

Search for pair production of first- and second-generation scalar leptoquarks in pp collisions at $\sqrt{s} = 7$ TeV

S. Chatrchyan *et al.**

(CMS Collaboration)

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Results are presented from a search for the pair production of first- and second-generation scalar leptoquarks in proton-proton collisions at $\sqrt{s} = 7$ TeV. The data sample corresponds to an integrated luminosity of 5.0 fb^{-1} , collected by the CMS detector at the LHC. The search signatures involve either two charged leptons of the same flavor (electrons or muons) and at least two jets or a single charged lepton (electron or muon), missing transverse energy, and at least two jets. If the branching fraction of the leptoquark decay into a charged lepton and a quark is assumed to be $\beta = 1$, leptoquark pair production is excluded at the 95% confidence level for masses below 830 GeV and 840 GeV for the first and second generations, respectively. For $\beta = 0.5$, masses below 640 GeV and 650 GeV are excluded. These limits are the most stringent to date.

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I. INTRODUCTION

The structure of the standard model (SM) of particle physics suggests a fundamental relationship between quarks and leptons. There are many models beyond the SM that predict the existence of leptoquarks (LQ), hypothetical particles that carry both baryon number and lepton number and couple to both quarks and leptons. Among these scenarios are grand unified theories [1,2], composite models [3], extended technicolor models [4–6], and superstring-inspired models [7]. Leptoquarks are color triplets with fractional electric charge and can be either scalar or vector particles. A leptoquark couples to a lepton and a quark with a coupling strength λ , and it decays to a charged lepton and a quark with an unknown branching fraction β or to a neutrino and a quark with branching fraction $1 - \beta$. To satisfy constraints from bounds on flavor-changing neutral currents and from rare pion and kaon decays [3,8], it is assumed that leptoquarks couple to quarks and leptons of a single generation. Leptoquarks are classified as first, second, or third generation, depending on the generation of leptons to which they couple. The dominant mechanisms for the production of leptoquark pairs at the Large Hadron Collider (LHC) are gluon-gluon (gg) fusion and quark-antiquark ($q\bar{q}$) annihilation, shown in Fig. 1. The dominant processes depend only on the strong coupling constant and have been calculated at next-to-leading order (NLO) [9]. The cross section for production via the unknown Yukawa coupling λ of a leptoquark to a lepton and a quark is typically smaller.

*Full author list given at the end of the article.

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This paper reports on a search for pair production of scalar leptoquarks. Several experiments have searched for pair-produced scalar leptoquarks, but none has obtained evidence for them [10–15]. This search uses a data sample corresponding to an integrated luminosity of 5.0 fb^{-1} recorded with the Compact Muon Solenoid (CMS) detector during the 2011 proton-proton run of the LHC at $\sqrt{s} = 7$ TeV. The analysis performed in this paper considers the decay of leptoquark pairs into two charged leptons of the same flavor (either electrons or muons) and two quarks; or into a charged lepton, a neutrino, and two quarks. As a result, two distinct classes of events are selected: one with two high-transverse-momentum (p_T) electrons or muons and at least two high- p_T jets ($\ell\ell jj$) and the other with one high- p_T electron or muon, large missing transverse energy (E_T^{miss}), and at least two high- p_T jets ($\ell\nu jj$).

The CMS detector, described in detail elsewhere [16], uses a cylindrical coordinate system with the z axis along the counterclockwise beam axis. The detector consists of an inner tracking system and electromagnetic (ECAL) and hadron (HCAL) calorimeters surrounded by a 3.8 T solenoid. The inner tracking system consists of a silicon pixel

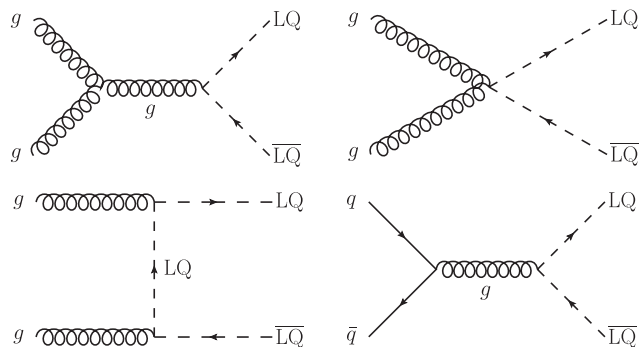


FIG. 1. Dominant leading order diagrams for the pair production of scalar leptoquarks.

and strip tracker, providing the required granularity and precision for the reconstruction of vertices of charged particles in the range $0 \leq \phi \leq 2\pi$ in azimuth and $|\eta| < 2.5$, where the pseudorapidity η is defined as $\eta = -\ln[\tan(\theta/2)]$, and θ is the polar angle measured with respect to the z axis. The crystal ECAL and the brass/scintillator sampling HCAL are used to measure with high resolution the energies of photons, electrons, and hadrons for $|\eta| < 3.0$. The three muon systems surrounding the solenoid cover a region $|\eta| < 2.4$ and are composed of drift tubes in the barrel region ($|\eta| < 1.2$), of cathode strip chambers in the endcaps ($0.9 < |\eta| < 2.4$), and of resistive plate chambers in both the barrel region and the end caps ($|\eta| < 1.6$). Events are recorded based on a trigger decision using information from either the calorimeter or muon systems. The final trigger decision is based on the information from all subsystems, which is passed on to the high-level trigger (HLT), consisting of a farm of computers running a version of the reconstruction software optimized for fast processing.

The $\ell\ell jj$ and $\ell\nu jj$ analyses are performed separately and the results are combined as a function of the branching fraction β and the leptoquark mass M_{LQ} for first and second generations independently. The analysis in all four decay channels searches for leptoquarks in an excess of events characteristic of the decay of heavy objects. Various triggers are used to collect events depending on the decay channel and the data taking periods as described in Sec. II. An initial selection isolates events with high- p_T final-state particles (two or more isolated leptons and two or more jets; or one isolated lepton, two or more jets, and large E_T^{miss} indicative of the emission of a neutrino). Kinematic variables are then identified to further separate a possible leptoquark signal from the expected backgrounds, and optimized thresholds on the values of these variables are derived to maximize the sensitivity to the possible presence of a signal in each decay mode. The variables used in the optimization are the invariant mass of jet-lepton pairs ($M_{\ell j}$), the scalar sum (S_T) of the p_T of each of the final-state objects, and either the invariant mass of the dilepton pair ($M_{\ell\ell}$) in the $\ell\ell jj$ channels or E_T^{miss} in the $\ell\nu jj$ channels.

