (see Fig. 3). Figure 3 also shows LSTC limits determined as a function of the ρ_{TC} and π_{TC} masses. The lower mass limits are obtained by extrapolating below 200 GeV. For the parameters chosen by the D0 experiment, $M(\rho_{TC}) < M(\pi_{TC}) + M(W)$, more stringent limits are obtained, excluding the range 180 to 938 GeV for $M(\rho_{TC})$. It can be seen that the LSTC interpretation of a deviation from the SM observed by the CDF experiment in the W + jets channel [41], with proposed parameters $M(\rho_{TC}) = 290$ GeV and $M(\pi_{TC}) = 160$ GeV [42], is excluded by the 95% C.L. upper bound of 150 GeV on $M(\pi_{TC})$ for the required ρ_{TC} mass. A more recent publication [43] proposes the evaluation of the cross section for $\rho_{TC} \to WZ$ as a function of the LSTC parameter $\sin\chi$. Changes in this parameter impact the decay branching fractions for WZ and $W\pi_{TC}$ (the channel studied in Ref. [42]), among others. Figure 2 shows the predicted cross sections corresponding to $\sin\chi = \frac{1}{2}$ and $\sin\chi = \frac{1}{4}$, as well as the value $\sin\chi = \frac{1}{3}$ used to establish the reported limit.

The W' production cross section and the $W' \to WZ$ branching fraction are both affected by the strength of the coupling between the W', W, and Z bosons. Figure 4 shows the 95% C.L. upper limit on the coupling as a function of the mass of the W' resonance.

In summary, a search for new exotic particles decaying via WZ to final states with electrons and muons has been performed using pp collisions at $\sqrt{s} = 7$ TeV corresponding to an integrated luminosity of 4.98 ± 0.11 fb^{-1}, collected by the CMS experiment. No significant excess was observed in the invariant mass distribution of WZ candidates, compared to the expectation from standard model processes. The results have been interpreted in the context of several theoretical models, with the data used to establish bounds at 95% C.L. on the masses of hypothetical particles decaying via WZ. In the framework of the sequential standard model, W' bosons with masses below 1143 GeV have been excluded. Technicolor ρ_{TC} hadrons with masses between 167 and 687 GeV have been excluded, assuming $M(\pi_{TC}) = \frac{3}{4}M(\rho_{TC}) - 25$ GeV. Under the alternative assumption $M(\rho_{TC}) < M(\pi_{TC}) + M(\mathrm{W})$, ρ_{TC} hadrons with masses between 180 and 938 GeV have been excluded. These are the most stringent limits to date in the WZ channel.

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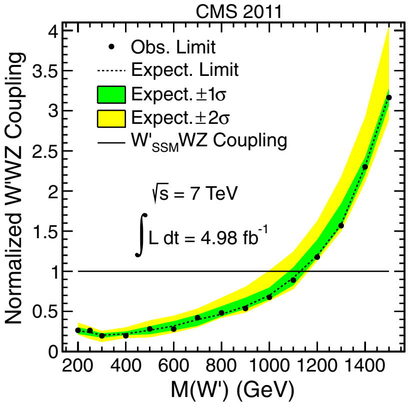

FIG. 4 (color online). Upper limit at 95% C.L. on the strength of the $W' \, WZ$ coupling normalized to the SSM prediction, as a function of the W' mass. The 1σ and 2σ combined statistical and systematic expected variation is shown as green (dark) and yellow (light) bands, respectively. PDF uncertainties on the theoretical cross section are not included.

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Van Onsem,[5] I. Villella,[5] B. Clerbaux,[6] G. De Lentdecker,[6] V. Dero,[6] A. P. R. Gay,[6] T. Hreus,[6] A. Léonard,[6] P. E. Marage,[6] T. Reis,[6] L. Thomas,[6] C. Vander Velde,[6] P. Vanlaer,[6] J. Wang,[6] V. Adler,[7] K. Beernaert,[7] A. Cimmino,[7] S. Costantini,[7] G. Garcia,[7] M. Grunewald,[7] B. Klein,[7] J. Lellouch,[7] A. Marinov,[7] J. Mccartin,[7] A. A. Ocampo Rios,[7] D. Ryckbosch,[7] N. Strobbe,[7] F. Thyssen,[7] M. Tytgat,[7] P. Verwilligen,[7] S. Walsh,[7] E. Yazgan,[7] N. Zaganidis,[7] S. Basegmez,[8] G. Bruno,[8] R. Castello,[8] L. Ceard,[8] C. Delaere,[8] T. du Pree,[8] D. Favart,[8] L. Forthomme,[8] A. Giammanco,[8,c] J. Hollar,[8] V. Lemaitre,[8] J. Liao,[8] O. Militaru,[8] C. Nuttens,[8] D. Pagano,[8] A. Pin,[8] K. Piotrzkowski,[8] N. Schul,[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] D. De Jesus Damiao,[10] T. Martins,[10] M. E. Pol,[10] M. H. G. Souza,[10] W. L. Aldá Júnior,[11] W. Carvalho,[11] A. Custódio,[11] E. M. Da Costa,[11] C. De Oliveira