Observation of the Associated Production of a Single Top Quark and a W Boson in pp Collisions at $\sqrt{s} = 8$ TeV

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The first observation of the associated production of a single top quark and a W boson is presented. The analysis is based on a data set corresponding to an integrated luminosity of 12.2 fb^{-1} of proton-proton collisions at $\sqrt{s} = 8$ TeV recorded by the CMS experiment at the LHC. Events with two leptons and a jet originating from a b quark are selected. A multivariate analysis based on kinematic and topological properties is used to separate the signal from the dominant $t\bar{t}$ background. An excess consistent with the signal hypothesis is observed, with a significance which corresponds to 6.1 standard deviations above a background-only hypothesis. The measured production cross section is 23.4 ± 5.4 pb, in agreement with the standard model prediction.

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Since its discovery in 1995 by the CDF [1] and D0 [2] experiments at the Tevatron, studies of the top quark have raised great interest within high energy physics. As the heaviest of all standard model (SM) particles, the top quark potentially plays an important role in electroweak symmetry breaking as well as in physics beyond the SM. The measurement of the different mechanisms by which top quarks can be produced is instrumental in advancing the understanding of physics at the TeV scale.

Top quarks are produced predominantly in pairs via the strong interaction in proton-proton (pp) collisions but they can also be produced singly via electroweak interactions, involving a Wtb vertex. In the SM, single-top-quark production occurs mainly through three processes: t-channel (tqb), s-channel (tb), and associated production of a top quark and a W boson (tW). Single-top-quark production was first observed by the D0 [3] and CDF [4] experiments. The t-channel production mode has been measured by D0 [5,6] and CDF [7] as well as at the Large Hadron Collider (LHC) by the Compact Muon Solenoid (CMS) [8] and ATLAS [9] experiments, while the observation of s-channel production was recently presented through a combination of the results of the CDF and D0 experiments [10]. The tW production cross section is negligible at the Tevatron, but large enough at the LHC to make it accessible. Evidence for this process was presented by both the ATLAS [11] and CMS [12] experiments using the 7 TeV collision data, with significances of 3.6 and 4.0σ, respectively. This Letter presents the first observation of tW production at a significance of at least 5σ, using data collected with the CMS experiment in pp collisions at $\sqrt{s} = 8$ TeV and corresponding to an integrated luminosity of 12.2 fb^{-1}.

In addition to testing the SM predictions at the electroweak scale, associated tW production is of interest because of its sensitivity to non-SM couplings of the Wtb vertex [13–17], while being relatively insensitive to scenarios that affect the other single-top-quark production channels.

The theoretical prediction for the cross section of tW production in pp collisions at $\sqrt{s} = 8$ TeV at approximate next-to-next-to-leading order (NNLO) is $22.2 \pm 0.6(\text{scale}) \pm 1.4(\text{PDF})$ pb [18], with the first uncertainty coming from factorization and renormalization scale variations and the second from variations in the parton distribution functions of the proton. At next-to-leading order (NLO), the definition of tW production in perturbative quantum chromodynamics mixes with top-quark pair production ($t\bar{t}$) [19–21]. Two schemes for defining the tW signal to distinguish it from $t\bar{t}$ production have been proposed: the "diagram removal" (DR) [19], in which all doubly resonant NLO tW diagrams are removed, and the "diagram subtraction" [19,22], where a gauge-invariant subtraction term modifies the NLO tW cross section to locally cancel the contribution from $t\bar{t}$. In this Letter, the DR scheme is used for simulating the signal, but it was verified that the results are consistent between the two methods and any differences are accounted for in the systematic uncertainties.

The analysis is performed using the dilepton decay channels, in which the W boson produced in association with the top quark and the W boson from the decay of the top quark both decay leptonically into a muon or an electron, and a neutrino. This leads to a final state composed of two oppositely charged isolated leptons, a jet resulting from the fragmentation of a b quark, and two neutrinos. The neutrinos escape detection and are only discernible by the presence of missing transverse energy

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($E_{\mathrm{T}}^{\mathrm{miss}}$), defined as the magnitude of the vector sum of the transverse momentum of all reconstructed particles. The primary background to tW production in this final state comes from $t\bar{t}$ production, with $\mathrm{Z}/\gamma^{\star}$ events being the next most significant.

The analysis uses a multivariate technique, exploiting kinematic and topological differences to distinguish the tW signal from the dominant $t\bar{t}$ background. To assess the robustness of the result, two additional analyses were conducted. One involves a fit to a single kinematic variable, the other is based on event counts.

The central feature of the CMS apparatus [23] is a superconducting solenoid with an internal diameter of 6 m, providing a magnetic field of 3.8 T. Within the bore of the solenoid are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel flux return yoke outside the magnet. In addition, CMS has extensive forward calorimetry. The detector covers a region of $|\eta| < 5.0$, where the pseudorapidity η is defined as $\eta = -\ln[\tan(\theta/2)]$, where θ is the polar angle.

Data samples are selected based on triggers requiring two leptons (either an electron or muon), one with transverse momentum, p_{T}, of at least 17 GeV and a second with p_{T} of at least 8 GeV. All events are required to have a well-reconstructed primary vertex [24]. The primary vertex with the largest sum of p_{T}^2 of associated tracks is chosen.

Electrons are reconstructed from energy deposits in the electromagnetic calorimeter (including energy deposits from radiated photons) matched to tracks in the silicon tracker. Muons, $E_{\mathrm{T}}^{\mathrm{miss}}$, and jets are reconstructed using the CMS particle flow (PF) algorithm [25,26], which performs a global event reconstruction. Electrons and muons are required to have $p_{\mathrm{T}} > 20$ GeV and fall within the pseudorapidity range of $|\eta| < 2.5$ for electrons and $|\eta| < 2.4$ for muons. Exactly two oppositely charged, isolated leptons are required in the event, and events are rejected if they contain additional leptons passing a looser criteria, for which the p_{T} threshold is lowered to 10 GeV. In order to limit the contribution from low-mass dilepton resonances, the invariant mass of the dilepton system, $m_{\ell\ell}$ ($\ell = e$ or μ), is required to be greater than 20 GeV. Events in the ee and $\mu\mu$ final states are rejected if $m_{\ell\ell}$ is between 81 and 101 GeV, to suppress the $\mathrm{Z} \to \ell\ell$ process in the same-flavor final states. Additionally, a requirement of $E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV is applied for these final states.