Major sources of SM background are $Z/\gamma^* + \text{jets}$, $W + \text{jets}$ processes, and $t\bar{t}$. Smaller contributions arise from single-top production, diboson processes, and QCD multijet processes. The major backgrounds are determined either from control samples in data or from Monte Carlo (MC) simulated samples normalized to data in selected control regions.

After final selection, the data are well described by the SM background predictions, and upper limits on the leptoquark pair-production cross section are set using a CL_S modified frequentist approach [17,18]. Using Poisson statistics, 95% confidence level (CL) upper limits are obtained on the leptoquark pair-production cross section

times branching fraction as a function of leptoquark mass (M_{LQ}). This is compared with the NLO predictions [9] to determine lower limits on M_{LQ} for $\beta = 1$ and $\beta = 0.5$. The $\ell\ell jj$ and $\ell\nu jj$ channels are combined to further maximize the exclusion in β and M_{LQ} , especially for the case $\beta \sim 0.5$, where combining the two channels increases the sensitivity of the search.

The data and the initial event selection are detailed in Sec. II of this paper, followed by a description of the signal modeling and background estimates in Secs. III and IV, respectively. Section V contains the final event selection, and Sec. VI describes the systematic uncertainties. The results of the search are presented in Sec. VII and summarized in Sec. VIII.

II. DATA SET AND OBJECT RECONSTRUCTION

For the first-generation $eejj$ analysis, events are required to pass a double-electron trigger or a double-photon trigger, with an electron or photon $p_T > 33$ GeV. For the first-generation $e\nu jj$ analysis, events are required to pass either a single-electron trigger or a trigger based on the requirement of one electron with p_T threshold between 17 and 30 GeV, missing transverse energy threshold between 15 and 20 GeV, and two jets with p_T threshold between 25 and 30 GeV. The trigger thresholds vary according to the run period. For the second-generation leptoquark analyses, events are required to pass a single-muon trigger without isolation requirements and with a p_T threshold of 40 GeV. For the $eejj$ channel, the trigger efficiency is greater than 99%. For the $e\nu jj$ channel, the electron trigger efficiency is measured to be 95%. For the $\mu\mu jj$ and $\mu\nu jj$ channels, the single-muon trigger efficiency is measured to be 92% per muon.

Electron candidates [19] are required to have an electromagnetic cluster with $p_T > 40$ GeV and pseudorapidity $|\eta| < 2.5(2.2)$ for the $eejj$ ($e\nu jj$) analysis, excluding the transition region between the barrel and the end cap detectors, $1.44 < |\eta| < 1.57$. The $e\nu jj$ analysis requires lower electron $|\eta|$ to reduce the QCD multijet background, with negligible reduction of the signal acceptance. Electron candidates are required to have an electromagnetic cluster in the ECAL that is spatially matched to a reconstructed track in the central tracking system in both η and the azimuthal angle ϕ , and to have a shower shape consistent with that of an electromagnetic shower. Electron candidates are further required to be isolated from additional energy deposits in the calorimeter and from reconstructed tracks beyond the matched track in the central tracking system. In addition, to reject electrons coming from photon conversion in the tracker material, the track associated with the reconstructed electron is required to have hits in all inner tracker layers.

Muons are reconstructed as tracks in the muon system that are matched to the tracks reconstructed in the inner tracking system [20]. Muons are required to have

$p_T > 40$ GeV and to be reconstructed in the HLT fiducial volume, i.e. with $|\eta| < 2.1$. In addition, muons must be isolated by requiring that the tracker-only relative isolation be less than 0.1. Here, the relative isolation is defined as a sum of the transverse momenta of all tracks in the tracker in a cone of $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.3$ around the muon track (excluding the muon track), divided by the muon p_T . To have a precise measurement of the transverse impact parameter of the muon track relative to the beam spot, only muons with tracks containing more than 10 hits in the silicon tracker and at least one hit in the pixel detector are considered. To reject muons from cosmic rays, the transverse impact parameter with respect to the primary vertex is required to be less than 2 mm.

Jets and E_T^{miss} are reconstructed using a particle-flow algorithm [21], which identifies and measures stable particles by combining information from all CMS subdetectors. The E_T^{miss} calculation uses calorimeter estimates improved by high precision inner tracking information as well as corrections based on particle-level information in the event. Jets are reconstructed using the anti- k_T [22] algorithm with a distance parameter of $R = 0.5$. The jet energy is calibrated using p_T balance of dijet and $\gamma + \text{jet}$ events [23]. In the $eejj$ and $\mu\mu jj$ ($evjj$ and $\mu\nu jj$) channels, jets are required to have $p_T > 30(40)$ GeV, and $|\eta| < 2.4$. Furthermore, jets are required to have a spatial separation from electron or muon candidates of $\Delta R > 0.3$.

The initial selection of $eejj$ or $\mu\mu jj$ events requires two electrons or two muons and at least two jets satisfying the conditions described above. The two leptons and the two highest- p_T jets are selected as the decay products from a pair of leptoquarks. The invariant mass of the two electrons (muons) is required to be $M_{\ell\ell} > 60(50)$ GeV. To reduce the combinatorial background, events with a scalar transverse energy $S_T^{\ell\ell} = p_T(\ell_1) + p_T(\ell_2) + p_T(j_1) + p_T(j_2)$ below 250 GeV are rejected.

TABLE I. Initial selection criteria in the $eejj$, $\mu\mu jj$, $evjj$, and $\mu\nu jj$ channels.

| Variable | $eejj$ | $\mu\mu jj$ | $evjj$ | $\mu\nu jj$ |
|---|--------|-------------|--------|-------------|
| $p_T(\ell_1)$ [GeV] | >40 | >40 | >40 | >40 |
| $p_T(\ell_2)$ [GeV] | >40 | >40 | ... | ... |
| $ \eta(\ell_1) $ | <2.5 | <2.1 | <2.2 | <2.1 |
| $ \eta(\ell_2) $ | <2.5 | <2.1 | ... | ... |
| $p_T(j_1)$ [GeV] | >30 | >30 | >40 | >40 |
| $p_T(j_2)$ [GeV] | >30 | >30 | >40 | >40 |
| $\Delta R(\ell, j)$ | >0.3 | >0.3 | >0.3 | >0.3 |
| E_T^{miss} [GeV] | ... | ... | >55 | >55 |
| $ \Delta\phi(E_T^{\text{miss}}, j_1) $ | ... | ... | >0.5 | >0.5 |
| $ \Delta\phi(E_T^{\text{miss}}, \ell) $ | ... | ... | >0.8 | >0.8 |
| $M_{\ell\ell}$ [GeV] | >60 | >50 | ... | ... |
| $M_T^{\ell\nu}$ [GeV] | ... | ... | >50 | >50 |
| $S_T^{\ell\ell}$ [GeV] | >250 | >250 | ... | ... |
| $S_T^{\ell\nu}$ [GeV] | ... | ... | >250 | >250 |