Martins,[11] S. Fonseca De Souza,[11] D. Matos Figueiredo,[11] L. Mundim,[11] H. Nogima,[11] V. Oguri,[11] W. L. Prado Da Silva,[11] A. Santoro,[11] L. Soares Jorge,[11] A. Sznajder,[11] T. S. Anjos,[12,d] C. A. Bernardes,[12,d] F. A. Dias,[12,e] T. R. Fernandez Perez Tomei,[12] E. M. Gregores,[12,d] C. Lagana,[12] F. Marinho,[12] P. G. Mercadante,[12,d] S. F. Novaes,[12] Sandra S. Padula,[12] V. Genchev,[13,f] P. Iaydjiev,[13,f] S. Piperov,[13] M. Rodozov,[13] S. Stoykova,[13] G. Sultanov,[13] V. Tcholakov,[13] R. Trayanov,[13] M. Vutova,[13] A. Dimitrov,[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] C. H. Jiang,[15] D. Liang,[15] S. Liang,[15] X. Meng,[15] J. Tao,[15] J. Wang,[15] X. Wang,[15] Z. Wang,[15] H. Xiao,[15] M. Xu,[15] J. Zang,[15] Z. Zhang,[15] C. Asawatangtrakuldee,[16] Y. Ban,[16] S. Guo,[16] Y. Guo,[16] W. Li,[16] S. Liu,[16] Y. Mao,[16] S. J. Qian,[16] H. Teng,[16] D. Wang,[16] L. Zhang,[16] B. Zhu,[16] W. Zou,[16] C. Avila,[17] J. P. Gomez,[17] B. Gomez Moreno,[17] A. F. Osorio Oliveros,[17] J. C. Sanabria,[17] N. Godinovic,[18] D. Lelas,[18] R. Plestina,[18,g] D. Polic,[18] I. Puljak,[18,f] Z. Antunovic,[19] M. Kovac,[19] V. Brigljevic,[20] S. Duric,[20] K. Kadija,[20] J. Luetic,[20] S. Morovic,[20] A. Attikis,[21] M. Galanti,[21] G. Mavromanolakis,[21] J. Mousa,[21] C. Nicolaou,[21] F. Ptochos,[21] P. A. Razis,[21] M. Finger,[22] M. Finger, Jr.,[22] Y. Assran,[23,h] S. Elgammal,[23,i] A. Ellithi Kamel,[23,j] S. Khalil,[23,i] M. A. Mahmoud,[23,k] A. Radi,[23,l] M. Kadastik,[24] M. Müntel,[24] M. Raidal,[24] L. Rebane,[24] A. Tiko,[24] P. Eerola,[25] G. Fedi,[25] M. Voutilainen,[25] J. Härkönen,[26] A. Heikkinen,[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] D. Ungaro,[26] L. Wendland,[26] K. Banzuzi,[27] A. Karjalainen,[27] A. Korpela,[27] T. Tuuva,[27] M. Besancon,[28] S. Choudhury,[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] L. Millischer,[28] A. Nayak,[28] J. Rander,[28] A. Rosowsky,[28] I. Shreyber,[28] M. Titov,[28] S. Baffioni,[29] F. Beaudette,[29] L. Benhabib,[29] L. Bianchini,[29] M. Bluj,[29,m] C. Broutin,[29] P. Busson,[29] C. Charlot,[29] N. Daci,[29] T. Dahms,[29] L. Dobrzynski,[29] R. Granier de Cassagnac,[29] M. Haguenauer,[29] P. Miné,[29] C. Mironov,[29] M. Nguyen,[29] C. Ochando,[29] P. Paganini,[29] D. Sabes,[29] R. Salerno,[29] Y. Sirois,[29] C. Veelken,[29] A. Zabi,[29] J.-L. Agram,[30,n] J. Andrea,[30] D. Bloch,[30] D. Bodin,[30] J.-M. Brom,[30] M. Cardaci,[30] E. C. Chabert,[30] C. Collard,[30] E. Conte,[30,n] F. Drouhin,[30,n] C. Ferro,[30] J.-C. Fontaine,[30,n] D. Gelé,[30] U. Goerlach,[30] P. Juillot,[30] A.-C. Le Bihan,[30] P. Van Hove,[30] F. Fassi,[31] D. Mercier,[31] S. Beauceron,[32] N. Beaupere,[32] O. Bondu,[32] G. Boudoul,[32] J. Chasserat,[32] R. Chierici,[32,f] D. Contardo,[32] P. Depasse,[32] H. El Mamouni,[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] V. Sordini,[32] Y. Tschudi,[32] P. Verdier,[32] S. Viret,[32] Z. Tsamalaidze,[33,y]
G. Anagnostou,[34] S. Beranek,[34] M. Edelhoff,[34] L. Feld,[34] N. Heracleous,[34] O. Hindrichs,[34] R. Jussen,[34] K. Klein,[34]
J. Merz,[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,o] 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] P. Kreuzer,[35] C. Magass,[35]
M. Merschmeyer,[35] A. Meyer,[35] M. Olschewski,[35] P. Papacz,[35] H. Pieta,[35] H. Reithler,[35] S. A. Schmitz,[35]
L. Sonnenschein,[35] J. Steggemann,[35] D. Teyssier,[35] M. Weber,[35] M. Bontenackels,[36] V. Cherepanov,[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] A. Nowack,[36]
L. Perchalla,[36] O. Pooth,[36] P. Sauerland,[36] A. Stahl,[36] M. Aldaya Martin,[37] J. Behr,[37] W. Behrenhoff,[37] U. Behrens,[37]
M. Bergholz,[37,p] A. Bethani,[37] K. Borras,[37] A. Burgmeier,[37] A. Cakir,[37] L. Calligaris,[37] A. Campbell,[37] E. Castro,[37]
F. Costanza,[37] D. Dammann,[37] C. Diez Pardos,[37] G. Eckerlin,[37] D. Eckstein,[37] G. Flucke,[37] A. Geiser,[37]
