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Search for Three-Jet Resonances in pp Collisions at $\sqrt{s}$= 7 TeV

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Search for Three-Jet Resonances in pp Collisions at $\sqrt{s} = 7$ TeV

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A search for three-jet hadronic resonance production in pp collisions at a center-of-mass energy of 7 TeV has been conducted by the CMS Collaboration at the LHC, using a data sample corresponding to an integrated luminosity of 35 pb^{-1}. Events with high jet multiplicity and a large scalar sum of jet transverse momenta are analyzed using a signature-based approach. The number of expected standard model background events is found to be in good agreement with the observed events. Limits on the cross section times branching ratio are set in a model of gluino pair production with an R-parity-violating decay to three quarks, and the data rule out such particles within the mass range of 200 to 280 GeV/c^2.

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Searches for new physics in multijet final states, although experimentally challenging at hadron colliders, are sensitive to many extensions of the standard model (SM). For example, variations of technicolor models, resulting in heavy colored fermions that transform as octets under $SU(3)_c$, have been proposed in a variety of forms [1–4]. Other models incorporate R-parity-violating (RPV) decays of supersymmetric gluinos ($\tilde{g}$) to three-quark final states, where the gluino represents a colored adjoint Majorana fermion [5–7]. In all cases, these high-mass resonances can be pair-produced, yielding a six-jet final state $pp \to \tilde{g}\,\tilde{g} + X$, where $\tilde{g} \to 3$ jets. Recent results from the Tevatron provide limits on gluino RPV decays for masses below 144 GeV/c^2 [8].

This Letter presents the first results of a dedicated search for three-jet hadronic resonances in multijet events in pp collisions. The results are based on a data sample of proton-proton collisions at $\sqrt{s} = 7$ TeV, corresponding to an integrated luminosity of $35.1 \pm 1.4\ \mathrm{pb}^{-1}$ [9], collected with the Compact Muon Solenoid (CMS) detector [10] at the large hadron collider (LHC) in the running period from March through November 2010. Events with at least six jets, each with high transverse momentum (p_T), are selected and investigated for evidence of three-jet resonances consistent with strongly coupled supersymmetric particle decays. The event selection criteria are optimized in the context of the gluino model mentioned above. However, the generic features of the selection criteria provide a robust signature-based method that can be applied to many extensions of the SM.

The CMS detector is a multipurpose apparatus, described in detail in Ref. [10]. Here, we briefly describe the subdetectors most relevant to this analysis. The high-resolution silicon pixel and strip tracker provides charged tracking coverage for $|\eta| < 2.4$, where $\eta = -\ln[\tan(\theta/2)]$ is the pseudorapidity and θ is the polar angle measured with respect to the counterclockwise proton beam direction. Immersed in the 3.8 T magnetic field of the superconducting solenoid, the tracker provides transverse momentum resolution of approximately 1.5% for charged particles with $p_T \approx 100\ \mathrm{GeV}/c$. Energy deposits of the jets are measured using electromagnetic (ECAL) and hadronic (HCAL) calorimeters. The ECAL has a barrel part and two endcaps, is composed of finely segmented crystals, and has an energy resolution of better than 0.5% for unconverted photons with transverse energies above 100 GeV. The ECAL barrel covers the pseudorapidity range $|\eta| < 1.4$ with a granularity of $\Delta\eta \times \Delta\phi = 0.0174 \times 0.0174$, where ϕ is the azimuthal angle, and the endcaps cover $1.4 < |\eta| < 3.0$ with a granularity that decreases to 0.05×0.05 for $|\eta| \approx 3.0$. A preshower detector consisting of two planes of silicon sensors interleaved with a total of three radiation lengths of lead is located in front of the ECAL endcaps. The HCAL extends up to $|\eta| \approx 5.0$ and its central and endcap regions consist of brass or scintillator sampling calorimeters that cover $|\eta| < 3.0$ with a granularity of $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ for central rapidities. The energy of charged pions and other quasistable hadrons is measured with the calorimeters (ECAL and HCAL combined) with a resolution of $\Delta E/E \approx 100\%/\sqrt{E[\mathrm{GeV}]} \oplus 5\%$.

Events are recorded using a two-tier trigger system. Objects satisfying the requirements at the first level (L1) are passed to the high level trigger (HLT) where the total recorded rate is limited to about ~350 Hz. Triggers based on the sum of all transverse energy from jets (H_T), reconstructed with only calorimeter information, are used to select recorded events. For the L1 trigger, the H_T threshold is 50 GeV. The corresponding threshold for the HLT varies between 100 and 150 GeV, depending on the run period.

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The CMS particle-flow algorithm [11] uses calorimeter information and combines it with reconstructed tracks to identify individual particles such as photons, leptons, and both neutral and charged hadrons within the jets. The energy of photons is directly obtained from the calibrated ECAL measurement. The energy of electrons is determined from a combination of the track momentum at the main interaction vertex, the corresponding ECAL cluster energy, and the energy sum of all bremsstrahlung photons attached to the track. The energy of muons is obtained from the corresponding track momentum. The energy of charged hadrons is determined from a combination of the track momentum and the corresponding ECAL and HCAL energy, corrected for zero-suppression effects, and calibrated for the nonlinear response of the calorimeters. Finally, the energy of neutral hadrons is obtained from the corresponding calibrated ECAL and HCAL energy. The particle-flow objects serve as input for jet reconstruction, performed using the anti-k_T algorithm [12] with a distance parameter of 0.5 in η-ϕ space. The jet energy resolution amounts typically to 15% at 10 GeV, 8% at 100 GeV, and 4% at 1 TeV, to be compared to about 40%, 12%, and 5% obtained when the calorimeters alone are used for jet clustering.

Jet energy scale corrections [13] derived from Monte Carlo (MC) simulation are applied to account for the nonlinear and nonuniform response of the calorimeters. The jet momenta are first corrected to account for the presence of additional proton-proton interactions. Next, an exclusive sample of azimuthally back-to-back jets is used to derive a relative correction of up to 8% to remove the pseudorapidity dependence of the jet momentum response. Finally, the absolute scale of the jet momentum response is set by applying a factor determined from an exclusive sample of a well-measured photon azimuthally back-to-back with a single hadronic jet. Additionally in data, a small residual correction factor of about 1% is included to correct for differences in jet response between data and simulation. The combined corrections are on the order of 5%–10%, and their corresponding uncertainties range from 3% to 5%, depending on the measured jet's pseudorapidity and energy. Jet quality criteria [14] are applied to remove misidentified jets arising primarily from calorimeter noise. For both data and simulated signal events, more than 99.8% of all selected jets satisfy these criteria.

Pair-produced gluinos are used to model the signal. Gluino production and decay are simulated using the PYTHIA [15] MC program (v6.420), where each gluino decays to three jets through the $\lambda_{\rm uds}$ quark RPV coupling. This coupling is set such that the branching ratio B of the gluino to three light jets is 100%. The mass of the gluino is varied between 200 and 500 GeV$/c^2$ in 50 GeV$/c^2$ steps. The leading-order cross section from PYTHIA is 325 pb for a gluino mass of 200 GeV$/c^2$, falling to ≈ 1 pb for a gluino mass of 500 GeV$/c^2$. For the generation of this signal all superpartners except the gluino are taken to be decoupled [7], the natural width of the gluino resonance is taken to be much smaller than the resolution of the detector, and no intermediate particles are produced in the gluino decay. The next-to-leading-order (NLO) correction factors (K factors), with values ranging from 1.7 to 2.2, are calculated using the PROSPINO [16] program and are applied to the leading-order cross sections, with uncertainties on the theoretical cross section that range from 15.5 to 17.1%. Simulation of the CMS detector is performed using GEANT4 [17].

Events recorded with the H_T trigger are required offline to have a good reconstructed primary event vertex [18]. Pair-produced three-jet resonances naturally yield events with high jet multiplicity and large transverse energy. Thus we require events to contain at least six jets, and that the total scalar sum of the p_T of those jets is larger than 425 GeV$/c$. The latter requirement also ensures that the trigger is fully efficient for these events. Jets are required to have $p_T > 45$ GeV$/c$ and $|\eta| < 3.0$, which also minimizes the effects from multiple proton-proton interactions.