For the $evjj$ ($\mu\nu jj$) initial selection, events are required to contain one electron (muon) satisfying the conditions described above and at least two jets with $p_T > 40$ GeV and $E_T^{\text{miss}} > 55$ GeV. The jet p_T threshold is higher than that in the dilepton channels to account for jet p_T thresholds in triggers used in the $evjj$ channel. A veto on the presence of extra muons (electrons) is also applied. The angle in the transverse plane between the leading p_T jet and the E_T^{miss} vector is required to be $\Delta\phi(E_T^{\text{miss}}, j_1) > 0.5$ to reject events with misreconstructed E_T^{miss} . To reduce the contribution from QCD multijet events, the lepton and the E_T^{miss} are required to be separated by $\Delta\phi(E_T^{\text{miss}}, \ell) > 0.8$. In addition, events are rejected if the scalar transverse energy $S_T^{\ell\nu} = p_T(\ell) + E_T^{\text{miss}} + p_T(j_1) + p_T(j_2)$ is below 250 GeV.

The initial selection criteria are summarized in Table I.

III. SIGNAL AND BACKGROUND MODELING

The MC samples for the signal processes are generated for a range of leptoquark mass hypotheses between 250 and 900 GeV, with a renormalization and factorization scale $\mu \approx M_{\text{LQ}}$. The MC generation uses the PYTHIA generator [24] (version 6.422) and CTEQ6L1 parton distribution functions (PDF) [25]. The MC samples used to estimate the contribution from SM background processes are $t\bar{t}$ + jets events, generated with MADGRAPH [26]; single-top events (s , t , and tW channels), generated with POWHEG [27]; $Z/\gamma^* + \text{jets}$ events and $W + \text{jets}$ events, generated with SHERPA [28]; VV events, where V represents either a W or a Z boson, generated with PYTHIA; QCD muon-enriched multijet events, generated with PYTHIA in bins of transverse momentum of the hard-scattering process from 15 GeV to the kinematic limit. The simulation of the CMS detector is based on GEANT4 [29] and includes multiple collisions in a single bunch crossing corresponding to the luminosity profile of the LHC during the data taking periods of interest.

IV. BACKGROUND ESTIMATE

The main processes that can mimic the signature of a leptoquark signal in the $\ell\ell jj$ channels are $Z/\gamma^* + \text{jets}$, $t\bar{t}$, $VV + \text{jets}$, $W + \text{jets}$, and QCD multijets. The $Z/\gamma^* + \text{jets}$ background is determined by comparing events from data and MC samples in two different regions: in the region of low (L) dilepton invariant mass around the Z boson mass ($70 < M_{\ell\ell} < 100$ GeV for electrons and $80 < M_{\ell\ell} < 100$ GeV for muons) and in the region of high (H) mass $M_{\ell\ell} > 100$ GeV. The low mass scaling factor $R_Z = N_L/N_L^{\text{MC}}$ is measured to be 1.27 ± 0.02 for the $eejj$ channel and 1.29 ± 0.02 for the $\mu\mu jj$ channel, where N_L and N_L^{MC} are the number of data and MC events, respectively, in the Z mass window. The number of $Z/\gamma^* + \text{jets}$ events above 100 GeV is then estimated as

$$N_H = R_Z N_H^{\text{MC}}, \quad (1)$$

TABLE II. Optimized thresholds for different mass hypotheses of the $\ell\ell jj$ signal.

| M_{LQ} [GeV] | 250 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 750 | 850 | 900 |
|-----------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $S_T^{\ell\ell} >$ [GeV] | 330 | 450 | 530 | 610 | 690 | 720 | 770 | 810 | 880 | 900 | 920 |
| $M_{\ell\ell} >$ [GeV] | 100 | 110 | 120 | 130 | 130 | 130 | 130 | 130 | 140 | 150 | 150 |
| $M_{\ell j}^{\min} >$ [GeV] | 60 | 160 | 200 | 250 | 300 | 340 | 370 | 400 | 470 | 500 | 520 |

TABLE III. Optimized thresholds for different mass hypotheses of the $\ell\nu jj$ signal.

| M_{LQ} [GeV] | 250 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 750 | 850 |
|-----------------------------|-----|-----|-----|-----|-----|-----|-----|-----|------|------|
| $S_T^{\ell\nu} >$ [GeV] | 450 | 570 | 650 | 700 | 800 | 850 | 890 | 970 | 1000 | 1000 |
| $E_T^{\text{miss}} >$ [GeV] | 100 | 120 | 120 | 140 | 160 | 160 | 180 | 180 | 220 | 240 |
| $M_{\ell j} >$ [GeV] | 150 | 300 | 360 | 360 | 360 | 480 | 480 | 540 | 540 | 540 |

where N_H^{MC} is the number of MC events with $M_{\ell\ell} > 100$ GeV. The estimated number of $Z/\gamma^* + \text{jets}$ events is obtained with the selection criteria optimized for different leptoquark mass hypotheses, and it is used in the limit setting procedure.

The number and kinematic distributions for the $t\bar{t}$ events with two leptons of the same flavor are estimated from the number of data events that contain one electron and one muon. This type of background is expected to produce the

ee final state or the $\mu\mu$ final state with half the probability of the $e\mu$ final state. In the data the number of ee or $\mu\mu$ events is estimated to be

$$N_{ee(\mu\mu)} = \frac{1}{2} \times \frac{\epsilon_{e(\mu)}}{\epsilon_{\mu(e)}} \times \frac{\epsilon_{ee(\mu\mu)}^{\text{trig}}}{\epsilon_{e\mu}^{\text{trig}}} \times N_{e\mu}, \quad (2)$$

where ϵ_{μ} and ϵ_e are the muon and electron reconstruction and identification efficiencies and ϵ^{trig} are the HLT efficiencies to select ee , $\mu\mu$, and $e\mu$ events.