I. Glushkov,[37] P. Gunnellini,[37] S. Habib,[37] J. Hauk,[37] G. Hellwig,[37] H. Jung,[37] M. Kasemann,[37] P. Katsas,[37]
C. Kleinwort,[37] H. Kluge,[37] A. Knutsson,[37] M. Krämer,[37] D. Krücker,[37] E. Kuznetsova,[37] W. Lange,[37]
W. Lohmann,[37,p] B. Lutz,[37] R. Mankel,[37] I. Marfin,[37] M. Marienfeld,[37] I.-A. Melzer-Pellmann,[37] A. B. Meyer,[37]
J. Mnich,[37] A. Mussgiller,[37] S. Naumann-Emme,[37] J. Olzem,[37] H. Perrey,[37] A. Petrukhin,[37] D. Pitzl,[37]
A. Raspereza,[37] P. M. Ribeiro Cipriano,[37] C. Riedl,[37] E. Ron,[37] M. Rosin,[37] J. Salfeld-Nebgen,[37] R. Schmidt,[37,p]
T. Schoerner-Sadenius,[37] N. Sen,[37] A. Spiridonov,[37] M. Stein,[37] R. Walsh,[37] C. Wissing,[37] C. Autermann,[38]
V. Blobel,[38] J. Draeger,[38] H. Enderle,[38] J. Erfle,[38] U. Gebbert,[38] M. Görner,[38] T. Hermanns,[38] R. S. Höing,[38]
K. Kaschube,[38] G. Kaussen,[38] H. Kirschenmann,[38] R. Klanner,[38] J. Lange,[38] B. Mura,[38] F. Nowak,[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. Schröder,[38]
T. Schum,[38] M. Seidel,[38] V. Sola,[38] H. Stadie,[38] G. Steinbrück,[38] J. Thomsen,[38] L. Vanelderen,[38] C. Barth,[39]
J. Berger,[39] C. Böser,[39] T. Chwalek,[39] W. De Boer,[39] A. Descroix,[39] A. Dierlamm,[39] M. Feindt,[39] M. Guthoff,[39,f]
C. Hackstein,[39] F. Hartmann,[39] T. Hauth,[39,f] M. Heinrich,[39] H. Held,[39] K. H. Hoffmann,[39] S. Honc,[39] I. Katkov,[39,o]
J. R. Komaragiri,[39] P. Lobelle Pardo,[39] D. Martschei,[39] S. Mueller,[39] Th. Müller,[39] M. Niegel,[39] A. Nürnberg,[39]
O. Oberst,[39] A. Oehler,[39] J. Ott,[39] G. Quast,[39] K. Rabbertz,[39] F. Ratnikov,[39] N. Ratnikova,[39] S. Röcker,[39]
A. Scheurer,[39] F.-P. Schilling,[39] G. Schott,[39] H. J. Simonis,[39] F. M. Stober,[39] D. Troendle,[39] R. Ulrich,[39]
J. Wagner-Kuhr,[39] S. Wayand,[39] T. Weiler,[39] M. Zeise,[39] G. Daskalakis,[40] T. Geralis,[40] S. Kesisoglou,[40]
A. Kyriakis,[40] D. Loukas,[40] I. Manolakos,[40] A. Markou,[40] C. Markou,[40] C. Mavrommatis,[40] E. Ntomari,[40]
L. Gouskos,[41] T. J. Mertzimekis,[41] A. Panagiotou,[41] N. Saoulidou,[41] I. Evangelou,[42] C. Foudas,[42,f] P. Kokkas,[42]
N. Manthos,[42] I. Papadopoulos,[42] V. Patras,[42] G. Bencze,[43] C. Hajdu,[43,f] P. Hidas,[43] D. Horvath,[43,q] F. Sikler,[43]
V. Veszpremi,[43] G. Vesztergombi,[43,r] 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. B. Beri,[46] V. Bhatnagar,[46] N. Dhingra,[46] R. Gupta,[46] M. Jindal,[46]
M. Kaur,[46] M. Z. Mehta,[46] N. Nishu,[46] L. K. Saini,[46] A. Sharma,[46] J. Singh,[46] S. Ahuja,[47] A. Bhardwaj,[47]
B. C. Choudhary,[47] A. Kumar,[47] A. Kumar,[47] S. Malhotra,[47] M. Naimuddin,[47] K. Ranjan,[47] V. Sharma,[47]
R. K. Shivpuri,[47] S. Banerjee,[48] S. Bhattacharya,[48] S. Dutta,[48] B. Gomber,[48] Sa. Jain,[48] Sh. Jain,[48] R. Khurana,[48]
S. Sarkar,[48] M. Sharan,[48] A. Abdulsalam,[49] R. K. Choudhury,[49] D. Dutta,[49] S. Kailas,[49] V. Kumar,[49] P. Mehta,[49]
A. K. Mohanty,[49,f] L. M. Pant,[49] P. Shukla,[49] T. Aziz,[50] S. Ganguly,[50] M. Guchait,[50,s] M. Maity,[50,t] G. Majumder,[50]
K. Mazumdar,[50] G. B. Mohanty,[50] B. Parida,[50] K. Sudhakar,[50] N. Wickramage,[50] S. Banerjee,[51] S. Dugad,[51]
H. Arfaei,[52] H. Bakhshiansohi,[52,u] S. M. Etesami,[52,v] A. Fahim,[52,u] M. Hashemi,[52] H. Hesari,[52] A. Jafari,[52,u]
M. Khakzad,[52] M. Mohammadi Najafabadi,[52] S. Paktinat Mehdiabadi,[52] B. Safarzadeh,[52,w] M. Zeinali,[52,v]
M. Abbrescia,[53a,53b] L. Barbone,[53a,53b] C. Calabria,[53a,53b,f] S. S. Chhibra,[53a,53b] A. Colaleo,[53a] D. Creanza,[53a,53c]
N. De Filippis,[53a,53c,f] M. De Palma,[53a,53b] L. Fiore,[53a] G. Iaselli,[53a,53c] L. Lusito,[53a,53b] G. Maggi,[53a,53c] M. Maggi,[53a]
B. Marangelli,[53a,53b] S. My,[53a,53c] S. Nuzzo,[53a,53b] N. Pacifico,[53a,53b] A. Pompili,[53a,53b] G. Pugliese,[53a,53c]
G. Selvaggi,[53a,53b] L. Silvestris,[53a] G. Singh,[53a,53b] R. Venditti,[53a] G. Zito,[53a] G. Abbiendi,[54a] A. C. Benvenuti,[54a]