To reconstruct the gluinos, the six highest-p_T jets are combined into all possible unique triplet combinations, resulting in 20 combinations of jet triplets. For signal events, each of the pair-produced gluinos corresponds to one of these 20 jet triplets, even in the case where all six jets come solely from the decay of these particles, leaving the 18 uncorrelated jet triplets as combinatorial background. Thus, the overall background arises not only from SM events, described by quantum chromodynamics (QCD), but also from spurious jet triplet combinations in signal events themselves. We impose additional requirements on each triplet to increase the signal sensitivity, while retaining as many signal triplets as possible. The invariant mass of background triplets is found to scale with the respective scalar sum of jet p_T, while for signal triplets the mass is constant. To reduce background, we therefore require each jet triplet to satisfy the following relation:

$$M_{jjj} < \sum_{i=1}^{3} |p_T|_i - \Delta, \tag{1}$$

where M_{jjj} is the triplet invariant mass, $\sum_{i=1}^{3} |p_T|_i$ is the scalar sum of jet p_T in the triplet (triplet scalar p_T), and Δ is an offset adjusted to optimize signal sensitivity. Figure 1 shows the simulated triplet invariant mass versus the triplet scalar p_T for a gluino mass of 250 GeV$/c^2$, and the insert displays the invariant mass distribution before and after the requirement. For each event, all 20 triplet combinations are included. The value of Δ is determined by maximizing the ratio of the number of signal triplets to the sum of the number of signal plus background triplets in a 1 standard deviation (σ) window around the center of the gluino mass peak. A common value of $\Delta = 130$ GeV$/c^2$ is taken for all gluino masses considered, which gives an efficiency in

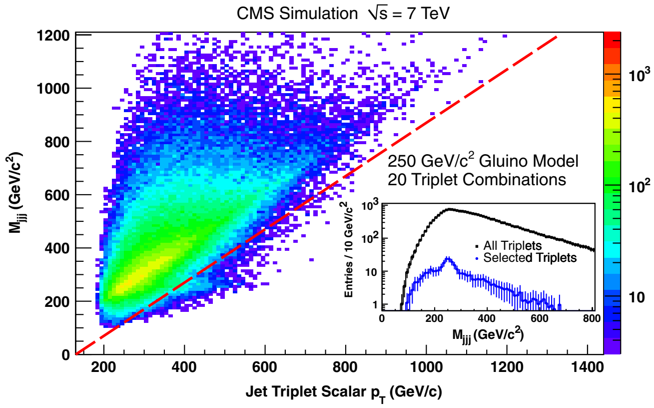

FIG. 1 (color online). Simulated triplet jet invariant mass M_{jjj} versus the triplet scalar p_T of all 20 triplets, for a gluino mass of 250 GeV/c^2. The red dashed line represents where $M_{jjj} = \Sigma_{i=1}^{3}|p_T|_i - 130$ GeV/c^2, and all triplets falling to the right of it pass the requirement of Eq. (1). In the insert, the invariant mass distribution for the same gluino mass is shown both before and after Eq. (1) is imposed.

signal events for triplets of 1 to 5%, and a background triplet selection efficiency of less than 0.05%.

Even after the final selection, background remains from both QCD multijet events and uncorrelated triplets in gluino signal events. The latter only contribute minimally, and the shape of their distribution is found to be consistent with that of the dominant background, from QCD multijet events. These QCD multijet events arise from hard two-particle interactions combined with initial- and final-state radiation in the form of gluon jets. Although the cross section falls with increasing jet multiplicity (N_{jet}), the underlying kinematic distributions are essentially the same among these events. Thus, we use a rescaled mass distribution of triplets in events with $N_{\text{jet}} = 4$, where the signal contributions are minimal, to estimate the shape of the background. Specifically, we select events in data with $N_{\text{jet}} = 4$ that satisfy all other selection criteria, form jet triplets, and require each to pass Eq. (1). The M_{jjj} values of these triplets are multiplied by the ratio of the average triplet scalar p_T in data for events with $N_{\text{jet}} \geq 6$ to the events with $N_{\text{jet}} = 4$, to account for expected minor kinematic differences between the two samples. The resulting M_{jjj} distribution is then fit to an exponential function of the form: $e^{P_0+P_1 M_{jjj}}$, where P_0 and P_1 are free parameters. The slope P_1 of the exponential function in the $N_{\text{jet}} \geq 6$ sample is constrained to be equal to that found for the scaled $N_{\text{jet}} = 4$ fit within its uncertainties. This is verified in QCD simulation, and as a cross-check in data, we apply this procedure to predict the shape of the M_{jjj} distribution for an $N_{\text{jet}} = 5$ sample, where the QCD multijet background is also expected to dominate, and find good agreement. To verify that the choice of the background model does not bias the derived limit, the exponential function is tested on an $N_{\text{jet}} \geq 6$ sample, defined by the standard selection criteria without the requirement of Eq. (1) imposed. The parameterization is found to be in agreement with the data in the fitted region, with the slope of the fit consistent with those of the $N_{\text{jet}} = 4$ and $N_{\text{jet}} = 5$ samples.

To estimate the number of signal events expected after all selection criteria are applied, the sum of a Gaussian function that represents the signal and the exponential function that models the background is fitted to the simulated M_{jjj} distribution for each gluino mass. The fit is performed in the range $170 < M_{jjj} < 800$ GeV/c^2. The width of the Gaussian function modeling the signal varies according to the detector resolution, and gluinos of mass from 200 to 500 GeV/c^2 correspond to widths from 10 to 25 GeV/c^2. The integral of the Gaussian component provides the estimate for the expected number of signal triplets produced, and the value of this integral, divided by the number of signal events generated, determines the signal acceptance for each gluino mass. The signal acceptance is parameterized using a second-degree polynomial as a function of gluino mass, and the acceptance ranges from 0.4% to 5% as the gluino mass increases from 200 to 500 GeV/c^2.

The systematic uncertainty on the signal acceptance is evaluated in the following way. An uncertainty related to the jet energy scale [13] is evaluated by varying the jet energy scale correction within its uncertainties, then recalculating the acceptance for different gluino mass values. The largest difference with respect to the nominal acceptance is taken as the systematic uncertainty and ranges from 7% to 16%. To address the sensitivity of the analysis to amount of initial- and final-state radiation in the signal simulation, samples with a varied amount of initial- and final-state radiation are generated and analyzed for each mass. The assigned systematic uncertainty for this effect is taken as the largest difference with respect to the nominal acceptance and is between 2% and 4% for all masses. To determine the effects of additional proton-proton interactions on the signal acceptance, signal samples are generated with the number of interactions per bunch crossing in the simulation set to the average of their distribution in the data. Applying the acceptance calculation on this sample leads to differences of 1% to 6%, which are taken as uncertainties. These contributions, combined with those from the luminosity measurement (4%) and choice of parton distribution function set (4%), give a total systematic uncertainty on the signal yield between 10% and 19%, depending on the value of the gluino mass. Other effects, such as additional background parameterizations and variations of the fit range, are also tested and found to be negligible.