Jets are reconstructed by clustering PF candidates using the anti-k_{T} algorithm [27] with a distance parameter of 0.5. Selected jets must be within $|\eta| < 2.4$ and have $p_{\mathrm{T}} > 30$ GeV. Corrections are made to the jet energies for detector response as a function of η and p_{T} [28]. Additional corrections are made to subtract energy in the jet from multiple pp collisions (pileup) [29]. Jets originating from the decay of a b quark are tagged based on the presence of a secondary vertex, identified using a multivariate algorithm combining tracking information in a discriminant [30]. A working point is chosen, corresponding to a b-tagging efficiency of approximately 70% and with a misidentification rate of 1%–2%. Loose jets, whose discrimination power against $t\bar{t}$ background is discussed later, are defined as jets failing the requirements on p_{T} and η, but passing the less restrictive selection requirement of $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 4.9$, while still passing all other selection criteria. In particular, loose jets that fall within $|\eta| < 2.4$ are classified as central loose jets.

For events passing the dilepton and $E_{\mathrm{T}}^{\mathrm{miss}}$ criteria described above, a region in which the tW signal is enhanced (signal region) and two regions dominated by background (control regions) are defined. The signal region contains events with exactly one jet passing the selection requirements, which is b tagged ($1j1t$ region). Two control regions enriched in $t\bar{t}$ background are defined as having exactly two jets with either one or both being b tagged ($2j1t$ and $2j2t$ regions, respectively).

Events from Monte Carlo simulation are used to estimate the contributions and kinematics of signal and background processes. Single-top-quark events are simulated at NLO with the POWHEG 1.0 event generator [31–34]; MADGRAPH 5.1.3 is used for simulating $t\bar{t}$ and single-boson events (V + jets, where $\mathrm{V} = W, Z$) [35]. Samples are produced using a top-quark mass $m_{\mathrm{t}} = 172.5$ GeV, consistent with its current best measurement [36]. Diboson backgrounds are simulated using PYTHIA 6.426 [37]. In all samples, fragmentation and hadronization are modeled with PYTHIA, and TAUOLA v27.121.5 is used to simulate τ decays [38]. The CTEQ6L1 and CTEQ6.6M PDF sets [39] are used for samples simulated at leading-order and NLO, respectively. A full simulation of the response of the CMS detector is performed for all generated events using a GEANT4 -based model [40]. The simulation includes modeling of pileup, with the distribution of the number of interactions in simulation matching that in data. Simulated samples are normalized to the NNLO cross sections for $t\bar{t}$ [$\sigma_{t\bar{t}} = 245.8^{+6.2}_{-8.4}(\mathrm{scale})^{+6.2}_{-6.4}(\mathrm{PDF})$ pb] [41], $\mathrm{Z}/\gamma^{\star}$, and W + jets processes, with approximate NNLO cross sections used for single top quark [18] and NLO for diboson processes. The $\mathrm{Z}/\gamma^{\star}$ simulation is reweighted to reproduce the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution observed in data, using events with $m_{\ell\ell}$ in the vicinity of the Z-boson mass (81 to 101 GeV) to derive scale factors.

After the selection, the simulated samples in the $1j1t$ signal region contain predominantly tW and $t\bar{t}$ events (comprising 16% and 76% of the events, respectively), with a smaller contribution from $\mathrm{Z}/\gamma^{\star}$ events (6%). The two control regions are dominated by $t\bar{t}$ production. Event yields in simulation and data in the signal and control regions are shown in Table I.

In order to separate the tW signal from the $t\bar{t}$ background, a multivariate analysis based on boosted decision

TABLE I. Event yields in the signal and control regions. Yields from simulation are shown with statistical (first) and systematic (second) uncertainties.

	$1j1t$	$2j1t$	$2j2t$
tW	$1500 \pm 20 \pm 130$	$790 \pm 20 \pm 80$	$220 \pm 10 \pm 30$
$t\bar{t}$	$7090 \pm 60 \pm 900$	$12910 \pm 80 \pm 1320$	$7650 \pm 60 \pm 1020$
$Z/\gamma^{\star}$, other	$670 \pm 30 \pm 90$	$370 \pm 30 \pm 60$	$36 \pm 7 \pm 12$
Total simulation	$9260 \pm 70 \pm 1040$	$14070 \pm 90 \pm 1410$	$7910 \pm 70 \pm 1020$
Data	9353	13479	7615

trees (BDT) [42] is used, implemented with the toolkit for multivariate data analysis [43]. The BDT analyzer is trained using 13 variables, chosen for their separation power in distinguishing tW and $t\bar{t}$, as well as being well modeled in simulation when checked in control regions. The most powerful variables are those involving loose jets in the event: the number of loose jets, number of central loose jets, and the number of loose jets that are b tagged. Other variables with significant separation power are related to the kinematics of the system comprised of the leptons, jets and $E_{\mathrm{T}}^{\mathrm{miss}}$: the scalar sum of their transverse momenta (H_{T}), the magnitude of the vector sum of their transverse momenta ($p_{\mathrm{T}}^{\mathrm{sys}}$), and invariant mass of the system. A complete list of the variables used can be found in the Supplemental Material [44]). The distributions of the number of loose jets and the p_{T} of the system in the $1j1t$ signal region are shown in Fig. 1 for all three final states (ee, $e\mu$, and $\mu\mu$) combined.

The BDT analyzer provides a single discriminant value for each event. The distributions of the BDT discriminant in data and simulation are shown in Fig. 2 for the $1j1t$, $2j1t$, and $2j2t$ regions, combining all three final states together.