D. Bonacorsi,[54a,54b] S. Braibant-Giacomelli,[54a,54b] L. Brigliadori,[54a,54b] P. Capiluppi,[54a,54b] A. Castro,[54a,54b]
F. R. Cavallo,[54a] M. Cuffiani,[54a,54b] G. M. Dallavalle,[54a] F. Fabbri,[54a] A. Fanfani,[54a,54b] D. Fasanella,[54a,54b,f]
P. Giacomelli,[54a] C. Grandi,[54a] L. Guiducci,[54a,54b] S. Marcellini,[54a] G. Masetti,[54a] M. Meneghelli,[54a,54b,f]
A. Montanari,[54a] F. L. Navarria,[54a,54b] F. Odorici,[54a] A. Perrotta,[54a] F. Primavera,[54a,54b] A. M. Rossi,[54a,54b]
T. Rovelli,[54a,54b] G. Siroli,[54a,54b] R. Travaglini,[54a,54b] S. Albergo,[55a,55b] G. Cappello,[55a,55b] M. Chiorboli,[55a,55b]
S. Costa,[55a,55b] R. Potenza,[55a,55b] A. Tricomi,[55a,55b] C. Tuve,[55a,55b] G. Barbagli,[56a] V. Ciulli,[56a,56b] C. Civinini,[56a]
R. D'Alessandro,[56a,56b] E. Focardi,[56a,56b] S. Frosali,[56a,56b] E. Gallo,[56a] S. Gonzi,[56a,56b] M. Meschini,[56a] S. Paoletti,[56a]

G. Sguazzoni,[56a] A. Tropiano,[56a,f] L. Benussi,[57] S. Bianco,[57] S. Colafranceschi,[57,x] F. Fabbri,[57] D. Piccolo,[57] P. Fabbricatore,[58] R. Musenich,[58] S. Tosi,[58] A. Benaglia,[59a,59b,f] F. De Guio,[59a,59b] L. Di Matteo,[59a,59b,f] S. Fiorendi,[59a,59b] S. Gennai,[59a,f] A. Ghezzi,[59a,59b] S. Malvezzi,[59a] R. A. Manzoni,[59a,59b] A. Martelli,[59a,59b] A. Massironi,[59a,59b,f] D. Menasce,[59a] L. Moroni,[59a] M. Paganoni,[59a,59b] D. Pedrini,[59a] S. Ragazzi,[59a,59b] N. Redaelli,[59a] S. Sala,[59a] T. Tabarelli de Fatis,[59a,59b] S. Buontempo,[60a] C. A. Carrillo Montoya,[60a,f] N. Cavallo,[60a,y] A. De Cosa,[60a,60b,f] O. Dogangun,[60a,60b] F. Fabozzi,[60a,y] A. O. M. Iorio,[60a] L. Lista,[60a] S. Meola,[60a,z] M. Merola,[60a,60b] P. Paolucci,[60a,f] P. Azzi,[61a] N. Bacchetta,[61a,f] P. Bellan,[61a,61b] D. Bisello,[61a,61b] A. Branca,[61a,f] R. Carlin,[61a,61b] P. Checchia,[61a] T. Dorigo,[61a] U. Dosselli,[61a] F. Gasparini,[61a,61b] U. Gasparini,[61a,61b] A. Gozzelino,[61a] K. Kanishchev,[61a,61c] S. Lacaprara,[61a] I. Lazzizzera,[61a,61c] M. Margoni,[61a,61b] A. T. Meneguzzo,[61a,61b] M. Nespolo,[61a,f] J. Pazzini,[61a] P. Ronchese,[61a,61b] F. Simonetto,[61a,61b] E. Torassa,[61a] S. Vanini,[61a,61b] P. Zotto,[61a,61b] G. Zumerle,[61a,61b] M. Gabusi,[62a,62b] S. P. Ratti,[62a,62b] C. Riccardi,[62a,62b] P. Torre,[62a,62b] P. Vitulo,[62a,62b] M. Biasini,[63a,63b] G. M. Bilei,[63a] L. Fanò,[63a,63b] P. Lariccia,[63a,63b] A. Lucaroni,[63a,63b,f] G. Mantovani,[63a,63b] M. Menichelli,[63a] A. Nappi,[63a,63b] F. Romeo,[63a,63b] A. Saha,[63a] A. Santocchia,[63a,63b] A. Spiezia,[63a,63b] S. Taroni,[63a,63b,f] P. Azzurri,[64a,64c] G. Bagliesi,[64a] T. Boccali,[64a] G. Broccolo,[64a,64c] R. Castaldi,[64a] R. T. D'Agnolo,[64a,64c] R. Dell'Orso,[64a] F. Fiori,[64a,64b,f] L. Foà,[64a,64c] A. Giassi,[64a] A. Kraan,[64a] F. Ligabue,[64a,64c] T. Lomtadze,[64a] L. Martini,[64a,aa] A. Messineo,[64a,64b] F. Palla,[64a] A. Rizzi,[64a,64b] A. T. Serban,[64a,bb] P. Spagnolo,[64a] P. Squillacioti,[64a,f] R. Tenchini,[64a] G. Tonelli,[64a,64b,f] A. Venturi,[64a,f] P. G. Verdini,[64a] L. Barone,[65a,65b] F. Cavallari,[65a] D. Del Re,[65a,65b,f] M. Diemoz,[65a] M. Grassi,[65a,65b,f] E. Longo,[65a,65b] P. Meridiani,[65a,f] F. Micheli,[65a,65b] S. Nourbakhsh,[65a,65b] G. Organtini,[65a,65b] R. Paramatti,[65a] S. Rahatlou,[65a,65b] M. Sigamani,[65a] L. Soffi,[65a,65b] N. Amapane,[66a,66b] R. Arcidiacono,[66a,66c] S. Argiro,[66a,66b] M. Arneodo,[66a,66c] C. Biino,[66a] N. Cartiglia,[66a] M. Costa,[66a,66b] N. Demaria,[66a] C. Mariotti,[66a,f] S. Maselli,[66a] E. Migliore,[66a,66b] V. Monaco,[66a,66b] M. Musich,[66a,f] M. M. Obertino,[66a,66c] N. Pastrone,[66a] M. Pelliccioni,[66a] A. Potenza,[66a,66b] A. Romero,[66a,66b] M. Ruspa,[66a,66c] R. Sacchi,[66a,66b] A. Solano,[66a,66b] A. Staiano,[66a] A. Vilela Pereira,[66a] S. Belforte,[67a] V. Candelise,[67a,67b] F. Cossutti,[67a] G. Della Ricca,[67a,67b] B. Gobbo,[67a] M. Marone,[67a,67b,f] D. Montanino,[67a,67b,f] A. Penzo,[67a] A. Schizzi,[67a,67b] S. G. Heo,[68] T. Y. Kim,[68] S. K. Nam,[68] S. Chang,[69] D. H. Kim,[69] G. N. Kim,[69] D. J. Kong,[69] H. Park,[69] S. R. Ro,[69] D. C. Son,[69] T. Son,[69] J. Y. Kim,[70] Zero