Figure 2 shows the three-jet invariant mass distribution for the $N_{\text{jet}} \geq 6$ sample with all selection criteria applied, and the exponential fit superimposed. The simulated signal distribution for a gluino mass of 250 GeV/c^2, normalized to the integrated luminosity of the data sample, is also

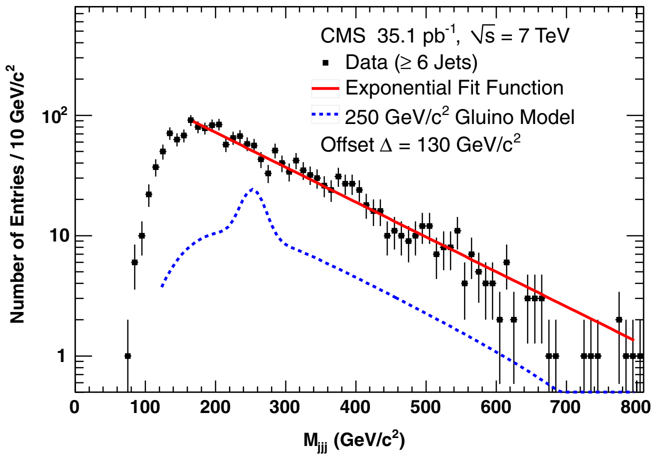

FIG. 2 (color online). Three-jet invariant mass distribution of triplets passing all selection criteria for the $N_{\rm jet} \geq 6$ data sample. An exponential function representing the background shape, constrained from the $N_{\rm jet} = 4$ distribution, and the expectation for a 250 GeV$/c^2$ gluino signal are also shown.

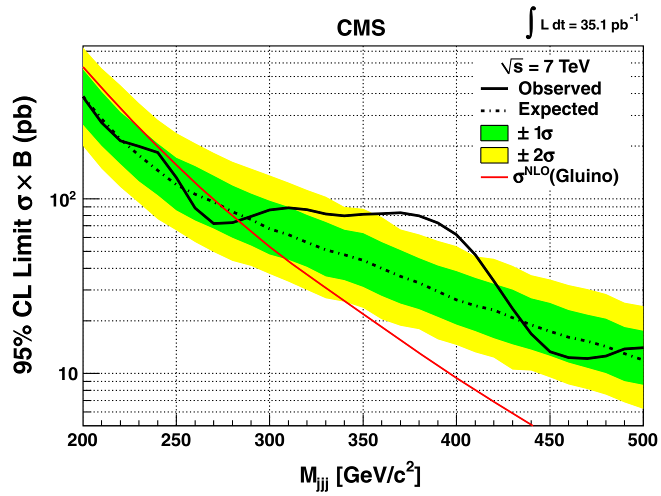

FIG. 3 (color online). Observed and expected 95% C.L. upper limits on the cross section for gluino pair production through RPV decays, where the branching ratio B of the gluino to three jets is 100%. Also shown are the $\pm 1\sigma$ and $\pm 2\sigma$ bands on the expected limit, as well as the theoretical NLO cross section for gluino production. The most significant excess of 1.9 standard deviations occurs at a mass of about 390 GeV$/c^2$.

shown. Because agreement is observed between the data and expected QCD background, a limit-setting procedure is performed.

Upper limits are placed on the cross section σ_S for the production of three-jet resonances in the $N_{\rm jet} \geq 6$ sample using a Bayesian approach. The background model parameters and their corresponding uncertainties are taken from the fit of the exponential function to the $N_{\rm jet} \geq 6$ distribution, constrained by the $N_{\rm jet} = 4$ sample, with all selection criteria applied. The uncertainties on the two parameters that describe the background shape, namely, the exponential slope and normalization, are included as Gaussian priors. The central value is set to the best fit value and the width to 1 standard deviation. The range is truncated at $\pm 3\sigma$. In addition to the background parameters, priors are included for the acceptance and integrated luminosity.

The integrated luminosity, acceptance, signal width, and the two parameters of the exponential background distribution are all treated as nuisance parameters. The likelihood is combined with the prior and nuisance parameters, and then marginalized to give the posterior density for σ_S. Integrating the posterior density to 0.95 of the total gives the 95% confidence level (C.L.) limit for σ_S. Marginalization and integration of the posterior density are performed with a Markov chain MC integration technique using ROOSTATS [19].

To determine the expected limits, a large set of pseudoexperiments (PEs) is generated using the background-only model. For every PE, each of the two parameters associated with the exponential is varied by generating a random number distributed according to a Gaussian probability distribution function centered at the central value, with a width corresponding to the associated uncertainty. The total number of events in a given PE is extracted according to the Poisson distribution with mean value equal to the number of events predicted by the exponential function in the fitted range. The same upper limit calculation performed on data is repeated for each PE at each mass, and the median of the upper limit distribution for all PEs is the expected limit.

The observed and expected 95% C.L. upper limits on the gluino pair production cross section times branching ratio as a function of gluino mass are presented in Fig. 3 and Table I. The corresponding 95% C.L. lower limit on the gluino mass is set by finding the mass value at which the 95% C.L. limit line crosses that of the NLO gluino cross section. We thus exclude at the 95% C.L. gluino masses in the range 200 to 280 GeV$/c^2$, with an expected lower limit of 270 GeV$/c^2$. The most significant excess occurs for a mass around 390 GeV$/c^2$, corresponding to a significance of 1.9 standard deviations, when the so-called look-elsewhere effect [20] is taken into account.

In summary, a search for three-jet hadronic resonance production in pp collisions at a center-of-mass energy of 7 TeV has been conducted by the CMS Collaboration, using a data sample corresponding to 35 pb^{-1}. Events having the properties of high jet multiplicity and large scalar sum of jet p_T, which are expected signatures of high-mass hadronic resonances, are analyzed for the presence of signal events with a signature-based approach. The number of expected SM background events is found to be in good agreement with the observed events. The production of gluinos decaying through the $\lambda_{\rm uds}$ RPV coupling is excluded for masses between 200 and 280 GeV$/c^2$ at 95% C.L. The reach of the search using the 2011 CMS dataset will be sensitive to a higher mass range, and these current

TABLE I. Observed and expected 95% C.L. upper limits on the cross section times branching ratio for the pair production of gluinos with masses (M_{jjj}) ranging from 200 to 500 GeV$/c^2$.

M_{jjj} (GeV$/c^2$)	Observed (pb)	Expected (pb)	M_{jjj} (GeV$/c^2$)	Observed (pb)	Expected (pb)
200	383	387	360	82	40
210	273	287	370	83	36
220	214	219	380	80	33
230	200	178	390	73	29
240	184	146	400	62	26
250	132	120	410	48	24
260	88	106	420	34	23
270	72	96	430	24	21
280	73	84	440	17	19
290	79	76	450	13	17
300	86	67	460	12	16
310	89	62	470	12	15
320	87	56	480	13	14
330	82	51	490	14	13
340	80	48	500	14	12
350	82	45			

results are complementary to recent results from the Tevatron, which rule out gluino masses below 144 GeV$/c^2$ [8]. These limits are the first from a dedicated search of this kind in pp collisions.