The uncertainty from all systematic sources is determined by estimating their effect on the normalization and shape of the BDT discriminant for all regions and final states. The dominant systematic uncertainties come from the choice of thresholds for the matrix element and parton showering (ME/PS) matching in simulation of $t\bar{t}$ production and the renormalization and factorization scale. The effect of these uncertainties was estimated by producing simulated samples with the value of the ME/PS matching thresholds and renormalization and factorization scale doubled and halved from their respective initial values of 20 GeV and $m_t^2 + \sum p_{\mathrm{T}}^2$ (where the sum is over all additional final state partons), contributing a 14% and 12% uncertainty, respectively, to the measured cross section. The uncertainty due to the value of the top-quark mass used in simulation is estimated by simulating tW and $t\bar{t}$ processes with a varied value for m_{t}, resulting in a 9% effect on the cross section. The complete list of systematic uncertainties and corresponding effects on the cross section can be found in the Supplemental Material [44].

A simultaneous binned likelihood fit to the rate and shape of the BDT distributions of the three final states in the three regions is performed. The two control regions are included in the fit to allow for better determination of the $t\bar{t}$ contribution. The distributions for signal and background are taken from simulation. In the likelihood function, for each source of systematic uncertainty u, a nuisance parameter θ_u is introduced. The rates of signal and background are allowed to vary in the fit, constrained in the likelihood function by the systematic uncertainties. The excess of events is quantified based on the score statistic q, chosen to enhance numerical stability, defined as

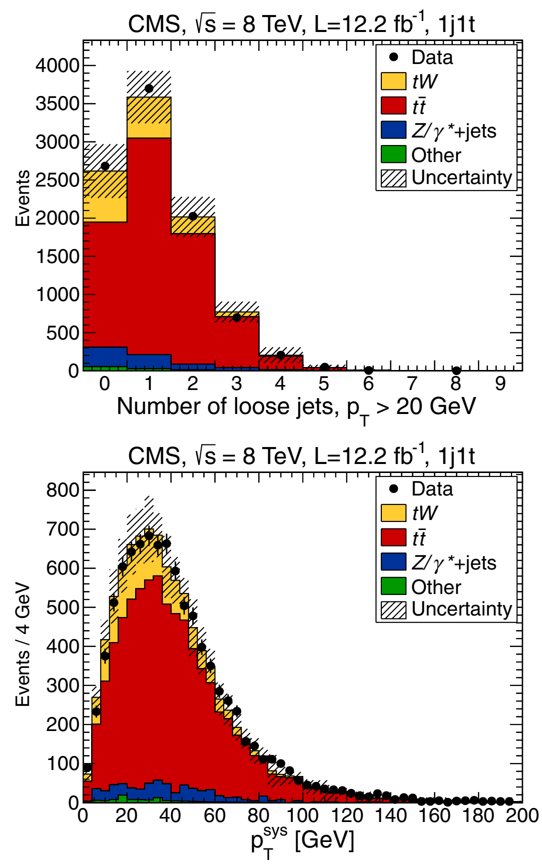

FIG. 1 (color online). The number of loose jets in the event and the p_{T} of the system ($p_{\mathrm{T}}^{\mathrm{sys}}$) composed of the jet, leptons, and $E_{\mathrm{T}}^{\mathrm{miss}}$, in the signal region ($1j1t$) for all final states combined. Shown are data (points) and simulation (histogram). The hatched band represents the combined effect of all sources of systematic uncertainty.

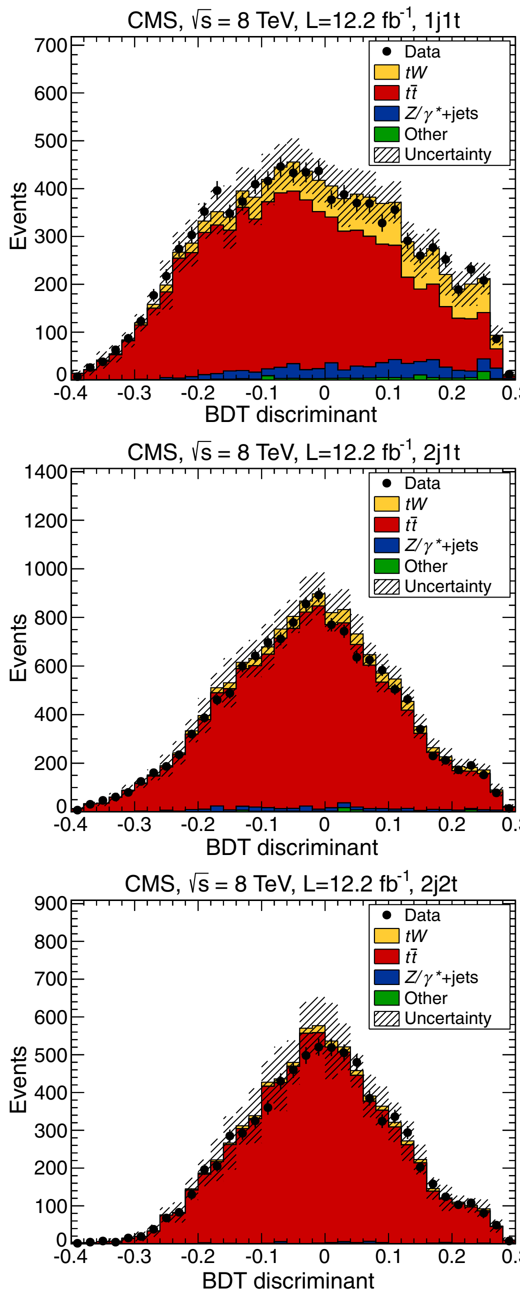

FIG. 2 (color online). The BDT discriminant, in the signal region ($1j1t$) and control regions ($2j1t$ and $2j2t$) for all final states combined. Shown are data (points) and simulation (histogram). The hatched band represents the combined effect of all sources of systematic uncertainty.

$$q = \frac{\partial}{\partial \mu} \ln \mathcal{L}(\mu = 0, \hat{\theta}_0 | \text{data}),$$

where μ is the signal strength parameter (defined as the signal cross section in units of the SM prediction) and $\hat{\theta}_0$ is the set of nuisance parameters that maximizes the likelihood $\mathcal{L}$ for a background-only hypothesis ($\mu = 0$). The score statistic is evaluated for sets of four billion