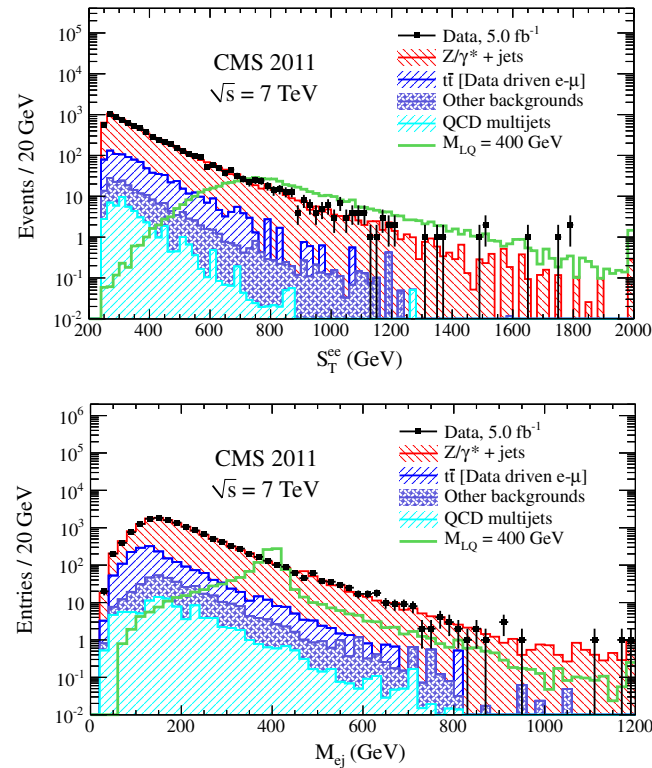


FIG. 2 (color online). $eejj$ channel: the distributions of S_T^{ee} (top) and of M_{ej} for each of the two electron-jet pairs (bottom) for events that pass the initial selection level. The data are indicated by the points, and the SM backgrounds are given as cumulative histograms. The expected contribution from a leptoquark signal with $M_{LQ} = 400$ GeV is also shown.

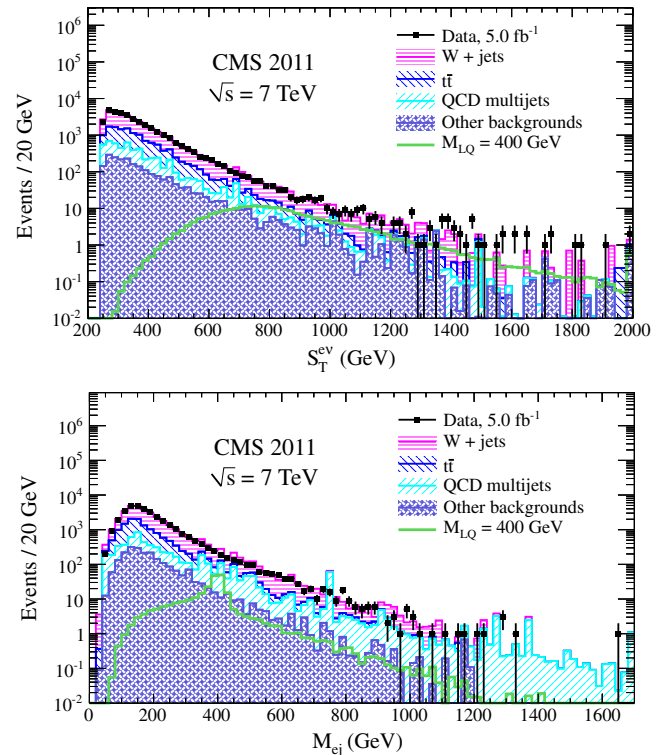


FIG. 3 (color online). $e\nu jj$ channel: the distributions of $S_T^{e\nu}$ (top) and of M_{ej} (bottom) for events that pass the initial selection level. The data are indicated by the points, and the SM backgrounds are given as cumulative histograms. The expected contribution from a leptoquark signal with $M_{LQ} = 400$ GeV is also shown.

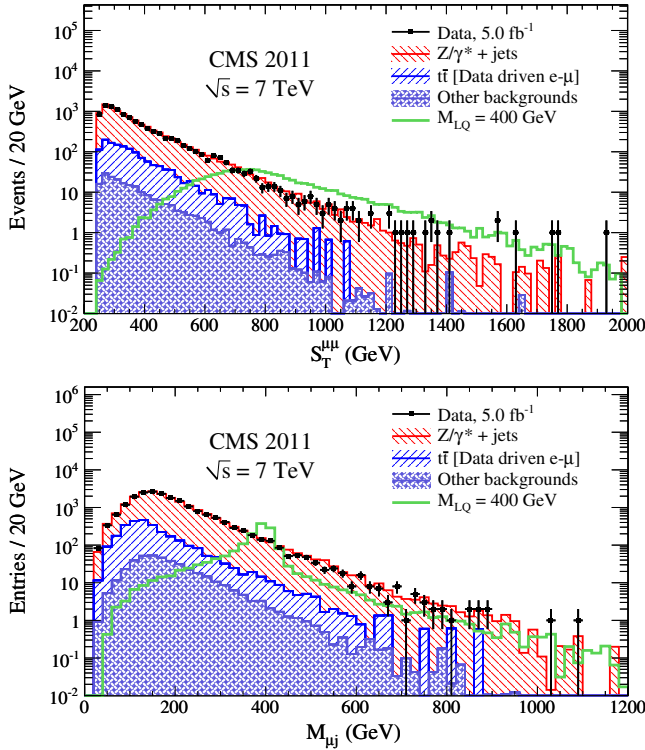


FIG. 4 (color online). $\mu\mu jj$ channel: the distributions of $S_T^{\mu\mu}$ (top) and of $M_{\mu j}$ for each of the two muon-jet pairs (bottom) for events that pass the initial selection level. The data are indicated by the points, and the SM backgrounds are given as cumulative histograms. The expected contribution from a leptoquark signal with $M_{LQ} = 400$ GeV is also shown.

No QCD multijet MC events pass the $\mu\mu jj$ final selection. A cross-check made using a data control sample containing same-sign muons confirms that the QCD multijet background is negligible in this channel.