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Ocampo Rios,[17] A. F. Osorio Oliveros,[17] J. C. Sanabria,[17] N. Godinovic,[18] D. Lelas,[18] K. Lelas,[18] R. Plestina,[18,d] D. Polic,[18] I. Puljak,[18] Z. Antunovic,[19] M. Dzelalija,[19] V. Brigljevic,[20] S. Duric,[20] K. Kadija,[20] S. Morovic,[20] A. Attikis,[21] M. Galanti,[21] J. Mousa,[21] C. Nicolaou,[21] F. Ptochos,[21] P. A. Razis,[21] M. Finger,[22] M. Finger, Jr.,[22] Y. Assran,[23,e] A. Ellithi Kamel,[23] S. Khalil,[23,f] M. A. Mahmoud,[23,g] A. Hektor,[24] M. Kadastik,[24] M. Müntel,[24] M. Raidal,[24] L. Rebane,[24] A. Tiko,[24] V. Azzolini,[25] P. Eerola,[25] G. Fedi,[25] S. Czellar,[26] 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] 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] D. Sillou,[28] M. Besancon,[29] S. Choudhury,[29] M. Dejardin,[29] D. Denegri,[29] B. Fabbro,[29] J. L. Faure,[29] F. Ferri,[29] S. Ganjour,[29] F. X. Gentit,[29] A. Givernaud,[29] P. Gras,[29] G. Hamel de Monchenault,[29] P. Jarry,[29] E. Locci,[29] J. Malcles,[29] M. Marionneau,[29] L. Millischer,[29] J. Rander,[29] A. Rosowsky,[29] I. Shreyber,[29] M. Titov,[29] P. Verrecchia,[29] S. Baffioni,[30] F. Beaudette,[30] L. Benhabib,[30] L. Bianchini,[30] M. Bluj,[30,h] C. Broutin,[30] P. Busson,[30] C. Charlot,[30] T. Dahms,[30] L. Dobrzynski,[30] S. Elgammal,[30] R. Granier de Cassagnac,[30] M. Haguenauer,[30] P. Miné,[30] C. Mironov,[30] C. Ochando,[30] P. Paganini,[30] D. Sabes,[30] R. Salerno,[30] Y. Sirois,[30] C. Thiebaux,[30] B. Wyslouch,[30,i] A. Zabi,[30] J.-L. Agram,[31,j] J. Andrea,[31] D. Bloch,[31] D. Bodin,[31] J.-M. Brom,[31] M. Cardaci,[31] E. C. Chabert,[31] C. Collard,[31] E. Conte,[31,j] F. Drouhin,[31,j] C. Ferro,[31] J.-C. Fontaine,[31,j] D. Gelé,[31] U. Goerlach,[31] S. Greder,[31] P. Juillot,[31] M. Karim,[31,j] A.-C. Le Bihan,[31] Y. Mikami,[31] P. Van Hove,[31] F. Fassi,[32] D. Mercier,[32] C. Baty,[33] S. Beauceron,[33] N. Beaupere,[33] M. Bedjidian,[33] O. Bondu,[33] G. Boudoul,[33] D. Boumediene,[33] H. Brun,[33] J. Chasserat,[33] R. Chierici,[33] D. Contardo,[33] P. Depasse,[33] H. El Mamouni,[33] J. Fay,[33] S. Gascon,[33] B. Ille,[33] T. Kurca,[33] T. Le Grand,[33] M. Lethuillier,[33] L. Mirabito,[33] S. Perries,[33] V. Sordini,[33] S. Tosi,[33] Y. Tschudi,[33] P. Verdier,[33] D. Lomidze,[34] G. Anagnostou,[35] S. Beranek,[35] M. Edelhoff,[35] L. Feld,[35] N. Heracleous,[35] O. Hindrichs,[35] R. Jussen,[35] K. Klein,[35] J. Merz,[35] N. Mohr,[35] A. Ostapchuk,[35] A. Perieanu,[35] F. Raupach,[35] J. Sammet,[35] S. Schael,[35] D. Sprenger,[35] H. Weber,[35] M. Weber,[35] B. Wittmer,[35] M. Ata,[36] E. Dietz-Laursonn,[36] M. Erdmann,[36] T. Hebbeker,[36] C. Heidemann,[36] A. Hinzmann,[36] K. Hoepfner,[36] T. Klimkovich,[36] D. Klingebiel,[36] P. Kreuzer,[36] D. Lanske,[36,a] J. Lingemann,[36] C. Magass,[36] M. Merschmeyer,[36] A. Meyer,[36] P. Papacz,[36] H. Pieta,[36] H. Reithler,[36] S. A. Schmitz,[36] L. Sonnenschein,[36]