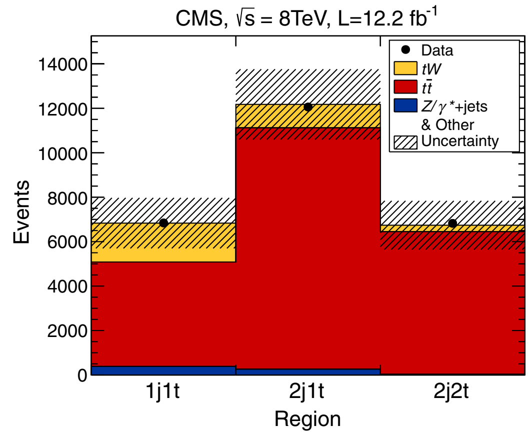

FIG. 3 (color online). Event yields in data and simulation for events passing additional requirements from the cross-check analyses. Yields are shown in the $1j1t$ signal regions and $2j1t$ and $2j2t$ control regions for a combination of all three final states, with the simulation scaled to the outcome of the statistical fit from the event-count analysis. The hatched band represents the combined effect of all systematic uncertainties on the event yields.

pseudoexperiments using a background-only hypothesis. The significance is determined based on the probability of producing a score statistic value in the background-only hypothesis as high or higher than that observed in data. The expected significance is evaluated using the median and central 68% interval of the score statistic values obtained in pseudo-experiments generated under a signal-plus-background hypothesis. A profile likelihood method is used to determine the signal cross section and 68% confidence level (C.L) interval.

We observe an excess of events above the expected background with a p value of 5×10^{-10} corresponding to a significance of 6.1σ, compared to an expected significance from simulation of $5.4 \pm 1.4\sigma$. The measured cross section is found to be 23.4 ± 5.4 pb, where the uncertainty is mainly systematic, in agreement with the predicted SM value of $22.2 \pm 0.6(\text{scale}) \pm 1.4(\text{PDF})$ pb.

The cross section measurement is used to determine the absolute value of the Cabibbo-Kobayashi-Maskawa matrix element $|V_{tb}|$, assuming $|V_{tb}| \gg |V_{td}|$ and $|V_{ts}|$

$$|V_{tb}| = \sqrt{\sigma_{tW}/\sigma_{tW}^{\text{th}}} = 1.03 \pm 0.12(\text{exp}) \pm 0.04(\text{th.}),$$

where σ_{tW}^{th} is the theoretical prediction of the tW cross section assuming $|V_{tb}| = 1$, and the uncertainties are separated into experimental and theoretical values. Using the SM assumption $0 \leq |V_{tb}|^2 \leq 1$, a lower bound $|V_{tb}| > 0.78$ at 95% C.L. is found using the approach of Feldman and Cousins [45].

Using the same selection as in the BDT analysis, two cross-check analyses are performed. Events containing any

b-tagged loose jets are rejected. Additionally, a requirement of $H_T > 160$ GeV is added in the $e\mu$ final state, where no E_T^{miss} requirement is applied. The effects of systematic uncertainties are taken into account in the same way as for the BDT analysis, and the same method for extraction of the significance and cross section is used. The first cross-check analysis is based on the distribution of p_T^{sys} rather than the BDT discriminant, and results in an observed significance of 4.0σ above a background-only hypothesis, with an expected significance of $3.2^{+0.4}_{-0.9}\sigma$, and a measured cross section of 24.3 ± 8.6 pb. The second cross-check analysis is based only on event counts after selection, and an excess of events is observed above the background with a significance of 3.6σ, with an expected significance based on simulation of $2.8 \pm 0.9\sigma$, and a measured cross section of 33.9 ± 8.6 pb. Event yields in data and simulation for this analysis are shown in Fig. 3, with the simulation scaled to the result of the statistical fit. The results of both analyses are consistent with those found in the BDT analysis, but with larger, mostly systematic, uncertainties.

In summary, the production of a single top quark in association with a W boson is observed for the first time. The analysis uses data collected by the CMS experiment in pp collisions at $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 12.2 fb^{-1}. An excess of events above background is found with a significance of 6.1σ, and a tW production cross section of 23.4 ± 5.4 pb is measured, in agreement with the standard model prediction.