J. Kim,[70] S. Song,[70] S. Choi,[71] D. Gyun,[71] B. Hong,[71] M. Jo,[71] H. Kim,[71] T. J. Kim,[71] K. S. Lee,[71] D. H. Moon,[71] S. K. Park,[71] M. Choi,[72] J. H. Kim,[72] C. Park,[72] I. C. Park,[72] S. Park,[72] G. Ryu,[72] Y. Cho,[73] Y. Choi,[73] Y. K. Choi,[73] J. Goh,[73] M. S. Kim,[73] E. Kwon,[73] B. Lee,[73] J. Lee,[73] S. Lee,[73] H. Seo,[73] I. Yu,[73] M. J. Bilinskas,[74] I. Grigelionis,[74] M. Janulis,[74] A. Juodagalvis,[74] H. Castilla-Valdez,[75] E. De La Cruz-Burelo,[75] I. Heredia-de La Cruz,[75] R. Lopez-Fernandez,[75] R. Magaña Villalba,[75] J. Martínez-Ortega,[75] A. Sánchez-Hernández,[75] L. M. Villasenor-Cendejas,[75] S. Carrillo Moreno,[76] F. Vazquez Valencia,[76] H. A. Salazar Ibarguen,[77] E. Casimiro Linares,[78] A. Morelos Pineda,[78] M. A. Reyes-Santos,[78] D. Krofcheck,[79] A. J. Bell,[80] P. H. Butler,[80] R. Doesburg,[80] S. Reucroft,[80] H. Silverwood,[80] M. Ahmad,[81] M. I. Asghar,[81] H. R. Hoorani,[81] S. Khalid,[81] W. A. Khan,[81] T. Khurshid,[81] S. Qazi,[81] M. A. Shah,[81] M. Shoaib,[81] G. Brona,[82] K. Bunkowski,[82] M. Cwiok,[82] W. Dominik,[82] K. Doroba,[82] A. Kalinowski,[82] M. Konecki,[82] J. Krolikowski,[82] H. Bialkowska,[83] B. Boimska,[83] T. Frueboes,[83] R. Gokieli,[83] M. Górski,[83] M. Kazana,[83] K. Nawrocki,[83] K. Romanowska-Rybinska,[83] M. Szleper,[83] G. Wrochna,[83] P. Zalewski,[83] N. Almeida,[84] P. Bargassa,[84] A. David,[84] P. Faccioli,[84] P. G. Ferreira Parracho,[84] M. Gallinaro,[84] J. Seixas,[84] J. Varela,[84] P. Vischia,[84] I. Belotelov,[85] P. Bunin,[85] M. Gavrilenko,[85] I. Golutvin,[85] I. Gorbunov,[85] A. Kamenev,[85] V. Karjavin,[85] G. Kozlov,[85] A. Lanev,[85] A. Malakhov,[85] P. Moisenz,[85] V. Palichik,[85] V. Perelygin,[85] S. Shmatov,[85] V. Smirnov,[85] A. Volodko,[85] A. Zarubin,[85] S. Evstyukhin,[86] V. Golovtsov,[86] Y. Ivanov,[86] V. Kim,[86] P. Levchenko,[86] V. Murzin,[86] V. Oreshkin,[86] I. Smirnov,[86] V. Sulimov,[86] L. Uvarov,[86] S. Vavilov,[86] A. Vorobyev,[86] An. Vorobyev,[86] Yu. Andreev,[87] A. Dermenev,[87] S. Gninenko,[87] N. Golubev,[87] M. Kirsanov,[87] N. Krasnikov,[87] V. Matveev,[87] A. Pashenkov,[87] D. Tlisov,[87] A. Toropin,[87] V. Epshteyn,[88] M. Erofeeva,[88] V. Gavrilov,[88] M. Kossov,[88,f] N. Lychkovskaya,[88] V. Popov,[88] G. Safronov,[88] S. Semenov,[88] V. Stolin,[88] E. Vlasov,[88] A. Zhokin,[88] A. Belyaev,[89] E. Boos,[89] M. Dubinin,[89,e] L. Dudko,[89] A. Ershov,[89] A. Gribushin,[89] V. Klyukhin,[89] O. Kodolova,[89] I. Lokhtin,[89] A. Markina,[89] S. Obraztsov,[89] M. Perfilov,[89] S. Petrushanko,[89] A. Popov,[89] L. Sarycheva,[89,a] V. Savrin,[89] A. Snigirev,[89] V. Andreev,[90] M. Azarkin,[90] I. Dremin,[90] M. Kirakosyan,[90] A. Leonidov,[90] G. Mesyats,[90] S. V. Rusakov,[90] A. Vinogradov,[90] I. Azhgirey,[91] I. Bayshev,[91] S. Bitioukov,[91] V. Grishin,[91,f] V. Kachanov,[91] D. Konstantinov,[91] A. Korablev,[91] V. Krychkine,[91] V. Petrov,[91] R. Ryutin,[91] A. Sobol,[91] L. Tourtchanovitch,[91] S. Troshin,[91] N. Tyurin,[91] A. Uzunian,[91] A. Volkov,[91] P. Adzic,[92,cc] M. Djordjevic,[92] M. Ekmedzic,[92] D. Krpic,[92,cc] J. Milosevic,[92]

M. Aguilar-Benitez,[93] J. Alcaraz Maestre,[93] P. Arce,[93] C. Battilana,[93] E. Calvo,[93] M. Cerrada,[93]
M. Chamizo Llatas,[93] N. Colino,[93] B. De La Cruz,[93] A. Delgado Peris,[93] D. Domínguez Vázquez,[93]
C. Fernandez Bedoya,[93] J. P. Fernández Ramos,[93] A. Ferrando,[93] J. Flix,[93] M. C. Fouz,[93] P. Garcia-Abia,[93]
O. Gonzalez Lopez,[93] S. Goy Lopez,[93] J. M. Hernandez,[93] M. I. Josa,[93] G. Merino,[93] J. Puerta Pelayo,[93]
A. Quintario Olmeda,[93] I. Redondo,[93] L. Romero,[93] J. Santaolalla,[93] M. S. Soares,[93] C. Willmott,[93] C. Albajar,[94]
G. Codispoti,[94] J. F. de Trocóniz,[94] H. Brun,[95] J. Cuevas,[95] J. Fernandez Menendez,[95] S. Folgueras,[95]