J. Steggemann,[36] D. Teyssier,[36] M. Bontenackels,[37] M. Davids,[37] M. Duda,[37] G. Flügge,[37] H. Geenen,[37] M. Giffels,[37] W. Haj Ahmad,[37] D. Heydhausen,[37] F. Hoehle,[37] B. Kargoll,[37] T. Kress,[37] Y. Kuessel,[37] A. Linn,[37] A. Nowack,[37] L. Perchalla,[37] O. Pooth,[37] J. Rennefeld,[37] P. Sauerland,[37] A. Stahl,[37] D. Tornier,[37] M. H. Zoeller,[37] M. Aldaya Martin,[38] W. Behrenhoff,[38] U. Behrens,[38] M. Bergholz,[38,k] A. Bethani,[38] K. Borras,[38] A. Cakir,[38] A. Campbell,[38] E. Castro,[38] D. Dammann,[38] G. Eckerlin,[38] D. Eckstein,[38] A. Flossdorf,[38] G. Flucke,[38] A. Geiser,[38] J. Hauk,[38] H. Jung,[38,b] M. Kasemann,[38] I. Katkov,[38,l] P. Katsas,[38] C. Kleinwort,[38] H. Kluge,[38] A. Knutsson,[38] M. Krämer,[38] D. Krücker,[38] E. Kuznetsova,[38] W. Lange,[38] W. Lohmann,[38,k] R. Mankel,[38] M. Marienfeld,[38] I.-A. Melzer-Pellmann,[38] A. B. Meyer,[38] J. Mnich,[38] A. Mussgiller,[38] J. Olzem,[38] A. Petrukhin,[38] D. Pitzl,[38] A. Raspereza,[38] M. Rosin,[38] R. Schmidt,[38,k] T. Schoerner-Sadenius,[38] N. Sen,[38] A. Spiridonov,[38] M. Stein,[38] J. Tomaszewska,[38] R. Walsh,[38] C. Wissing,[38] C. Autermann,[39] V. Blobel,[39] S. Bobrovskyi,[39] J. Draeger,[39] H. Enderle,[39] U. Gebbert,[39] M. Görner,[39] T. Hermanns,[39] K. Kaschube,[39] G. Kaussen,[39] H. Kirschenmann,[39] R. Klanner,[39] J. Lange,[39] B. Mura,[39] S. Naumann-Emme,[39] F. Nowak,[39] N. Pietsch,[39] C. Sander,[39] H. Schettler,[39] P. Schleper,[39] E. Schlieckau,[39] M. Schröder,[39] T. Schum,[39] H. Stadie,[39] G. Steinbrück,[39] J. Thomsen,[39] C. Barth,[40] J. Bauer,[40] J. Berger,[40] V. Buege,[40] T. Chwalek,[40] W. De Boer,[40] A. Dierlamm,[40] G. Dirkes,[40] M. Feindt,[40] J. Gruschke,[40] C. Hackstein,[40] F. Hartmann,[40] M. Heinrich,[40] H. Held,[40] K. H. Hoffmann,[40] S. Honc,[40] J. R. Komaragiri,[40] T. Kuhr,[40] D. Martschei,[40] S. Mueller,[40] Th. Müller,[40] M. Niegel,[40] O. Oberst,[40] A. Oehler,[40] J. Ott,[40] T. Peiffer,[40] G. Quast,[40] K. Rabbertz,[40] F. Ratnikov,[40] N. Ratnikova,[40] M. Renz,[40] C. Saout,[40] A. Scheurer,[40] P. Schieferdecker,[40] F.-P. Schilling,[40] G. Schott,[40] H. J. Simonis,[40] F. M. Stober,[40] D. Troendle,[40] J. Wagner-Kuhr,[40] T. Weiler,[40] M. Zeise,[40] V. Zhukov,[40,l] E. B. Ziebarth,[40] G. Daskalakis,[41] T. Geralis,[41] S. Kesisoglou,[41] A. Kyriakis,[41] D. Loukas,[41] I. Manolakos,[41] A. Markou,[41] C. Markou,[41] C. Mavrommatis,[41] E. Ntomari,[41] E. Petrakou,[41] L. Gouskos,[42] T. J. Mertzimekis,[42] A. Panagiotou,[42] N. Saoulidou,[42] E. Stiliaris,[42] I. Evangelou,[43] C. Foudas,[43] P. Kokkas,[43] N. Manthos,[43] I. Papadopoulos,[43] V. Patras,[43] F. A. Triantis,[43] A. Aranyi,[44] G. Bencze,[44] L. Boldizsar,[44] C. Hajdu,[44,b] P. Hidas,[44] D. Horvath,[44,m] A. Kapusi,[44] K. Krajczar,[44,n] F. Sikler,[44,b] G. I. Veres,[44,n] G. Vesztergombi,[44,n] N. Beni,[45] J. Molnar,[45] J. Palinkas,[45] Z. Szillasi,[45] V. Veszpremi,[45] P. Raics,[46] Z. L. Trocsanyi,[46] B. Ujvari,[46] S. B. Beri,[47] V. Bhatnagar,[47] N. Dhingra,[47] R. Gupta,[47] M. Jindal,[47] M. Kaur,[47] J. M. Kohli,[47] M. Z. Mehta,[47] N. Nishu,[47] L. K. Saini,[47] A. Sharma,[47] A. P. Singh,[47] J. Singh,[47] S. P. Singh,[47] S. Ahuja,[48] B. C. Choudhary,[48] P. Gupta,[48] S. Jain,[48] A. Kumar,[48] A. Kumar,[48] M. Naimuddin,[48] K. Ranjan,[48] R. K. Shivpuri,[48] S. Banerjee,[49] S. Bhattacharya,[49] S. Dutta,[49] B. Gomber,[49] S. Jain,[49] R. Khurana,[49] S. Sarkar,[49] R. K. Choudhury,[50] D. Dutta,[50] S. Kailas,[50] V. Kumar,[50] P. Mehta,[50] A. K. Mohanty,[50,b] L. M. Pant,[50] P. Shukla,[50] T. Aziz,[51] M. Guchait,[51,o] A. Gurtu,[51] M. Maity,[51,p] D. Majumder,[51] G. Majumder,[51] K. Mazumdar,[51] G. B. Mohanty,[51] A. Saha,[51] K. Sudhakar,[51] N. Wickramage,[51] S. Banerjee,[52] S. Dugad,[52] N. K. Mondal,[52] H. Arfaei,[53] H. Bakhshiansohi,[53,q] S. M. Etesami,[53] A. Fahim,[53,q] M. Hashemi,[53] H. Hesari,[53] A. Jafari,[53,q] M. Khakzad,[53] A. Mohammadi,[53,r] M. Mohammadi Najafabadi,[53] S. Paktinat Mehdiabadi,[53] B. Safarzadeh,[53] M. Zeinali,[53,s] M. Abbrescia,[54a,54b] L. Barbone,[54a,54b] C. Calabria,[54a,54b] A. Colaleo,[54a] D. Creanza,[54a,54c] N. De Filippis,[54a,54c,b] M. De Palma,[54a,54b] L. Fiore,[54a] G. Iaselli,[54a,54c] L. Lusito,[54a,54b] G. Maggi,[54a,54c] M. Maggi,[54a] N. Manna,[54a,54b] B. Marangelli,[54a,54b] S. My,[54a,54c] S. Nuzzo,[54a,54b] N. Pacifico,[54a,54b] G. A. Pierro,[54a] A. Pompili,[54a,54b] G. Pugliese,[54a,54c] F. Romano,[54a,54c] G. Roselli,[54a,54b] G. Selvaggi,[54a,54b] L. Silvestris,[54a] R. Trentadue,[54a] S. Tupputi,[54a,54b] G. Zito,[54a] G. Abbiendi,[55a] A. C. Benvenuti,[55a] D. Bonacorsi,[55a] S. Braibant-Giacomelli,[55a,55b] L. Brigliadori,[55a] P. Capiluppi,[55a,55b] A. Castro,[55a,55b] F. R. Cavallo,[55a] M. Cuffiani,[55a,55b] G. M. Dallavalle,[55a] F. Fabbri,[55a] A. Fanfani,[55a,55b] D. Fasanella,[55a] P. Giacomelli,[55a] M. Giunta,[55a] C. Grandi,[55a] S. Marcellini,[55a] G. Masetti,[55b] M. Meneghelli,[55a,55b] A. Montanari,[55a] F. L. Navarria,[55a,55b] F. Odorici,[55a] A. Perrotta,[55a] F. Primavera,[55a] A. M. Rossi,[55a,55b] T. Rovelli,[55a,55b] G. Siroli,[55a,55b] R. Travaglini,[55a,55b] S. Albergo,[56a,56b] G. Cappello,[56a,56b] M. Chiorboli,[56a,56b,b] S. Costa,[56a,56b] R. Potenza,[56a,56b] A. Tricomi,[56a,56b] C. Tuve,[56a,56b] G. Barbagli,[57a] V. Ciulli,[57a,57b] C. Civinini,[57a] R. D'Alessandro,[57a,57b] E. Focardi,[57a,57b] S. Frosali,[57a,57b] E. Gallo,[57a] S. Gonzi,[57a,57b] P. Lenzi,[57a,57b] M. Meschini,[57a] S. Paoletti,[57a] G. Sguazzoni,[57a] A. Tropiano,[57a,b] L. Benussi,[58] S. Bianco,[58] S. Colafranceschi,[58,t] F. Fabbri,[58] D. Piccolo,[58] P. Fabbricatore,[59] R. Musenich,[59] A. Benaglia,[60a,60b] F. De Guio,[60a,60b,b] L. Di Matteo,[60a,60b] S. Gennai,[60a,b] A. Ghezzi,[60a,60b] S. Malvezzi,[60a] A. Martelli,[60a,60b] A. Massironi,[60a,60b] D. Menasce,[60a] L. Moroni,[60a] M. Paganoni,[60a,60b] D. Pedrini,[60a] S. Ragazzi,[60a,60b] N. Redaelli,[60a] S. Sala,[60a] T. Tabarelli de Fatis,[60a,60b] S. Buontempo,[61a] C. A. Carrillo Montoya,[61a,b] N. Cavallo,[61a,u] A. De Cosa,[61a,61b] F. Fabozzi,[61a,u] A. O. M. Iorio,[61a,b] L. Lista,[61a] M. Merola,[61a,61b] P. Paolucci,[61a] P. Azzi,[62a] N. Bacchetta,[62a] P. Bellan,[62a,62b] D. Bisello,[62a,62b] A. Branca,[62a] R. Carlin,[62a,62b] P. Checchia,[62a] T. Dorigo,[62a]