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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] P. Miné,[29] C. Mironov,[29] I. N. Naranjo,[29] M. Nguyen,[29] C. Ochando,[29] P. Paganini,[29] D. Sabes,[29] R. 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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] J. Kieseler,[37] C. Kleinwort,[37] M. Krämer,[37] D. Krücker,[37] W. Lange,[37] J. Leonard,[37] K. Lipka,[37] W. Lohmann,[37,r] B. Lutz,[37] R. Mankel,[37] I. Marfin,[37] I.-A. Melzer-Pellmann,[37] A. B. Meyer,[37] J. Mnich,[37] A. Mussgiller,[37] S. Naumann-Emme,[37] O. Novgorodova,[37] F. Nowak,[37] H. Perrey,[37] A. Petrukhin,[37] D. Pitzl,[37] R. Placakyte,[37] A. Raspereza,[37] P. M. Ribeiro Cipriano,[37] C. Riedl,[37] E. Ron,[37] M. Ö. Sahin,[37] J. Salfeld-Nebgen,[37] P. Saxena,[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] K. Goebel,[38] M. 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N. Wickramage,[51,y] S. Banerjee,[52] S. Dugad,[52] H. Arfaei,[53] H. Bakhshiansohi,[53] H. Behnamian,[53] S. M. Etesami,[53,z] A. Fahim,[53,aa] A. Jafari,[53] M. Khakzad,[53] M. Mohammadi Najafabadi,[53] M. Naseri,[53] S. Paktinat Mehdiabadi,[53] B. Safarzadeh,[53,bb] 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] M. Galanti,[63a,63b,c] F. Gasparini,[63a,63b] U. Gasparini,[63a,63b] P. Giubilato,[63a,63b] A. Gozzelino,[63a] K. Kanishchev,[63a,63c] S. Lacaprara,[63a] I. Lazzizzera,[63a,63c] M. Margoni,[63a,63b] A. T. Meneguzzo,[63a,63b] J. Pazzini,[63a,63b] N. Pozzobon,[63a,63b] P. Ronchese,[63a,63b] F. Simonetto,[63a,63b] E. Torassa,[63a] M. Tosi,[63a,63b] A. Triossi,[63a] S. Vanini,[63a,63b] S. Ventura,[63a] 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] F. Romeo,[65a,65b] A. Saha,[65a] A. Santocchia,[65a,65b] A. Spiezia,[65a,65b] K. Androsov,[66a,cc] P. Azzurri,[66a] G. Bagliesi,[66a] J. Bernardini,[66a] T. Boccali,[66a] G. Broccolo,[66a,66c] R. Castaldi,[66a] M. A. Ciocci,[66a,cc] R. Dell'Orso,[66a] F. Fiori,[66a,66c] L. Foà,[66a,66c] A. Giassi,[66a] M. T. Grippo,[66a,cc] A. Kraan,[66a] F. Ligabue,[66a,66c] T. Lomtadze,[66a] L. Martini,[66a,66b] A. Messineo,[66a,66b] C. S. Moon,[66a,dd] F. Palla,[66a] A. Rizzi,[66a,66b] A. Savoy-Navarro,[66a,ee] A. T. Serban,[66a] P. Spagnolo,[66a] P. Squillacioti,[66a,cc] 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] G. Della Ricca,[69a,69b] B. Gobbo,[69a] C. La Licata,[69a,69b] M. Marone,[69a,69b] D. Montanino,[69a,69b] A. Penzo,[69a] A. Schizzi,[69a,69b] T. Umer,[69a,69b] A. Zanetti,[69a] S. Chang,[70] T. Y. Kim,[70] S. K. Nam,[70] D. H. Kim,[71] G. N. Kim,[71] J. E. Kim,[71] D. J. Kong,[71] S. Lee,[71] Y. D. Oh,[71] H. Park,[71] D. C. Son,[71] J. Y. Kim,[72] Zero J. Kim,[72] S. Song,[72] S. Choi,[73] D. Gyun,[73] B. Hong,[73] M. Jo,[73] H. Kim,[73] Y. Kim,[73] K. S. Lee,[73] S. K. Park,[73] Y. Roh,[73] M. Choi,[74] J. H. Kim,[74] C. Park,[74] I. C. Park,[74] S. Park,[74] G. Ryu,[74] Y. Choi,[75] Y. K. Choi,[75] J. Goh,[75] M. S. Kim,[75] E. Kwon,[75] B. Lee,[75] J. Lee,[75] S. Lee,[75] H. Seo,[75] I. Yu,[75] A. Juodagalvis,[76] J. R. Komaragiri,[77] H. Castilla-Valdez,[78] E. De La Cruz-Burelo,[78] I. Heredia-de La Cruz,[78,ff] R. Lopez-Fernandez,[78] J. Martínez-Ortega,[78] A. Sanchez-Hernandez,[78] L. M. Villasenor-Cendejas,[78] S. Carrillo Moreno,[79] F. Vazquez Valencia,[79] H. A. Salazar Ibarguen,[80] E. Casimiro Linares,[81] A. Morelos Pineda,[81] D. Krofcheck,[82] P. H. Butler,[83] R. Doesburg,[83] S. Reucroft,[83] H. Silverwood,[83] M. Ahmad,[84] M. I. Asghar,[84] J. Butt,[84] H. R. Hoorani,[84] W. A. Khan,[84] T. Khurshid,[84] S. Qazi,[84] M. A. Shah,[84] M. Shoaib,[84] H. Bialkowska,[85] M. Bluj,[85,gg] B. Boimska,[85] T. Frueboes,[85] M. Górski,[85] M. Kazana,[85] K. Nawrocki,[85] K. Romanowska-Rybinska,[85] M. Szleper,[85] G. Wrochna,[85] P. Zalewski,[85] G. Brona,[86] K. Bunkowski,[86] M. Cwiok,[86] W. Dominik,[86] K. Doroba,[86] A. Kalinowski,[86] M. Konecki,[86] J. Krolikowski,[86] M. Misiura,[86] W. Wolszczak,[86] P. Bargassa,[87]