I. Gonzalez Caballero,[95] L. Lloret Iglesias,[95] J. Piedra Gomez,[95,dd] J. A. Brochero Cifuentes,[96] I. J. Cabrillo,[96]
A. Calderon,[96] S. H. Chuang,[96] J. Duarte Campderros,[96] M. Felcini,[96,ee] M. Fernandez,[96] G. Gomez,[96]
J. Gonzalez Sanchez,[96] A. Graziano,[96] C. Jorda,[96] A. Lopez Virto,[96] J. Marco,[96] R. Marco,[96] C. Martinez Rivero,[96]
F. Matorras,[96] F. J. Munoz Sanchez,[96] T. Rodrigo,[96] A. Y. Rodríguez-Marrero,[96] A. Ruiz-Jimeno,[96] L. Scodellaro,[96]
M. Sobron Sanudo,[96] I. Vila,[96] R. Vilar Cortabitarte,[96] D. Abbaneo,[97] E. Auffray,[97] G. Auzinger,[97] P. Baillon,[97]
A. H. Ball,[97] D. Barney,[97] J. F. Benitez,[97] C. Bernet,[97,g] G. Bianchi,[97] P. Bloch,[97] A. Bocci,[97] A. Bonato,[97] C. Botta,[97]
H. Breuker,[97] T. Camporesi,[97] G. Cerminara,[97] T. Christiansen,[97] J. A. Coarasa Perez,[97] D. D'Enterria,[97]
A. Dabrowski,[97] A. De Roeck,[97] S. Di Guida,[97] M. Dobson,[97] N. Dupont-Sagorin,[97] A. Elliott-Peisert,[97] B. Frisch,[97]
W. Funk,[97] G. Georgiou,[97] M. Giffels,[97] D. Gigi,[97] K. Gill,[97] D. Giordano,[97] M. Giunta,[97] F. Glege,[97]
R. Gomez-Reino Garrido,[97] P. Govoni,[97] S. Gowdy,[97] R. Guida,[97] M. Hansen,[97] P. Harris,[97] C. Hartl,[97] J. Harvey,[97]
B. Hegner,[97] A. Hinzmann,[97] V. Innocente,[97] P. Janot,[97] K. Kaadze,[97] E. Karavakis,[97] K. Kousouris,[97] P. Lecoq,[97]
Y.-J. Lee,[97] P. Lenzi,[97] C. Lourenço,[97] T. Mäki,[97] M. Malberti,[97] L. Malgeri,[97] M. Mannelli,[97] L. Masetti,[97]
F. Meijers,[97] S. Mersi,[97] E. Meschi,[97] R. Moser,[97] M. U. Mozer,[97] M. Mulders,[97] P. Musella,[97] E. Nesvold,[97]
T. Orimoto,[97] L. Orsini,[97] E. Palencia Cortezon,[97] E. Perez,[97] L. Perrozzi,[97] A. Petrilli,[97] A. Pfeiffer,[97] M. Pierini,[97]
M. Pimiä,[97] D. Piparo,[97] G. Polese,[97] L. Quertenmont,[97] A. Racz,[97] W. Reece,[97] J. Rodrigues Antunes,[97]
G. Rolandi,[97,ff] T. Rommerskirchen,[97] C. Rovelli,[97,gg] M. Rovere,[97] H. Sakulin,[97] F. Santanastasio,[97] C. Schäfer,[97]
C. Schwick,[97] I. Segoni,[97] S. Sekmen,[97] A. Sharma,[97] P. Siegrist,[97] P. Silva,[97] M. Simon,[97] P. Sphicas,[97,hh]
D. Spiga,[97] A. Tsirou,[97] G. I. Veres,[97,r] J. R. Vlimant,[97] H. K. Wöhri,[97] S. D. Worm,[97,ii] W. D. Zeuner,[97] W. Bertl,[98]
K. Deiters,[98] W. Erdmann,[98] K. Gabathuler,[98] R. Horisberger,[98] Q. Ingram,[98] H. C. Kaestli,[98] S. König,[98]
D. Kotlinski,[98] U. Langenegger,[98] F. Meier,[98] D. Renker,[98] T. Rohe,[98] J. Sibille,[98,jj] L. Bäni,[99] P. Bortignon,[99]
M. A. Buchmann,[99] B. Casal,[99] N. Chanon,[99] A. Deisher,[99] G. Dissertori,[99] M. Dittmar,[99] M. Donegà,[99] M. Dünser,[99]
J. Eugster,[99] K. Freudenreich,[99] C. Grab,[99] D. Hits,[99] P. Lecomte,[99] W. Lustermann,[99] A. C. Marini,[99]
P. Martinez Ruiz del Arbol,[99] N. Mohr,[99] F. Moortgat,[99] C. Nägeli,[99,kk] P. Nef,[99] F. Nessi-Tedaldi,[99] F. Pandolfi,[99]
L. Pape,[99] F. Pauss,[99] M. Peruzzi,[99] F. J. Ronga,[99] M. Rossini,[99] L. Sala,[99] A. K. Sanchez,[99] A. Starodumov,[99,ll]
B. Stieger,[99] M. Takahashi,[99] L. Tauscher,[99,a] A. Thea,[99] K. Theofilatos,[99] D. Treille,[99] C. Urscheler,[99] R. Wallny,[99]
H. A. Weber,[99] L. Wehrli,[99] C. Amsler,[100] V. Chiochia,[100] S. De Visscher,[100] C. Favaro,[100] M. Ivova Rikova,[100]
B. Millan Mejias,[100] P. Otiougova,[100] P. Robmann,[100] H. Snoek,[100] S. Tupputi,[100] M. Verzetti,[100] Y. H. Chang,[101]
K. H. Chen,[101] C. M. Kuo,[101] S. W. Li,[101] W. Lin,[101] Z. K. Liu,[101] Y. J. Lu,[101] D. Mekterovic,[101] A. P. Singh,[101]
R. Volpe,[101] S. S. Yu,[101] P. Bartalini,[102] P. Chang,[102] Y. H. Chang,[102] Y. W. Chang,[102] Y. Chao,[102] K. F. Chen,[102]
C. Dietz,[102] U. Grundler,[102] W.-S. Hou,[102] Y. Hsiung,[102] K. Y. Kao,[102] Y. J. Lei,[102] R.-S. Lu,[102] D. Majumder,[102]
E. Petrakou,[102] X. Shi,[102] J. G. Shiu,[102] Y. M. Tzeng,[102] X. Wan,[102] M. Wang,[102] A. Adiguzel,[103]
M. N. Bakirci,[103,mm] S. Cerci,[103,nn] C. Dozen,[103] I. Dumanoglu,[103] E. Eskut,[103] S. Girgis,[103] G. Gokbulut,[103]