U. Dosselli,[62a] F. Fanzago,[62a] F. Gasparini,[62a,62b] U. Gasparini,[62a,62b] A. Gozzelino,[62a] S. Lacaprara,[62a] I. Lazzizzera,[62a,62c] M. Margoni,[62a,62b] M. Mazzucato,[62a] A. T. Meneguzzo,[62a,62b] M. Nespolo,[62a,b] L. Perrozzi,[62a,b] N. Pozzobon,[62a,62b] P. Ronchese,[62a,62b] F. Simonetto,[62a,62b] E. Torassa,[62a] M. Tosi,[62a,62b] S. Vanini,[62a,62b] P. Zotto,[62a,62b] G. Zumerle,[62a,62b] P. Baesso,[63a,63b] U. Berzano,[63a] S. P. Ratti,[63a,63b] C. Riccardi,[63a,63b] P. Torre,[63a,63b] P. Vitulo,[63a,63b] C. Viviani,[63a,63b] M. Biasini,[64a,64b] G. M. Bilei,[64a] B. Caponeri,[64a,64b] L. Fanò,[64a,64b] P. Lariccia,[64a,64b] A. Lucaroni,[64a,64b,b] G. Mantovani,[64a,64b] M. Menichelli,[64a] A. Nappi,[64a,64b] F. Romeo,[64a,64b] A. Santocchia,[64a,64b] S. Taroni,[64a,64b,b] M. Valdata,[64a,64b] P. Azzurri,[65a,65c] G. Bagliesi,[65a] J. Bernardini,[65a,65b] T. Boccali,[65a,b] G. Broccolo,[65a,65c] R. Castaldi,[65a] R. T. D'Agnolo,[65a,65c] R. Dell'Orso,[65a] F. Fiori,[65a,65b] L. Foà,[65a,65c] A. Giassi,[65a] A. Kraan,[65a] F. Ligabue,[65a,65c] T. Lomtadze,[65a] L. Martini,[65a,v] A. Messineo,[65a,65b] F. Palla,[65a] F. Palmonari,[65a] G. Segneri,[65a] A. T. Serban,[65a] P. Spagnolo,[65a] R. Tenchini,[65a] G. Tonelli,[65a,65b,b] A. Venturi,[65a,b] P. G. Verdini,[65a] L. Barone,[66a,66b] F. Cavallari,[66a] D. Del Re,[66a,66b] E. Di Marco,[66a,66b] M. Diemoz,[66a] D. Franci,[66a,66b] M. Grassi,[66a,b] E. Longo,[66a,66b] P. Meridiani,[66a] S. Nourbakhsh,[66a] G. Organtini,[66a,66b] F. Pandolfi,[66a,66b,b] R. Paramatti,[66a] S. Rahatlou,[66a,66b] C. Rovelli,[66a,b] N. Amapane,[67a,67b] R. Arcidiacono,[67a,67c] S. Argiro,[67a,67b] M. Arneodo,[67a,67c] C. Biino,[67a] C. Botta,[67a,67b,b] N. Cartiglia,[67a] R. Castello,[67a,67b] M. Costa,[67a,67b] N. Demaria,[67a] A. Graziano,[67a,67b,b] C. Mariotti,[67a] M. Marone,[67a,67b] S. Maselli,[67a] E. Migliore,[67a,67b] G. Mila,[67a,67b] V. Monaco,[67a,67b] M. Musich,[67a] M. M. Obertino,[67a,67c] N. Pastrone,[67a] M. Pelliccioni,[67a,67b] A. Potenza,[67a,67b] A. Romero,[67a,67b] M. Ruspa,[67a,67c] R. Sacchi,[67a,67b] V. Sola,[67a,67b] A. Solano,[67a,67b] A. Staiano,[67a] A. Vilela Pereira,[67a] S. Belforte,[68a] F. Cossutti,[68a] G. Della Ricca,[68a,68b] B. Gobbo,[68a] D. Montanino,[68a,68b] A. Penzo,[68a] S. G. Heo,[69] S. K. Nam,[69] S. Chang,[70] J. Chung,[70] D. H. Kim,[70] G. N. Kim,[70] J. E. Kim,[70] D. J. Kong,[70] H. Park,[70] S. R. Ro,[70] D. C. Son,[70] T. Son,[70] Zero Kim,[71] J. Y. Kim,[71] S. Song,[71] S. Choi,[72] B. Hong,[72] M. Jo,[72] H. Kim,[72] J. H. Kim,[72] T. J. Kim,[72] K. S. Lee,[72] D. H. Moon,[72] S. K. Park,[72] K. S. Sim,[72] M. Choi,[73] S. Kang,[73] H. Kim,[73] C. Park,[73] I. C. Park,[73] S. Park,[73] G. Ryu,[73] Y. Choi,[74] Y. K. Choi,[74] J. Goh,[74] M. S. Kim,[74] B. Lee,[74] J. Lee,[74] S. Lee,[74] H. Seo,[74] I. Yu,[74] M. J. Bilinskas,[75] I. Grigelionis,[75] M. Janulis,[75] D. Martisiute,[75] P. Petrov,[75] M. Polujanskas,[75] T. Sabonis,[75] H. Castilla-Valdez,[76] E. De La Cruz-Burelo,[76] I. Heredia-de La Cruz,[76] R. Lopez-Fernandez,[76] R. Magaña Villalba,[76] A. Sánchez-Hernández,[76] L. M. Villasenor-Cendejas,[76] S. Carrillo Moreno,[77] F. Vazquez Valencia,[77] H. A. Salazar Ibarguen,[78] E. Casimiro Linares,[79] A. Morelos Pineda,[79] M. A. Reyes-Santos,[79] D. Krofcheck,[80] J. Tam,[80] P. H. Butler,[81] R. Doesburg,[81] H. Silverwood,[81] M. Ahmad,[82] I. Ahmed,[82] M. I. Asghar,[82] H. R. Hoorani,[82] S. Khalid,[82] W. A. Khan,[82] T. Khurshid,[82] S. Qazi,[82] M. A. Shah,[82] G. Brona,[83] M. Cwiok,[83] W. Dominik,[83] K. Doroba,[83] A. Kalinowski,[83] M. Konecki,[83] J. Krolikowski,[83] T. Frueboes,[84] R. Gokieli,[84] M. Górski,[84] M. Kazana,[84] K. Nawrocki,[84] K. Romanowska-Rybinska,[84] M. Szleper,[84] G. Wrochna,[84] P. Zalewski,[84] N. Almeida,[85] P. Bargassa,[85] A. David,[85] P. Faccioli,[85] P. G. Ferreira Parracho,[85] M. Gallinaro,[85,b] P. Musella,[85] A. Nayak,[85] J. Pela,[85,b] P. Q. Ribeiro,[85] J. Seixas,[85] J. Varela,[85] S. Afanasiev,[86] P. Bunin,[86] I. Golutvin,[86] V. Karjavin,[86] V. Konoplyanikov,[86] G. Kozlov,[86] A. Lanev,[86] P. Moisenz,[86] V. Palichik,[86] V. Perelygin,[86] M. Savina,[86] S. Shmatov,[86] V. Smirnov,[86] A. Volodko,[86] A. Zarubin,[86] V. Golovtsov,[87] Y. Ivanov,[87] V. Kim,[87] P. Levchenko,[87] V. Murzin,[87] V. Oreshkin,[87] I. Smirnov,[87] V. Sulimov,[87] L. Uvarov,[87] S. Vavilov,[87] A. Vorobyev,[87] An. Vorobyev,[87] Yu. Andreev,[88] A. Dermenev,[88] S. Gninenko,[88] N. Golubev,[88] M. Kirsanov,[88] N. Krasnikov,[88] V. Matveev,[88] A. Pashenkov,[88] A. Toropin,[88] S. Troitsky,[88] V. Epshteyn,[89] V. Gavrilov,[89] V. Kaftanov,[89,a] M. Kossov,[89,b] A. Krokhotin,[89] N. Lychkovskaya,[89] V. Popov,[89] G. Safronov,[89] S. Semenov,[89] V. Stolin,[89] E. Vlasov,[89] A. Zhokin,[89] A. Belyaev,[90] E. Boos,[90] M. Dubinin,[90,w] L. Dudko,[90] A. Ershov,[90] A. Gribushin,[90] O. Kodolova,[90] I. Lokhtin,[90] A. Markina,[90] S. Obraztsov,[90] M. Perfilov,[90] S. Petrushanko,[90] L. Sarycheva,[90] V. Savrin,[90] A. Snigirev,[90] V. Andreev,[91] M. Azarkin,[91] I. Dremin,[91] M. Kirakosyan,[91] A. Leonidov,[91] S. V. Rusakov,[91] A. Vinogradov,[91] I. Azhgirey,[92] I. Bayshev,[92] S. Bitioukov,[92] V. Grishin,[92,b] V. Kachanov,[92] D. Konstantinov,[92] A. Korablev,[92] V. Krychkine,[92] V. Petrov,[92] R. Ryutin,[92] A. Sobol,[92] L. Tourtchanovitch,[92] S. Troshin,[92] N. Tyurin,[92] A. Uzunian,[92] A. Volkov,[92] P. Adzic,[93,x] M. Djordjevic,[93] D. Krpic,[93,x] J. Milosevic,[93] M. Aguilar-Benitez,[94] J. Alcaraz Maestre,[94] P. Arce,[94] C. Battilana,[94] E. Calvo,[94] M. Cepeda,[94] M. Cerrada,[94] M. Chamizo Llatas,[94] N. Colino,[94] B. De La Cruz,[94] A. Delgado Peris,[94] C. Diez Pardos,[94] D. Domínguez Vázquez,[94] C. Fernandez Bedoya,[94] J. P. Fernández Ramos,[94] A. Ferrando,[94] J. Flix,[94] M. C. Fouz,[94] P. Garcia-Abia,[94] O. Gonzalez Lopez,[94] S. Goy Lopez,[94] J. M. Hernandez,[94] M. I. Josa,[94] G. Merino,[94] J. Puerta Pelayo,[94] I. Redondo,[94] L. Romero,[94] J. Santaolalla,[94] M. S. Soares,[94] C. Willmott,[94] C. Albajar,[95] G. Codispoti,[95] J. F. de Trocóniz,[95] J. Cuevas,[96] J. Fernandez Menendez,[96] S. Folgueras,[96] I. Gonzalez Caballero,[96] L. Lloret Iglesias,[96] J. M. Vizan Garcia,[96] J. A. Brochero Cifuentes,[97] I. J. Cabrillo,[97]