C. Beirão Da Cruz E Silva,[87] P. Faccioli,[87] P. G. Ferreira Parracho,[87] M. Gallinaro,[87] F. Nguyen,[87] J. Rodrigues Antunes,[87] J. Seixas,[87,c] J. Varela,[87] P. Vischia,[87] S. Afanasiev,[88] P. Bunin,[88] I. Golutvin,[88] I. Gorbunov,[88] A. Kamenev,[88] V. Karjavin,[88] V. Konoplyanikov,[88] G. Kozlov,[88] A. Lanev,[88] A. Malakhov,[88] V. Matveev,[88,hh] P. Moisenz,[88] V. Palichik,[88] V. Perelygin,[88] S. Shmatov,[88] N. Skatchkov,[88] V. Smirnov,[88] A. Zarubin,[88] V. Golovtsov,[89] Y. Ivanov,[89] V. Kim,[89] P. Levchenko,[89] V. Murzin,[89] V. Oreshkin,[89] I. Smirnov,[89] V. Sulimov,[89] L. Uvarov,[89] S. Vavilov,[89] A. Vorobyev,[89] An. Vorobyev,[89] Yu. Andreev,[90] A. Dermenev,[90] S. Gninenko,[90] N. Golubev,[90] M. Kirsanov,[90] N. Krasnikov,[90] A. Pashenkov,[90] D. Tlisov,[90] A. Toropin,[90] V. Epshteyn,[91] V. Gavrilov,[91] N. Lychkovskaya,[91] V. Popov,[91] G. Safronov,[91] S. Semenov,[91] A. Spiridonov,[91] V. Stolin,[91] E. Vlasov,[91] A. Zhokin,[91] V. Andreev,[92] M. Azarkin,[92] I. Dremin,[92] M. Kirakosyan,[92] A. Leonidov,[92] G. Mesyats,[92] S. V. Rusakov,[92] A. Vinogradov,[92] A. Belyaev,[93] E. Boos,[93] V. Bunichev,[93] M. Dubinin,[93,h] L. Dudko,[93] A. Gribushin,[93] V. Klyukhin,[93] I. Lokhtin,[93] S. Obraztsov,[93] M. Perfilov,[93] V. Savrin,[93] A. Snigirev,[93] N. Tsirova,[93] I. Azhgirey,[94] I. Bayshev,[94] S. Bitioukov,[94] V. Kachanov,[94] A. Kalinin,[94] D. Konstantinov,[94] V. Krychkine,[94] V. Petrov,[94] R. Ryutin,[94] A. Sobol,[94] L. Tourtchanovitch,[94] S. Troshin,[94] N. Tyurin,[94] A. Uzunian,[94] A. Volkov,[94] P. Adzic,[95,ii] M. Djordjevic,[95] M. Ekmedzic,[95] J. Milosevic,[95] M. Aguilar-Benitez,[96] J. Alcaraz Maestre,[96] C. Battilana,[96] E. Calvo,[96] M. Cerrada,[96] M. Chamizo Llatas,[96,c] N. Colino,[96] B. De La Cruz,[96] A. Delgado Peris,[96] D. Domínguez Vázquez,[96] C. Fernandez Bedoya,[96] J. P. Fernández Ramos,[96] A. Ferrando,[96] J. Flix,[96] M. C. Fouz,[96] P. Garcia-Abia,[96] O. Gonzalez Lopez,[96] S. Goy Lopez,[96] J. M. Hernandez,[96] M. I. Josa,[96] G. Merino,[96] E. Navarro De Martino,[96] J. Puerta Pelayo,[96] A. Quintario Olmeda,[96] I. Redondo,[96] L. Romero,[96] M. S. Soares,[96] C. Willmott,[96] C. Albajar,[97] J. F. de Trocóniz,[97] M. Missiroli,[97] H. Brun,[98] J. Cuevas,[98] J. Fernandez Menendez,[98] S. Folgueras,[98] I. Gonzalez Caballero,[98] L. Lloret Iglesias,[98] J. A. Brochero Cifuentes,[99] I. J. Cabrillo,[99] A. Calderon,[99] S. H. Chuang,[99] J. Duarte Campderros,[99] M. Fernandez,[99] G. Gomez,[99] J. Gonzalez Sanchez,[99] A. Graziano,[99] A. Lopez Virto,[99] J. Marco,[99] R. Marco,[99] C. Martinez Rivero,[99] F. Matorras,[99] F. J. Munoz Sanchez,[99] J. Piedra Gomez,[99] T. Rodrigo,[99] A. Y. Rodríguez-Marrero,[99] A. Ruiz-Jimeno,[99] L. Scodellaro,[99] I. Vila,[99] R. Vilar Cortabitarte,[99] D. Abbaneo,[100] E. Auffray,[100] G. Auzinger,[100] M. Bachtis,[100] P. Baillon,[100] A. H. Ball,[100] D. Barney,[100] J. Bendavid,[100] L. Benhabib,[100] J. F. Benitez,[100] C. Bernet,[100,i] G. Bianchi,[100] P. Bloch,[100] A. Bocci,[100] A. Bonato,[100] O. Bondu,[100] C. Botta,[100] H. Breuker,[100] T. Camporesi,[100] G. Cerminara,[100] T. Christiansen,[100] J. A. Coarasa