E. Gurpinar,[103] I. Hos,[103] E. E. Kangal,[103] T. Karaman,[103] G. Karapinar,[103,oo] A. Kayis Topaksu,[103] G. Onengut,[103]
K. Ozdemir,[103] S. Ozturk,[103,pp] A. Polatoz,[103] K. Sogut,[103,qq] D. Sunar Cerci,[103,nn] B. Tali,[103,nn] H. Topakli,[103,mm]
L. N. Vergili,[103] M. Vergili,[103] I. V. Akin,[104] T. Aliev,[104] B. Bilin,[104] S. Bilmis,[104] M. Deniz,[104] H. Gamsizkan,[104]
A. M. Guler,[104] K. Ocalan,[104] A. Ozpineci,[104] M. Serin,[104] R. Sever,[104] U. E. Surat,[104] M. Yalvac,[104] E. Yildirim,[104]
M. Zeyrek,[104] E. Gülmez,[105] B. Isildak,[105,rr] M. Kaya,[105,ss] O. Kaya,[105,ss] S. Ozkorucuklu,[105,tt] N. Sonmez,[105,uu]
K. Cankocak,[106] L. Levchuk,[107] F. Bostock,[108] J. J. Brooke,[108] E. Clement,[108] D. Cussans,[108] H. Flacher,[108]
R. Frazier,[108] J. Goldstein,[108] M. Grimes,[108] G. P. Heath,[108] H. F. Heath,[108] L. Kreczko,[108] S. Metson,[108]
D. M. Newbold,[108,ii] K. Nirunpong,[108] A. Poll,[108] S. Senkin,[108] V. J. Smith,[108] T. Williams,[108] L. Basso,[109,vv]
K. W. Bell,[109] A. Belyaev,[109,vv] C. Brew,[109] R. M. Brown,[109] D. J. A. Cockerill,[109] J. A. Coughlan,[109] K. Harder,[109]
S. Harper,[109] J. Jackson,[109] B. W. Kennedy,[109] E. Olaiya,[109] D. Petyt,[109] B. C. Radburn-Smith,[109]
C. H. Shepherd-Themistocleous,[109] I. R. Tomalin,[109] W. J. Womersley,[109] R. Bainbridge,[110] G. Ball,[110]
R. Beuselinck,[110] O. Buchmuller,[110] D. Colling,[110] N. Cripps,[110] M. Cutajar,[110] P. Dauncey,[110] G. Davies,[110]
M. Della Negra,[110] W. Ferguson,[110] J. Fulcher,[110] D. Futyan,[110] A. Gilbert,[110] A. Guneratne Bryer,[110] G. Hall,[110]

Z. Hatherell,[110] J. Hays,[110] G. Iles,[110] M. Jarvis,[110] G. Karapostoli,[110] L. Lyons,[110] A.-M. Magnan,[110]
J. Marrouche,[110] B. Mathias,[110] R. Nandi,[110] J. Nash,[110] A. Nikitenko,[110,ll] A. Papageorgiou,[110] J. Pela,[110,f]
M. Pesaresi,[110] K. Petridis,[110] M. Pioppi,[110,ww] D. M. Raymond,[110] S. Rogerson,[110] A. Rose,[110] M. J. Ryan,[110]
C. Seez,[110] P. Sharp,[110,a] A. Sparrow,[110] M. Stoye,[110] A. Tapper,[110] M. Vazquez Acosta,[110] T. Virdee,[110]
S. Wakefield,[110] N. Wardle,[110] T. Whyntie,[110] M. Chadwick,[111] J. E. Cole,[111] P. R. Hobson,[111] A. Khan,[111]
P. Kyberd,[111] D. Leggat,[111] D. Leslie,[111] W. Martin,[111] I. D. Reid,[111] P. Symonds,[111] L. Teodorescu,[111] M. Turner,[111]
K. Hatakeyama,[112] H. Liu,[112] T. Scarborough,[112] O. Charaf,[113] C. Henderson,[113] P. Rumerio,[113] A. Avetisyan,[114]
T. Bose,[114] C. Fantasia,[114] A. Heister,[114] J. St. John,[114] P. Lawson,[114] D. Lazic,[114] J. Rohlf,[114] D. Sperka,[114]
L. Sulak,[114] J. Alimena,[115] S. Bhattacharya,[115] D. Cutts,[115] A. Ferapontov,[115] U. Heintz,[115] S. Jabeen,[115]
G. Kukartsev,[115] E. Laird,[115] G. Landsberg,[115] M. Luk,[115] M. Narain,[115] D. Nguyen,[115] M. Segala,[115]
T. Sinthuprasith,[115] T. Speer,[115] K. V. Tsang,[115] R. Breedon,[116] G. Breto,[116] M. Calderon de la Barca Sanchez,[116]
S. Chauhan,[116] M. Chertok,[116] J. Conway,[116] R. Conway,[116] P. T. Cox,[116] J. Dolen,[116] R. Erbacher,[116] M. Gardner,[116]
R. Houtz,[116] W. Ko,[116] A. Kopecky,[116] R. Lander,[116] T. Miceli,[116] D. Pellett,[116] F. Ricci-tam,[116] B. Rutherford,[116]
M. Searle,[116] J. Smith,[116] M. Squires,[116] M. Tripathi,[116] R. Vasquez Sierra,[116] V. Andreev,[117] D. Cline,[117]
R. Cousins,[117] J. Duris,[117] S. Erhan,[117] P. Everaerts,[117] C. Farrell,[117] J. Hauser,[117] M. Ignatenko,[117] C. Jarvis,[117]
C. Plager,[117] G. Rakness,[117] P. Schlein,[117,a] V. Valuev,[117] M. Weber,[117] J. Babb,[118] R. Clare,[118] M. E. Dinardo,[118]
J. Ellison,[118] J. W. Gary,[118] F. Giordano,[118] G. Hanson,[118] G. Y. Jeng,[118,xx] H. Liu,[118] O. R. Long,[118] A. Luthra,[118]
H. Nguyen,[118] S. Paramesvaran,[118] J. Sturdy,[118] S. Sumowidagdo,[118] R. Wilken,[118] S. Wimpenny,[118] W. Andrews,[119]