For the first-generation leptoquark analyses the multijet background contribution is estimated from a data control sample as follows. The probability that an electron candidate passing loose electron requirements additionally passes all electron requirements is measured as a function of p_T and η in a data sample with one and only one electron candidate, two or more jets, and low E_T^{miss} . This sample is dominated by QCD multijet events and is similar in terms of jet activity to the $eejj$ and $evjj$ analysis samples. A correction for a small contamination of genuine electrons passing all electron requirements is derived from MC simulations. The QCD multijet background in the final $eejj$ ($evjj$) selection is predicted by applying twice (once) the above probability to a sample with two electron candidates (one electron candidate and large E_T^{miss}), and two or more jets, which satisfy all the requirements of the signal selections. The resulting estimate is $\sim 1\%$ ($\sim 8\%$) of the total background for the selections corresponding to the region of leptoquark masses where the exclusion limits are placed.

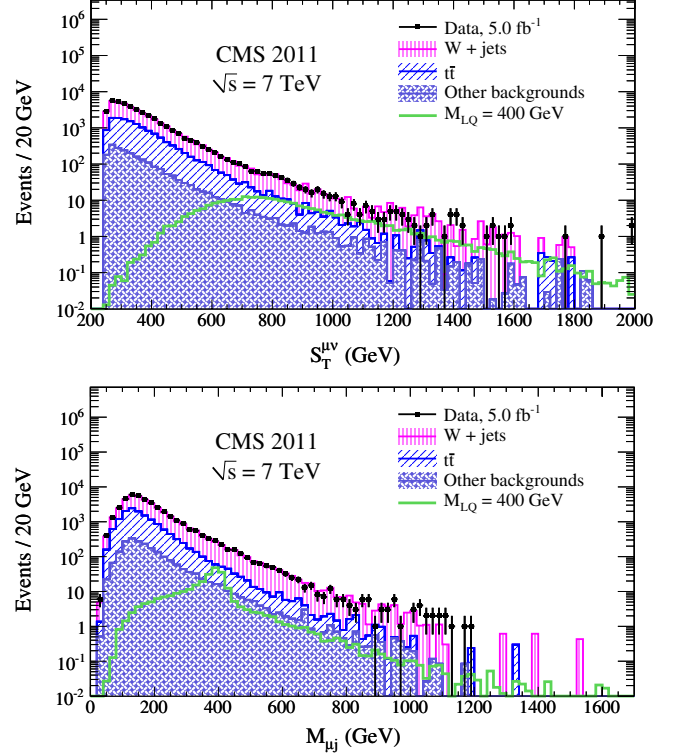


FIG. 5 (color online). $\mu\nu jj$ channel: the distributions of $S_T^{\mu\nu}$ (top) and of $M_{\mu j}$ (bottom) for events that pass the initial selection level. The data are indicated by the points, and the SM backgrounds are given as cumulative histograms. The expected contribution from a leptoquark signal with $M_{LQ} = 400$ GeV is also shown.

Contributions to the $\ell\ell jj$ background from $VV + \text{jets}$ processes and single-top production are small, and they are estimated using MC simulation.

In the $\ell\nu jj$ channel, the main backgrounds come from three sources: processes that lead to the production of a genuine W boson such as $W + \text{jets}$, $t\bar{t}$, single-top production, diboson processes (WW , WZ); instrumental background, mostly caused by the misidentification of jets as leptons in multijet processes, thus creating misidentified electrons or muons and misreconstructed E_T^{miss} in the final state; and Z boson production, such as $Z/\gamma^* + \text{jets}$ and ZZ processes. The contribution from the principal backgrounds, $W + \text{jets}$ and $t\bar{t}$, is estimated with MC simulation normalized to data at the initial selection level in the region $50 < M_T < 110$ GeV, where M_T is the transverse mass calculated from the lepton p_T and E_T^{miss} .

The region $50 < M_T < 110$ GeV is used to determine both the $W + \text{jets}$ and the $t\bar{t}$ normalization factors using two mutually exclusive selections (less than four jets or at least four jets with $p_T > 40$ GeV and $|\eta| < 2.4$) that separately enhance the samples with $W + \text{jets}$ and with $t\bar{t}$ events. The results of these two selections are used to form a system of equations:

$$\begin{aligned}
N_1 &= R_{t\bar{t}}N_{1,t\bar{t}} + R_W N_{1,W} + N_{1,\text{QCD}} + N_{1,o}; \\
N_2 &= R_{t\bar{t}}N_{2,t\bar{t}} + R_W N_{2,W} + N_{2,\text{QCD}} + N_{2,o},
\end{aligned}
\tag{3}$$

where N_i , $N_{i,W}$, $N_{i,t\bar{t}}$, $N_{i,o}$, and $N_{i,\text{QCD}}$ are the number of events in data, $W + \text{jets}$ MC simulation, $t\bar{t}$ MC simulation, other MC-simulated backgrounds, and QCD multijet events obtained from data, passing selection i . In the $e\nu jj$ analysis, the solution of the system yields the following normalization factors: $R_{t\bar{t}} = 0.82 \pm 0.04(\text{stat}) \pm 0.02(\text{syst})$

and $R_W = 1.21 \pm 0.03(\text{stat}) \pm 0.02(\text{syst})$, where the systematic errors reflect the uncertainties on the QCD multijet background estimate. In the $\mu\nu jj$ analysis, the normalization factors are $R_{t\bar{t}} = 0.84 \pm 0.03(\text{stat})$ and $R_W = 1.24 \pm 0.02(\text{stat})$.

The contribution from QCD multijet processes after all selection criteria are applied to the $\mu\nu jj$ sample is estimated to be negligible. No QCD MC events survive the full selection criteria optimized for any leptoquark mass hypothesis.

TABLE IV. Individual background (BG) sources, expected signal, data, and total background event yields after the initial (first row) and final selections for the $eejj$ analysis. Other BG includes single top, $W + \text{jets}$, $\gamma + \text{jets}$, and $VV + \text{jets}$. Only statistical uncertainties are reported.