A. Calderon,[97] S. H. Chuang,[97] J. Duarte Campderros,[97] M. Felcini,[97,y] M. Fernandez,[97] G. Gomez,[97] J. Gonzalez Sanchez,[97] C. Jorda,[97] P. Lobelle Pardo,[97] A. Lopez Virto,[97] J. Marco,[97] R. Marco,[97] C. Martinez Rivero,[97] F. Matorras,[97] F. J. Munoz Sanchez,[97] J. Piedra Gomez,[97,z] T. Rodrigo,[97] A. Y. Rodríguez-Marrero,[97] A. Ruiz-Jimeno,[97] L. Scodellaro,[97] M. Sobron Sanudo,[97] I. Vila,[97] R. Vilar Cortabitarte,[97] D. Abbaneo,[98] E. Auffray,[98] G. Auzinger,[98] P. Baillon,[98] A. H. Ball,[98] D. Barney,[98] A. J. Bell,[98,aa] D. Benedetti,[98] C. Bernet,[98,d] W. Bialas,[98] P. Bloch,[98] A. Bocci,[98] S. Bolognesi,[98] M. Bona,[98] H. Breuker,[98] K. Bunkowski,[98] T. Camporesi,[98] G. Cerminara,[98] T. Christiansen,[98] J. A. Coarasa Perez,[98] B. Curé,[98] D. D'Enterria,[98] A. De Roeck,[98] S. Di Guida,[98] N. Dupont-Sagorin,[98] A. Elliott-Peisert,[98] B. Frisch,[98] W. Funk,[98] A. Gaddi,[98] G. Georgiou,[98] H. Gerwig,[98] D. Gigi,[98] K. Gill,[98] D. Giordano,[98] F. Glege,[98] R. Gomez-Reino Garrido,[98] M. Gouzevitch,[98] P. Govoni,[98] S. Gowdy,[98] L. Guiducci,[98] M. Hansen,[98] C. Hartl,[98] J. Harvey,[98] J. Hegeman,[98] B. Hegner,[98] H. F. Hoffmann,[98] A. Honma,[98] V. Innocente,[98] P. Janot,[98] K. Kaadze,[98] E. Karavakis,[98] P. Lecoq,[98] C. Lourenço,[98] T. Mäki,[98] M. Malberti,[98] L. Malgeri,[98] M. Mannelli,[98] L. Masetti,[98] A. Maurisset,[98] F. Meijers,[98] S. Mersi,[98] E. Meschi,[98] R. Moser,[98] M. U. Mozer,[98] M. Mulders,[98] E. Nesvold,[98,b] M. Nguyen,[98] T. Orimoto,[98] L. Orsini,[98] E. Palencia Cortezon,[98] E. Perez,[98] A. Petrilli,[98] A. Pfeiffer,[98] M. Pierini,[98] M. Pimiä,[98] D. Piparo,[98] G. Polese,[98] A. Racz,[98] W. Reece,[98] J. Rodrigues Antunes,[98] G. Rolandi,[98,bb] T. Rommerskirchen,[98] M. Rovere,[98] H. Sakulin,[98] C. Schäfer,[98] C. Schwick,[98] I. Segoni,[98] A. Sharma,[98] P. Siegrist,[98] P. Silva,[98] M. Simon,[98] P. Sphicas,[98,cc] M. Spiropulu,[98,w] M. Stoye,[98] P. Tropea,[98] A. Tsirou,[98] P. Vichoudis,[98] M. Voutilainen,[98] W. D. Zeuner,[98] W. Bertl,[99] K. Deiters,[99] W. Erdmann,[99] K. Gabathuler,[99] R. Horisberger,[99] Q. Ingram,[99] H. C. Kaestli,[99] S. König,[99] D. Kotlinski,[99] U. Langenegger,[99] F. Meier,[99] D. Renker,[99] T. Rohe,[99] J. Sibille,[99,dd] A. Starodumov,[99,ee] L. Bäni,[100] P. Bortignon,[100] L. Caminada,[100,ff] B. Casal,[100] N. Chanon,[100] Z. Chen,[100] S. Cittolin,[100] G. Dissertori,[100] M. Dittmar,[100] J. Eugster,[100] K. Freudenreich,[100] C. Grab,[100] W. Hintz,[100] P. Lecomte,[100] W. Lustermann,[100] C. Marchica,[100,ff] P. Martinez Ruiz del Arbol,[100] P. Milenovic,[100,gg] F. Moortgat,[100] C. Nägeli,[100,ff] P. Nef,[100] F. Nessi-Tedaldi,[100] L. Pape,[100] F. Pauss,[100] T. Punz,[100] A. Rizzi,[100] F. J. Ronga,[100] M. Rossini,[100] L. Sala,[100] A. K. Sanchez,[100] M.-C. Sawley,[100] B. Stieger,[100] L. Tauscher,[100,a] A. Thea,[100] K. Theofilatos,[100] D. Treille,[100] C. Urscheler,[100] R. Wallny,[100] M. Weber,[100] L. Wehrli,[100] J. Weng,[100] E. Aguilo,[101] C. Amsler,[101] V. Chiochia,[101] S. De Visscher,[101] C. Favaro,[101] M. Ivova Rikova,[101] B. Millan Mejias,[101] P. Otiougova,[101] P. Robmann,[101] A. Schmidt,[101] H. Snoek,[101] Y. H. Chang,[102] K. H. Chen,[102] C. M. Kuo,[102] S. W. Li,[102] W. Lin,[102] Z. K. Liu,[102] Y. J. Lu,[102] D. Mekterovic,[102] R. Volpe,[102] J. H. Wu,[102] S. S. Yu,[102] P. Bartalini,[103] P. Chang,[103] Y. H. Chang,[103] Y. W. Chang,[103] Y. Chao,[103] K. F. Chen,[103] W.-S. Hou,[103] Y. Hsiung,[103] K. Y. Kao,[103] Y. J. Lei,[103] R.-S. Lu,[103] J. G. Shiu,[103] Y. M. Tzeng,[103] X. Wan,[103] M. Wang,[103] A. Adiguzel,[104] M. N. Bakirci,[104,hh] S. Cerci,[104,ii] C. Dozen,[104] I. Dumanoglu,[104] E. Eskut,[104] S. Girgis,[104] G. Gokbulut,[104] I. Hos,[104] E. E. Kangal,[104] A. Kayis Topaksu,[104] G. Onengut,[104] K. Ozdemir,[104] S. Ozturk,[104,jj] A. Polatoz,[104] K. Sogut,[104,kk] D. Sunar Cerci,[104,ii] B. Tali,[104,ii] H. Topakli,[104,hh] D. Uzun,[104] L. N. Vergili,[104] M. Vergili,[104] I. V. Akin,[105] T. Aliev,[105] B. Bilin,[105] S. Bilmis,[105] M. Deniz,[105] H. Gamsizkan,[105] A. M. Guler,[105] K. Ocalan,[105] A. Ozpineci,[105] M. Serin,[105] R. Sever,[105] U. E. Surat,[105] M. Yalvac,[105] E. Yildirim,[105] M. Zeyrek,[105] M. Deliomeroglu,[106] D. Demir,[106,ll] E. Gülmez,[106] B. Isildak,[106] M. Kaya,[106,mm] O. Kaya,[106,mm] M. Özbek,[106] S. Ozkorucuklu,[106,nn] N. Sonmez,[106,oo] L. Levchuk,[107] F. Bostock,[108] J. J. Brooke,[108] T. L. Cheng,[108] E. Clement,[108] D. Cussans,[108] R. Frazier,[108] J. Goldstein,[108] M. Grimes,[108] D. Hartley,[108] G. P. Heath,[108] H. F. Heath,[108] L. Kreczko,[108] S. Metson,[108] D. M. Newbold,[108,pp] K. Nirunpong,[108] A. Poll,[108] S. Senkin,[108] V. J. Smith,[108] L. Basso,[109,qq] K. W. Bell,[109] A. Belyaev,[109,qq] C. Brew,[109] R. M. Brown,[109] B. Camanzi,[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] S. D. Worm,[109] R. Bainbridge,[110] G. Ball,[110] J. Ballin,[110] R. Beuselinck,[110] O. Buchmuller,[110] D. Colling,[110] N. Cripps,[110] M. Cutajar,[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] B. C. MacEvoy,[110] A.