J. G. Branson,[119] G. B. Cerati,[119] S. Cittolin,[119] D. Evans,[119] F. Golf,[119] A. Holzner,[119] R. Kelley,[119]
M. Lebourgeois,[119] J. Letts,[119] I. Macneill,[119] B. Mangano,[119] S. Padhi,[119] C. Palmer,[119] G. Petrucciani,[119]
M. Pieri,[119] M. Sani,[119] V. Sharma,[119] S. Simon,[119] E. Sudano,[119] M. Tadel,[119] Y. Tu,[119] A. Vartak,[119]
S. Wasserbaech,[119,yy] F. Würthwein,[119] A. Yagil,[119] J. Yoo,[119] D. Barge,[120] R. Bellan,[120] C. Campagnari,[120]
M. D'Alfonso,[120] T. Danielson,[120] K. Flowers,[120] P. Geffert,[120] J. Incandela,[120] C. Justus,[120] P. Kalavase,[120]
S. A. Koay,[120] D. Kovalskyi,[120] V. Krutelyov,[120] S. Lowette,[120] N. Mccoll,[120] V. Pavlunin,[120] F. Rebassoo,[120]
J. Ribnik,[120] J. Richman,[120] R. Rossin,[120] D. Stuart,[120] W. To,[120] C. West,[120] A. Apresyan,[121] A. Bornheim,[121]
Y. Chen,[121] E. Di Marco,[121] J. Duarte,[121] M. Gataullin,[121] Y. Ma,[121] A. Mott,[121] H. B. Newman,[121] C. Rogan,[121]
M. Spiropulu,[121,e] V. Timciuc,[121] P. Traczyk,[121] J. Veverka,[121] R. Wilkinson,[121] Y. Yang,[121] R. Y. Zhu,[121]
B. Akgun,[122] V. Azzolini,[122] R. Carroll,[122] T. Ferguson,[122] Y. Iiyama,[122] D. W. Jang,[122] Y. F. Liu,[122] M. Paulini,[122]
H. Vogel,[122] I. Vorobiev,[122] J. P. Cumalat,[123] B. R. Drell,[123] C. J. Edelmaier,[123] W. T. Ford,[123] A. Gaz,[123]
B. Heyburn,[123] E. Luiggi Lopez,[123] J. G. Smith,[123] K. Stenson,[123] K. A. Ulmer,[123] S. R. Wagner,[123] J. Alexander,[124]
A. Chatterjee,[124] N. Eggert,[124] L. K. Gibbons,[124] B. Heltsley,[124] A. Khukhunaishvili,[124] B. Kreis,[124] N. Mirman,[124]
G. Nicolas Kaufman,[124] J. R. Patterson,[124] A. Ryd,[124] E. Salvati,[124] W. Sun,[124] W. D. Teo,[124] J. Thom,[124]
J. Thompson,[124] J. Tucker,[124] J. Vaughan,[124] Y. Weng,[124] L. Winstrom,[124] P. Wittich,[124] D. Winn,[125] S. Abdullin,[126]
M. Albrow,[126] J. Anderson,[126] L. A. T. Bauerdick,[126] A. Beretvas,[126] J. Berryhill,[126] P. C. Bhat,[126] I. Bloch,[126]
K. Burkett,[126] J. N. Butler,[126] V. Chetluru,[126] H. W. K. Cheung,[126] F. Chlebana,[126] V. D. Elvira,[126] I. Fisk,[126]
J. Freeman,[126] Y. Gao,[126] D. Green,[126] O. Gutsche,[126] J. Hanlon,[126] R. M. Harris,[126] J. Hirschauer,[126]
B. Hooberman,[126] S. Jindariani,[126] M. Johnson,[126] U. Joshi,[126] B. Kilminster,[126] B. Klima,[126] S. Kunori,[126]
S. Kwan,[126] C. Leonidopoulos,[126] J. Linacre,[126] D. Lincoln,[126] R. Lipton,[126] J. Lykken,[126] K. Maeshima,[126]
J. M. Marraffino,[126] S. Maruyama,[126] D. Mason,[126] P. McBride,[126] K. Mishra,[126] S. Mrenna,[126] Y. Musienko,[126,zz]
C. Newman-Holmes,[126] V. O'Dell,[126] O. Prokofyev,[126] E. Sexton-Kennedy,[126] S. Sharma,[126] W. J. Spalding,[126]
L. Spiegel,[126] P. Tan,[126] L. Taylor,[126] S. Tkaczyk,[126] N. V. Tran,[126] L. Uplegger,[126] E. W. Vaandering,[126] R. Vidal,[126]
J. Whitmore,[126] W. Wu,[126] F. Yang,[126] F. Yumiceva,[126] J. C. Yun,[126] D. Acosta,[127] P. Avery,[127] D. Bourilkov,[127]
M. Chen,[127] T. Cheng,[127] S. Das,[127] M. De Gruttola,[127] G. P. Di Giovanni,[127] D. Dobur,[127] A. Drozdetskiy,[127]
R. D. Field,[127] M. Fisher,[127] Y. Fu,[127] I. K. Furic,[127] J. Gartner,[127] J. Hugon,[127] B. Kim,[127] J. Konigsberg,[127]
A. Korytov,[127] A. Kropivnitskaya,[127] T. Kypreos,[127] J. F. Low,[127] K. Matchev,[127] P. Milenovic,[127,aaa]
G. Mitselmakher,[127] L. Muniz,[127] R. Remington,[127] A. Rinkevicius,[127] P. Sellers,[127] N. Skhirtladze,[127]
M. Snowball,[127] J. Yelton,[127] M. Zakaria,[127] V. Gaultney,[128] S. Hewamanage,[128] L. M. Lebolo,[128] S. Linn,[128]
P. Markowitz,[128] G. Martinez,[128] J. L. Rodriguez,[128] T. Adams,[129] A. Askew,[129] J. Bochenek,[129] J. Chen,[129]
B. Diamond,[129] S. V. Gleyzer,[129] J. Haas,[129] S. Hagopian,[129] V. Hagopian,[129] M. Jenkins,[129] K. F. Johnson,[129]
H. Prosper,[129] V. Veeraraghavan,[129] M. Weinberg,[129] M. M. Baarmand,[130] B. Dorney,[130] M. Hohlmann,[130]
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