| M_{LQ} | $Z + \text{jets}$ | $t\bar{t}$ | QCD | Other BG | LQ signal | Data | Total BG |
|-----------------|-------------------|-------------------------|-----------------------|-----------------|---------------------|------|------------------------|
| ... | 6234 ± 24 | 768 ± 19 | 49.59 ± 0.43 | 147.6 ± 2.3 | ... | 7201 | 7199 ± 31 |
| 400 | 35.7 ± 1.8 | 19.1 ± 3.1 | 0.877 ± 0.022 | 3.12 ± 0.56 | 487.4 ± 2.2 | 55 | 58.8 ± 3.6 |
| 500 | 6.55 ± 0.70 | 2.45 ± 1.10 | 0.192 ± 0.012 | 1.03 ± 0.42 | 109.30 ± 0.46 | 14 | 10.2 ± 1.4 |
| 550 | 4.65 ± 0.58 | 0.98 ± 0.69 | 0.139 ± 0.012 | 0.84 ± 0.42 | 57.35 ± 0.23 | 11 | 6.60 ± 0.99 |
| 600 | 3.04 ± 0.46 | 0.49 ± 0.49 | 0.088 ± 0.011 | 0.72 ± 0.41 | 30.95 ± 0.14 | 8 | 4.34 ± 0.79 |
| 650 | 2.14 ± 0.38 | 0.49 ± 0.49 | 0.073 ± 0.011 | 0.48 ± 0.40 | 16.998 ± 0.065 | 6 | 3.18 ± 0.74 |
| 750 | 1.04 ± 0.26 | $0.000^{+0.56}_{-0.00}$ | 0.0092 ± 0.0020 | 0.41 ± 0.40 | 5.526 ± 0.023 | 0 | $1.45^{+0.73}_{-0.47}$ |
| 850 | 0.81 ± 0.23 | $0.000^{+0.56}_{-0.00}$ | 0.00101 ± 0.00022 | 0.40 ± 0.40 | 1.9679 ± 0.0078 | 0 | $1.21^{+0.72}_{-0.46}$ |

TABLE V. Individual background (BG) sources, expected signal, data, and total background event yields after the initial (first row) and final selections for the $e\nu jj$ analysis. Other BG includes single top, $Z + \text{jets}$, $\gamma + \text{jets}$, and $VV + \text{jets}$. Only statistical uncertainties are reported.

| M_{LQ} | $W + \text{jets}$ | $t\bar{t}$ | QCD | Other | LQ signal | Data | Total BG |
|-----------------|-------------------|-----------------|-------------------|-----------------|---------------------|---------|-------------------|
| ... | $20\,108 \pm 99$ | 9301 ± 42 | 3267 ± 26 | 1913 ± 53 | ... | 34\,135 | $34\,590 \pm 120$ |
| 400 | 28.7 ± 3.6 | 17.5 ± 1.8 | 6.20 ± 0.46 | 6.01 ± 0.77 | 126.01 ± 0.82 | 43 | 58.4 ± 4.1 |
| 500 | 13.3 ± 2.4 | 6.3 ± 1.1 | 1.72 ± 0.22 | 2.80 ± 0.37 | 34.70 ± 0.23 | 18 | 24.2 ± 2.6 |
| 550 | 2.98 ± 0.95 | 3.38 ± 0.82 | 0.65 ± 0.10 | 1.46 ± 0.26 | 16.25 ± 0.10 | 10 | 8.5 ± 1.3 |
| 600 | 2.45 ± 0.87 | 2.33 ± 0.67 | 0.57 ± 0.10 | 1.29 ± 0.25 | 9.442 ± 0.056 | 6 | 6.6 ± 1.1 |
| 650 | 2.03 ± 0.83 | 1.01 ± 0.41 | 0.335 ± 0.079 | 0.76 ± 0.20 | 5.202 ± 0.032 | 4 | 4.14 ± 0.95 |
| 750 | 1.45 ± 0.65 | 0.62 ± 0.31 | 0.287 ± 0.080 | 0.65 ± 0.18 | 1.851 ± 0.010 | 4 | 3.01 ± 0.75 |
| 850 | 1.22 ± 0.61 | 0.62 ± 0.31 | 0.251 ± 0.078 | 0.61 ± 0.19 | 0.6973 ± 0.0037 | 4 | 2.70 ± 0.71 |

TABLE VI. Individual background (BG) sources, expected signal, data, and total background event yields after the initial (first row) and final selections for the $\mu\mu jj$ analysis. Other BG includes single top, $W + \text{jets}$, and $VV + \text{jets}$. Only statistical uncertainties are reported.

| M_{LQ} | $Z + \text{jets}$ | $t\bar{t}$ | Other BG | LQ signal | Data | Total BG |
|-----------------|-------------------|------------------------|------------------------|-------------------|------|----------------------|
| ... | 8644 ± 47 | 1218 ± 27 | 201.7 ± 2.8 | ... | 9897 | $10\,063 \pm 54$ |
| 400 | 46.9 ± 2.4 | 30.1 ± 4.2 | $3.58^{+0.70}_{-0.40}$ | 629.3 ± 4.0 | 68 | $80.6^{+4.9}_{-4.9}$ |
| 500 | 10.4 ± 1.1 | 4.1 ± 1.6 | $0.89^{+0.62}_{-0.21}$ | 136.73 ± 0.86 | 14 | $15.4^{+2.0}_{-1.9}$ |
| 550 | 7.29 ± 0.94 | 2.4 ± 1.2 | $0.53^{+0.60}_{-0.17}$ | 70.49 ± 0.40 | 9 | $10.2^{+1.6}_{-1.5}$ |
| 600 | 5.03 ± 0.75 | 0.59 ± 0.59 | $0.47^{+0.60}_{-0.16}$ | 37.39 ± 0.22 | 6 | $6.1^{+1.1}_{-1.0}$ |
| 650 | 3.82 ± 0.65 | 0.59 ± 0.59 | $0.24^{+0.59}_{-0.12}$ | 20.56 ± 0.13 | 5 | $4.7^{+1.1}_{-0.9}$ |
| 750 | 2.03 ± 0.47 | $0.00^{+0.67}_{-0.00}$ | $0.09^{+0.59}_{-0.08}$ | 6.529 ± 0.038 | 1 | $2.1^{+1.0}_{-0.5}$ |
| 850 | 1.56 ± 0.42 | $0.00^{+0.67}_{-0.00}$ | $0.08^{+0.59}_{-0.08}$ | 2.327 ± 0.014 | 0 | $1.6^{+1.0}_{-0.4}$ |

TABLE VIII. Systematic uncertainties and their effects on signal (S) and background (B) in all channels for the $M_{LQ} = 600$ GeV final selection. All uncertainties are symmetric.