Perez,[100] S. Colafranceschi,[100,jj] M. D'Alfonso,[100] D. d'Enterria,[100] A. Dabrowski,[100] A. David,[100] F. De Guio,[100] A. De Roeck,[100] S. De Visscher,[100] S. Di Guida,[100] M. Dobson,[100] N. Dupont-Sagorin,[100] A. Elliott-Peisert,[100] J. Eugster,[100] G. Franzoni,[100] W. Funk,[100] M. Giffels,[100] D. Gigi,[100] K. Gill,[100] M. Girone,[100] M. Giunta,[100] F. Glege,[100] R. Gomez-Reino Garrido,[100] S. Gowdy,[100] R. Guida,[100] J. Hammer,[100] M. Hansen,[100] P. Harris,[100] V. Innocente,[100] P. Janot,[100] E. Karavakis,[100] K. Kousouris,[100] K. Krajczar,[100] P. Lecoq,[100] C. Lourenço,[100] N. Magini,[100] L. Malgeri,[100] M. Mannelli,[100] L. Masetti,[100] F. Meijers,[100] S. Mersi,[100] E. Meschi,[100] F. Moortgat,[100] M. Mulders,[100] P. Musella,[100] L. Orsini,[100] E. Palencia Cortezon,[100] E. Perez,[100] L. Perrozzi,[100] A. Petrilli,[100] G. Petrucciani,[100] A. Pfeiffer,[100] M. Pierini,[100] M. Pimiä,[100] D. Piparo,[100] M. Plagge,[100] A. Racz,[100] W. Reece,[100] G. Rolandi,[100,kk] M. Rovere,[100] H. Sakulin,[100] F. Santanastasio,[100] C. Schäfer,[100] C. Schwick,[100] S. Sekmen,[100] A. Sharma,[100] P. Siegrist,[100] P. Silva,[100] M. Simon,[100] P. Sphicas,[100,ll] J. Steggemann,[100] B. Stieger,[100] M. Stoye,[100] A. Tsirou,[100] G. I. Veres,[100,u] J. R. Vlimant,[100] H. K. Wöhri,[100] W. D. Zeuner,[100] W. Bertl,[101] K. Deiters,[101] W. Erdmann,[101] R. Horisberger,[101] Q. Ingram,[101] H. C. Kaestli,[101] S. König,[101] D. Kotlinski,[101] U. Langenegger,[101] D. Renker,[101] T. Rohe,[101] F. Bachmair,[102] L. Bäni,[102] L. Bianchini,[102] P. Bortignon,[102] M. A. Buchmann,[102] B. Casal,[102] N. Chanon,[102] A. Deisher,[102] G. Dissertori,[102] M. Dittmar,[102] M. Donegà,[102] M. Dünser,[102] P. Eller,[102] C. Grab,[102] D. Hits,[102] W. Lustermann,[102] B. Mangano,[102] A. C. Marini,[102] P. Martinez Ruiz del Arbol,[102] D. Meister,[102] N. Mohr,[102] C. Nägeli,[102,mm] P. Nef,[102] F. Nessi-Tedaldi,[102] F. Pandolfi,[102] L. Pape,[102] F. Pauss,[102] M. Peruzzi,[102] M. Quittnat,[102] F. J. Ronga,[102] M. Rossini,[102] A. Starodumov,[102,nn] M. Takahashi,[102] L. Tauscher,[102,a] K. Theofilatos,[102] D. Treille,[102] R. Wallny,[102] H. A. Weber,[102] C. Amsler,[103,oo] V. Chiochia,[103] A. De Cosa,[103] C. Favaro,[103] A. Hinzmann,[103] T. Hreus,[103] M. Ivova Rikova,[103] B. Kilminster,[103] B. Millan Mejias,[103] J. Ngadiuba,[103] P. Robmann,[103] H. Snoek,[103] S. Taroni,[103] M. Verzetti,[103] Y. Yang,[103] M. Cardaci,[104] K. H. Chen,[104] C. Ferro,[104] C. M. Kuo,[104] S. W. Li,[104] W. Lin,[104] Y. J. Lu,[104] R. Volpe,[104] S. S. Yu,[104] P. Bartalini,[105] P. Chang,[105] Y. H. Chang,[105] Y. W. Chang,[105] Y. Chao,[105] K. F. Chen,[105] P. H. Chen,[105] C. Dietz,[105] U. Grundler,[105] W.-S. Hou,[105] Y. Hsiung,[105] K. Y. Kao,[105] Y. J. Lei,[105] Y. F. Liu,[105] R.-S. Lu,[105] D. Majumder,[105] E. Petrakou,[105] X. Shi,[105] J. G. Shiu,[105] Y. M. Tzeng,[105] M. Wang,[105] R. Wilken,[105] B. Asavapibhop,[106] N. Suwonjandee,[106] A. Adiguzel,[107] M. N. Bakirci,[107,pp] S. Cerci,[107,qq] C. Dozen,[107] I. Dumanoglu,[107] E. Eskut,[107] S. Girgis,[107] G. Gokbulut,[107] E. Gurpinar,[107] I. Hos,[107] E. E. Kangal,[107] A. Kayis Topaksu,[107] G. Onengut,[107,rr] K. Ozdemir,[107] S. Ozturk,[107,pp]