-M. Magnan,[110] J. Marrouche,[110] B. Mathias,[110] R. Nandi,[110] J. Nash,[110] A. Nikitenko,[110,ee] A. Papageorgiou,[110] M. Pesaresi,[110] K. Petridis,[110] M. Pioppi,[110,rr] D. M. Raymond,[110] S. Rogerson,[110] N. Rompotis,[110] A. Rose,[110] M. J. Ryan,[110] C. Seez,[110] P. Sharp,[110] A. Sparrow,[110] A. Tapper,[110] S. Tourneur,[110] M. Vazquez Acosta,[110] T. Virdee,[110] S. Wakefield,[110] N. Wardle,[110] D. Wardrope,[110] T. Whyntie,[110] M. Barrett,[111] M. Chadwick,[111] J. E. Cole,[111] P. R. Hobson,[111] A. Khan,[111] P. Kyberd,[111] D. Leslie,[111] W. Martin,[111] I. D. Reid,[111] L. Teodorescu,[111] K. Hatakeyama,[112] H. Liu,[112] C. Henderson,[113] T. Bose,[114] E. Carrera Jarrin,[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] A. Avetisyan,[115] S. Bhattacharya,[115] J. P. Chou,[115] D. Cutts,[115] A. Ferapontov,[115] U. Heintz,[115] S. Jabeen,[115] G. Kukartsev,[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] P. T. Cox,[116] J. Dolen,[116] R. Erbacher,[116] E. Friis,[116] W. Ko,[116] A. Kopecky,[116] R. Lander,[116] H. Liu,[116] S. Maruyama,[116] T. Miceli,[116] M. Nikolic,[116] D. Pellett,[116] J. Robles,[116] B. Rutherford,[116] S. Salur,[116] T. Schwarz,[116] M. Searle,[116] J. Smith,[116] M. Squires,[116] M. Tripathi,[116] R. Vasquez Sierra,[116] C. Veelken,[116] V. Andreev,[117] K. Arisaka,[117] D. Cline,[117] R. Cousins,[117] A. Deisher,[117] J. Duris,[117] S. Erhan,[117] C. Farrell,[117] J. Hauser,[117] M. Ignatenko,[117] C. Jarvis,[117] C. Plager,[117] G. Rakness,[117] P. Schlein,[117,a] J. Tucker,[117] V. Valuev,[117] J. Babb,[118] A. Chandra,[118] R. Clare,[118] J. Ellison,[118] J. W. Gary,[118] F. Giordano,[118] G. Hanson,[118] G. Y. Jeng,[118] S. C. Kao,[118] F. Liu,[118] H. Liu,[118] O. R. Long,[118] A. Luthra,[118] H. Nguyen,[118] S. Paramesvaran,[118] B. C. Shen,[118,a] R. Stringer,[118] J. Sturdy,[118] S. Sumowidagdo,[118] R. Wilken,[118] S. Wimpenny,[118] W. Andrews,[119] J. G. Branson,[119] G. B. Cerati,[119] D. Evans,[119] F. Golf,[119] A. Holzner,[119] R. Kelley,[119] M. Lebourgeois,[119] J. Letts,[119] B. Mangano,[119] S. Padhi,[119] C. Palmer,[119] G. Petrucciani,[119] H. Pi,[119] M. Pieri,[119] R. Ranieri,[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,ss] 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] J. R. Vlimant,[120] A. Apresyan,[121] A. Bornheim,[121] J. Bunn,[121] Y. Chen,[121] M. Gataullin,[121] Y. Ma,[121] A. Mott,[121] H. B. Newman,[121] C. Rogan,[121] K. Shin,[121] V. Timciuc,[121] P. Traczyk,[121] J. Veverka,[121] R. Wilkinson,[121] Y. Yang,[121] R. Y. Zhu,[121] B. Akgun,[122] R. Carroll,[122] T. Ferguson,[122] Y. Iiyama,[122] D. W. Jang,[122] S. Y. Jun,[122] Y. F. Liu,[122] M. Paulini,[122] J. Russ,[122] H. Vogel,[122] I. Vorobiev,[122] J. P. Cumalat,[123] M. E. Dinardo,[123] B. R. Drell,[123] C. J. Edelmaier,[123] W. T. Ford,[123] A. Gaz,[123] B. Heyburn,[123] E. Luiggi Lopez,[123] U. Nauenberg,[123] J. G. Smith,[123] K. Stenson,[123] K. A. Ulmer,[123] S. R. Wagner,[123] S. L. Zang,[123] L. Agostino,[124] J. Alexander,[124] A. Chatterjee,[124] N. Eggert,[124] L. K. Gibbons,[124] B. Heltsley,[124] K. Henriksson,[124] W. Hopkins,[124] A. Khukhunaishvili,[124] B. Kreis,[124] Y. Liu,[124] G. Nicolas Kaufman,[124] J. R. Patterson,[124] D. Puigh,[124] A. Ryd,[124] M. Saelim,[124] E. Salvati,[124] X. Shi,[124] W. Sun,[124] W. D. Teo,[124] J. Thom,[124] J. Thompson,[124] J. Vaughan,[124] Y. Weng,[124] L. Winstrom,[124] P. Wittich,[124] A. Biselli,[125] G. Cirino,[125] D. Winn,[125] S. Abdullin,[126] M. Albrow,[126] J. Anderson,[126] G. Apollinari,[126] M. Atac,[126] J. A. Bakken,[126] L. A. T. Bauerdick,[126] A. Beretvas,[126] J. Berryhill,[126] P. C. Bhat,[126] I. Bloch,[126] F. Borcherding,[126] K. Burkett,[126] J. N. Butler,[126] V. Chetluru,[126] H. W. K. Cheung,[126] F. Chlebana,[126] S. Cihangir,[126] W. Cooper,[126] D. P. Eartly,[126] V. D. Elvira,[126] S. Esen,[126] I. Fisk,[126] J. Freeman,[126] Y. Gao,[126] E. Gottschalk,[126] D. Green,[126] K. Gunthoti,[126] O. Gutsche,[126] J. Hanlon,[126] R. M. Harris,[126] J. Hirschauer,[126] B. Hooberman,[126] H. Jensen,[126] M. Johnson,[126] U. Joshi,[126] R. Khatiwada,[126] B. Klima,[126] K. Kousouris,[126] S. Kunori,[126] S. Kwan,[126] C. Leonidopoulos,[126] P. Limon,[126] D. Lincoln,[126] R. Lipton,[126] J. Lykken,[126] K. Maeshima,[126] J. M. Marraffino,[126] D. Mason,[126] P. McBride,[126] T. Miao,[126] K. Mishra,[126] S. Mrenna,[126] Y. Musienko,[126,tt] C. Newman-Holmes,[126] V. O'Dell,[126] J. Pivarski,[126] R. Pordes,[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] 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] 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] G. Mitselmakher,[127] L. Muniz,[127] C. Prescott,[127] R. Remington,[127] A. Rinkevicius,[127] M. Schmitt,[127] B. Scurlock,[127] P. Sellers,[127] N. Skhirtladze,[127] M. Snowball,[127] D. Wang,[127] J. Yelton,[127] M. Zakaria,[127] V. Gaultney,[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] L. Quertenmont,[129] S. Sekmen,[129] V. Veeraraghavan,[129] M. M. Baarmand,[130] B. Dorney,[130] S. Guragain,[130] M. Hohlmann,[130] H. Kalakhety,[130] I. Vodopiyanov,[130] M. R. Adams,[131] I. M. Anghel,[131] L. Apanasevich,[131] Y. 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