| Systematic uncertainties | Magnitude [%] | $eejj$ | | $\mu\mu jj$ | | $evjj$ | | $\mu\nu jj$ | |
|--------------------------|---------------|---------|---------|-------------|---------|---------|---------|-------------|---------|
| | | S [%] | B [%] | S [%] | B [%] | S [%] | B [%] | S [%] | B [%] |
| Jet energy scale | 4 | 2 | 1 | 1 | 1 | 5 | 8.5 | 3 | 7 |
| Background modeling | ... | ... | 11 | ... | 9 | ... | 11 | ... | 10 |
| Electron energy scale | 1(3) | 1 | 6 | ... | ... | 1.5 | 4.5 | ... | ... |
| Muon momentum scale | 1 | ... | ... | 0.5 | 4 | ... | ... | 1 | 2 |
| Muon Reco/ID/Iso | 1 | ... | ... | 2 | ... | ... | ... | 1 | ... |
| Jet resolution | (5–14) | 0.5 | 0.5 | <0.5 | <0.5 | <0.5 | 2 | <0.5 | 2.5 |
| Electron resolution | 1(3) | 0.5 | 1 | ... | ... | <0.5 | 1.5 | ... | ... |
| Muon resolution | 4 | ... | ... | <0.5 | 5 | ... | ... | <0.5 | 1 |
| Pileup | 8 | 1 | 1 | 0.5 | <0.5 | 1 | 1.5 | 1 | 4 |
| Integrated luminosity | 2.2 | 2.2 | ... | 2.2 | ... | 2.2 | ... | 2.2 | ... |
| Total | | 3 | 13 | 3 | 11 | 6 | 15 | 4 | 13 |

However, as multijet processes are difficult to accurately model by MC simulation, several cross-checks are made with data control samples to ensure that the QCD multijet background in the $\mu\nu jj$ analysis is negligible. The method used to determine the QCD multijet background in the $evjj$ analysis is similar to the one used for the $eejj$ channel.

V. EVENT SELECTION OPTIMIZATION

After the initial selection, the sensitivity of the search is optimized by maximizing the Gaussian signal significance $S/\sqrt{S+B}$ in all channels. Optimized thresholds on the following variables are applied for each leptoquark mass hypothesis in the $\ell\ell jj$ channels: $M_{\ell\ell}$, $S_T^{\ell\ell}$, and $M_{\ell j}^{\min}$. The invariant mass of the dilepton pair, $M_{\ell\ell}$, is used to remove the majority of the contribution from the $Z/\gamma^* + \text{jets}$ background. The variable $M_{\ell j}^{\min}$ is defined as the smaller lepton-jet invariant mass for the assignment of jets and leptons to leptoquarks, which minimizes the $LQ\text{-}\bar{L}\bar{Q}$ invariant mass difference.

Thresholds on the following variables are optimized for each leptoquark mass hypothesis in the $\ell\nu jj$ channels: E_T^{miss} , $S_T^{\ell\nu}$, and $M_{\ell j}$. A minimum threshold on E_T^{miss} is used, primarily to reduce the dominant $W + \text{jets}$ background. The variable $M_{\ell j}$ is defined as the invariant mass of the lepton-jet combination, which minimizes the $LQ\text{-}\bar{L}\bar{Q}$ transverse mass difference. In addition, a lower threshold is applied on the transverse mass of the lepton (electron or muon) and E_T^{miss} in the event, $M_T > 120$ GeV.

The resulting optimized thresholds are summarized in Tables II and III for the $\ell\ell jj$ and the $\ell\nu jj$ channels, respectively.

After the initial selection criteria are applied, the yields in data are found to be consistent with SM predictions. Distributions of variables used in the final selection for the $eejj$, $evjj$, $\mu\mu jj$, and $\mu\nu jj$ analyses are shown in Figs. 2–5.

The number of events selected in data and estimated backgrounds are then compared at different stages of

selection. This information is shown in Tables IV, V, VI, and VII for the initial selection and for the final selection for each channel separately.

Data and background predictions after final selection are also shown in Figs. 6–9, which compare S_T and the best combination for the lepton-jet invariant mass for a signal

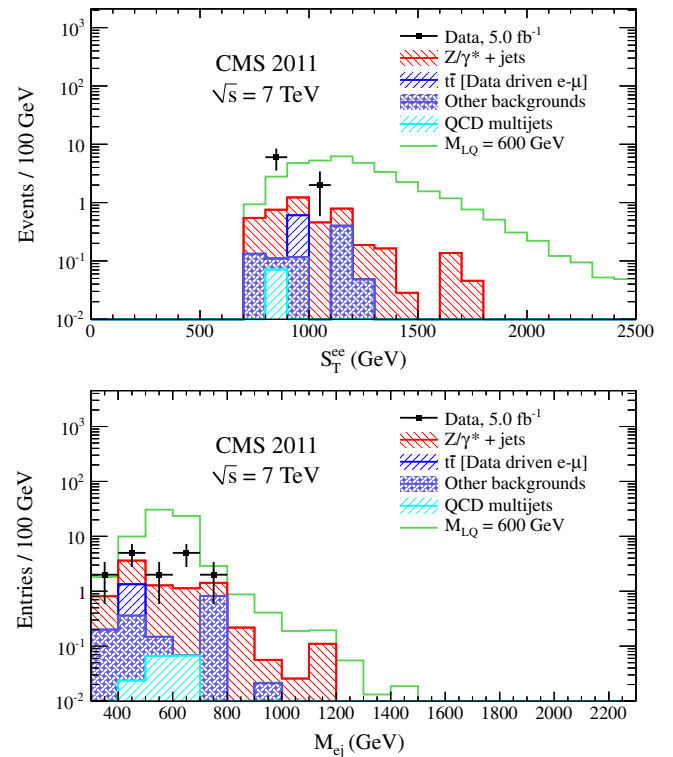


FIG. 6 (color online). $eejj$ channel: the distributions of S_T^{ee} (top) and of M_{ej} for each of the two electron-jet pairs (bottom) for events that pass the final selection criteria optimized for a signal leptoquark mass of 600 GeV. The data are indicated by the points, and the SM backgrounds are given as cumulative histograms. The expected contribution from a leptoquark signal with $M_{LQ} = 600$ GeV is also shown.