A. Polatoz,[107] K. Sogut,[107,ss] D. Sunar Cerci,[107,qq] B. Tali,[107,qq] H. Topakli,[107,pp] M. Vergili,[107] I. V. Akin,[108] T. Aliev,[108] B. Bilin,[108] S. Bilmis,[108] M. Deniz,[108] H. Gamsizkan,[108] A. M. Guler,[108] G. Karapinar,[108,tt] K. Ocalan,[108] A. Ozpineci,[108] M. Serin,[108] R. Sever,[108] U. E. Surat,[108] M. Yalvac,[108] M. Zeyrek,[108] E. Gülmez,[109] B. Isildak,[109,uu] M. Kaya,[109,vv] O. Kaya,[109,vv] S. Ozkorucuklu,[109,ww] H. Bahtiyar,[110,xx] E. Barlas,[110] K. Cankocak,[110] Y. O. Günaydin,[110,yy] F. I. Vardarlı,[110] M. Yücel,[110] L. Levchuk,[111] P. Sorokin,[111] J. J. Brooke,[112] E. Clement,[112] D. Cussans,[112] H. Flacher,[112] R. Frazier,[112] J. Goldstein,[112] M. Grimes,[112] G. P. Heath,[112] H. F. Heath,[112] J. Jacob,[112] L. Kreczko,[112] C. Lucas,[112] Z. Meng,[112] D. M. Newbold,[112,zz] S. Paramesvaran,[112] A. Poll,[112] S. Senkin,[112] V. J. Smith,[112] T. Williams,[112] K. W. Bell,[113] A. Belyaev,[113,aaa] C. Brew,[113] R. M. Brown,[113] D. J. A. Cockerill,[113] J. A. Coughlan,[113] K. Harder,[113] S. Harper,[113] J. Ilic,[113] E. Olaiya,[113] D. Petyt,[113] C. H. Shepherd-Themistocleous,[113] A. Thea,[113] I. R. Tomalin,[113] W. J. Womersley,[113] S. D. Worm,[113] M. Baber,[114] R. Bainbridge,[114] O. Buchmuller,[114] D. Burton,[114] D. Colling,[114] N. Cripps,[114] M. Cutajar,[114] P. Dauncey,[114] G. Davies,[114] M. Della Negra,[114] W. Ferguson,[114] J. Fulcher,[114] D. Futyan,[114] A. Gilbert,[114] A. Guneratne Bryer,[114] G. Hall,[114] Z. Hatherell,[114] J. Hays,[114] G. Iles,[114] M. Jarvis,[114] G. Karapostoli,[114] M. Kenzie,[114] R. Lane,[114] R. Lucas,[114,zz] L. Lyons,[114] A.-M. Magnan,[114] J. Marrouche,[114] B. Mathias,[114] R. Nandi,[114] J. Nash,[114] A. Nikitenko,[114,nn] J. Pela,[114] M. Pesaresi,[114] K. Petridis,[114] M. Pioppi,[114,bbb] D. M. Raymond,[114] S. Rogerson,[114] A. Rose,[114] C. Seez,[114] P. Sharp,[114,a] A. Sparrow,[114] A. Tapper,[114] M. Vazquez Acosta,[114] T. Virdee,[114] S. Wakefield,[114] N. Wardle,[114] J. E. Cole,[115] P. R. Hobson,[115] A. Khan,[115] P. Kyberd,[115] D. Leggat,[115] D. Leslie,[115] W. Martin,[115] I. D. Reid,[115] P. Symonds,[115] L. Teodorescu,[115] M. Turner,[115] J. Dittmann,[116] K. Hatakeyama,[116] A. Kasmi,[116] H. Liu,[116] T. Scarborough,[116] O. Charaf,[117] S. I. Cooper,[117] C. Henderson,[117] P. Rumerio,[117] A. Avetisyan,[118] T. Bose,[118] C. Fantasia,[118] A. Heister,[118] P. Lawson,[118] D. Lazic,[118] J. Rohlf,[118] D. Sperka,[118] J. St. John,[118] L. Sulak,[118] J. Alimena,[119] S. Bhattacharya,[119] G. Christopher,[119] D. Cutts,[119] Z. Demiragli,[119] A. Ferapontov,[119] A. Garabedian,[119] U. Heintz,[119] S. Jabeen,[119] G. Kukartsev,[119] E. Laird,[119] G. Landsberg,[119] M. Luk,[119] M. Narain,[119] M. Segala,[119] T. Sinthuprasith,[119] T. Speer,[119] J. Swanson,[119] R. Breedon,[120] G. Breto,[120] M. Calderon De La Barca Sanchez,[120] S. Chauhan,[120] M. Chertok,[120] J. Conway,[120] R. Conway,[120] P. T. Cox,[120] R. Erbacher,[120] M. Gardner,[120] W. Ko,[120] A. Kopecky,[120] R. Lander,[120] T. Miceli,[120] D. Pellett,[120] J. Pilot,[120] F. Ricci-Tam,[120] B. Rutherford,[120] M. Searle,[120] S. Shalhout,[120] J. Smith,[120] M. Squires,[120] M. Tripathi,[120] S. Wilbur,[120] R. Yohay,[120] V. Andreev,[121] D. Cline,[121] R. Cousins,[121] S. Erhan,[121] P. Everaerts,[121] C. Farrell,[121] M. Felcini,[121] J. Hauser,[121] M. Ignatenko,[121] C. Jarvis,[121] G. Rakness,[121] P. Schlein,[121,a] E. Takasugi,[121] V. Valuev,[121] M. Weber,[121] J. Babb,[122] R. Clare,[122] J. Ellison,[122] J. W. Gary,[122] G. Hanson,[122] J. Heilman,[122] P. Jandir,[122] F. Lacroix,[122] H. Liu,[122] O. R. Long,[122] A. Luthra,[122] M. Malberti,[122] H. Nguyen,[122] A. Shrinivas,[122] J. Sturdy,[122] S. Sumowidagdo,[122] S. Wimpenny,[122] W. Andrews,[123] J. G. Branson,[123] G. B. Cerati,[123] S. Cittolin,[123] R. T. D'Agnolo,[123] D. Evans,[123] A. Holzner,[123] R. Kelley,[123] D. Kovalskyi,[123] M. Lebourgeois,[123] J. Letts,[123] I. Macneill,[123] S. Padhi,[123] C. Palmer,[123] M. Pieri,[123] M. Sani,[123] V. Sharma,[123] S. Simon,[123] E. Sudano,[123] M. Tadel,[123] Y. Tu,[123] A. Vartak,[123] S. Wasserbaech,[123,ccc] F. Würthwein,[123] A. Yagil,[123] J. Yoo,[123] D. Barge,[124] C. Campagnari,[124] T. Danielson,[124] K. Flowers,[124] P. Geffert,[124] C. George,[124] F. Golf,[124] J. Incandela,[124] C. Justus,[124] R. Magaña Villalba,[124] N. Mccoll,[124] V. Pavlunin,[124] J. Richman,[124] R. Rossin,[124] D. Stuart,[124] W. To,[124] C. West,[124] A. Apresyan,[125] A. Bornheim,[125] J. Bunn,[125] Y. Chen,[125] E. Di Marco,[125] J. Duarte,[125] D. Kcira,[125] A. Mott,[125] H. B. Newman,[125] C. Pena,[125] C. Rogan,[125] M. Spiropulu,[125] V. Timciuc,[125] R. Wilkinson,[125] S. Xie,[125] R. Y. Zhu,[125] V. Azzolini,[126] A. Calamba,[126] R. Carroll,[126] T. Ferguson,[126] Y. Iiyama,[126] D. W. Jang,[126] M. Paulini,[126] J. Russ,[126] H. Vogel,[126] I. Vorobiev,[126] J. P. Cumalat,[127] B. R. Drell,[127] W. T. Ford,[127] A. Gaz,[127] E. Luiggi Lopez,[127] U. Nauenberg,[127] J. G. Smith,[127] K. Stenson,[127] K. A. Ulmer,[127] S. R. Wagner,[127] J. Alexander,[128] A. Chatterjee,[128] N. Eggert,[128] L. K. Gibbons,[128] W. Hopkins,[128] A. Khukhunaishvili,[128] B. Kreis,[128] N. Mirman,[128] G. Nicolas Kaufman,[128] J. R. Patterson,[128] A. Ryd,[128] E. Salvati,[128] W. Sun,[128] W. D. Teo,[128] J. Thom,[128] J. Thompson,[128] J. Tucker,[128] Y. Weng,[128] L. Winstrom,[128] P. Wittich,[128] D. Winn,[129] S. Abdullin,[130] M. Albrow,[130] J. Anderson,[130] G. Apollinari,[130] L. A. T. Bauerdick,[130] A. Beretvas,[130] J. Berryhill,[130] P. C. Bhat,[130] K. Burkett,[130] J. N. Butler,[130] V. Chetluru,[130] H. W. K. Cheung,[130] F. Chlebana,[130] S. Cihangir,[130] V. D. Elvira,[130] I. Fisk,[130] J. Freeman,[130] Y. Gao,[130] E. Gottschalk,[130] L. Gray,[130] D. Green,[130] S. Grünendahl,[130] O. Gutsche,[130] D. Hare,[130] R. M. Harris,[130] J. Hirschauer,[130] B. Hooberman,[130] S. Jindariani,[130] M. Johnson,[130] U. Joshi,[130] K. Kaadze,[130] B. Klima,[130] S. Kwan,[130] J. Linacre,[130] D. Lincoln,[130] R. Lipton,[130] J. Lykken,[130] K. Maeshima,[130] J. M. Marraffino,[130] V. I. Martinez Outschoorn,[130] S. Maruyama,[130] D. Mason,[130] P. McBride,[130] K. Mishra,[130] S. Mrenna,[130] Y. Musienko,[130,hh] S. Nahn,[130] C. Newman-Holmes,[130] V. O'Dell,[130] O. Prokofyev,[130] N. Ratnikova,[130] E. Sexton-Kennedy,[130] S. Sharma,[130] W. J. Spalding,[130] L. Spiegel,[130] L. Taylor,[130] S. Tkaczyk,[130] N. V. Tran,[130] L. Uplegger,[130] E. W. Vaandering,[130] R. Vidal,[130]

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