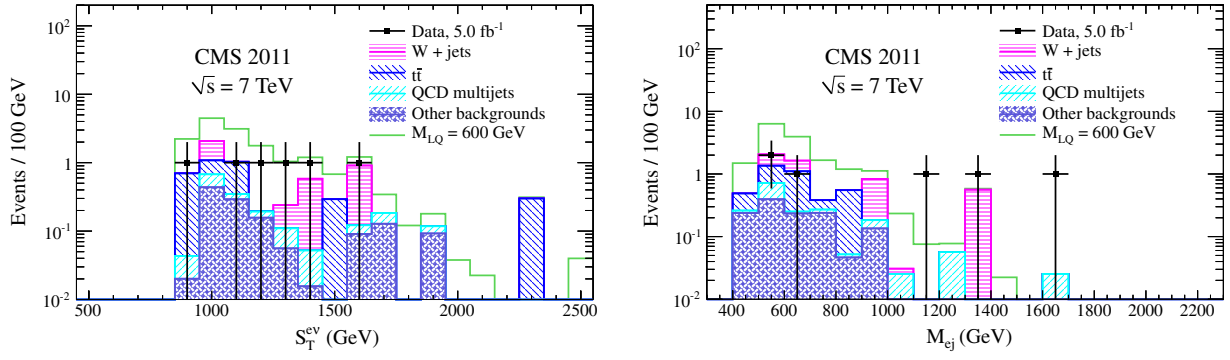


FIG. 7 (color online). $evjj$ channel: the distributions of $S_T^{e\nu}$ (left) and of M_{ej} (right) for events that pass the final selection criteria optimized for a signal leptoquark mass of 600 GeV. The data are indicated by the points, and the SM backgrounds are given as cumulative histograms. The expected contribution from a leptoquark signal with $M_{LQ} = 600$ GeV is also shown.

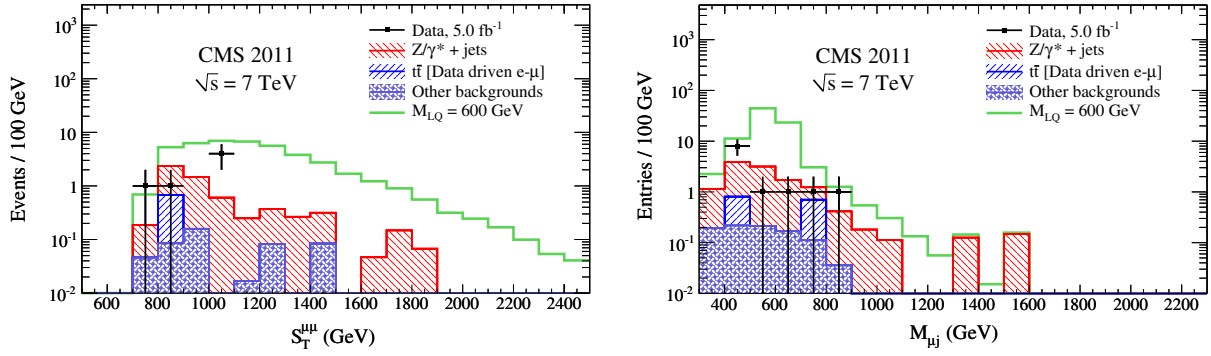


FIG. 8 (color online). $\mu\mu jj$ channel: the distributions of $S_T^{\mu\mu}$ (left) and of $M_{\mu j}$ for each of the two muon-jet pairs (right) for events that pass the final selection criteria optimized for a signal leptoquark mass of 600 GeV. The data are indicated by the points, and the SM backgrounds are given as cumulative histograms. The expected contribution from a leptoquark signal with $M_{LQ} = 600$ GeV is also shown.

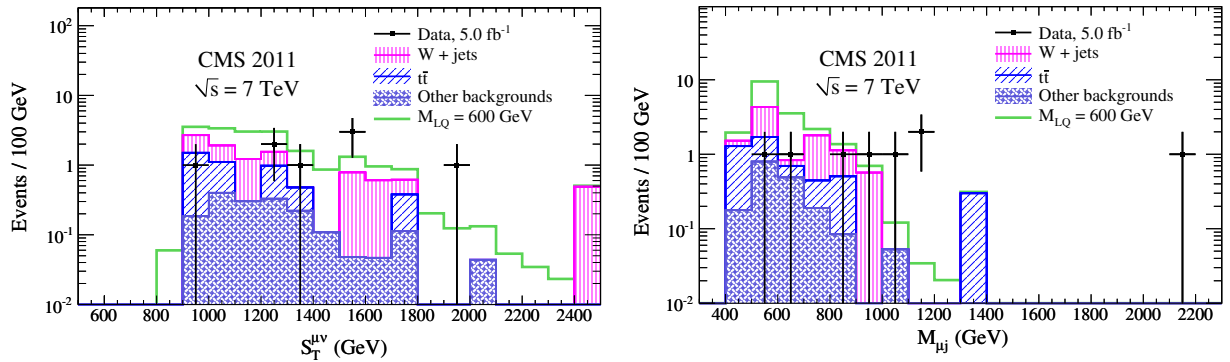


FIG. 9 (color online). $\mu\nu jj$ channel: the distributions of $S_T^{\mu\nu}$ (left) and of $M_{\mu j}$ (right) for events that pass the final selection criteria optimized for a signal leptoquark mass of 600 GeV. The data are indicated by the points, and the SM backgrounds are given as cumulative histograms. The expected contribution from a leptoquark signal with $M_{LQ} = 600$ GeV is also shown.

leptoquark mass of 600 GeV in the four decay channels considered.

VI. SYSTEMATIC UNCERTAINTIES

The uncertainty on the integrated luminosity is taken as 2.2% [30].

The statistical uncertainties on the values of R_Z (R_W) after initial selection requirements are used as an estimate

of the uncertainty on the normalization of the $Z/\gamma^* + \text{jets}$ ($W + \text{jets}$) backgrounds. The uncertainty on the shape of the $Z/\gamma^* + \text{jets}$ and $W + \text{jets}$ distributions is calculated to be 15% (10%) and 20% (11%) for first (second) generation, respectively, by comparing the predictions of MADGRAPH samples produced with factorization or renormalization scales and matrix element-parton shower matching threshold varied up and down by a factor of 2.

TABLE VII. Individual background (BG) sources, expected signal, data, and total background event yields after the initial (first row) and final selections for the $\mu\nu jj$ analysis. Other BG includes single top, Z + jets, and VV + jets. Only statistical uncertainties are reported.

| M_{LQ} | W + jets | $t\bar{t}$ | Other BG | LQ signal | Data | Total BG |
|----------|-------------------|------------------|-----------------|---------------------|--------|-------------------|
| ... | $23\,910 \pm 161$ | $12\,254 \pm 58$ | 2146 ± 18 | ... | 39 585 | $38\,311 \pm 173$ |
| 400 | 31.8 ± 4.4 | 23.9 ± 2.6 | 5.68 ± 0.64 | 118.3 ± 1.2 | 60 | 61.5 ± 5.2 |
| 500 | 18.0 ± 3.3 | 9.6 ± 1.7 | 3.38 ± 0.51 | 33.94 ± 0.28 | 26 | 31.0 ± 3.7 |
| 550 | 5.7 ± 1.8 | 4.2 ± 1.1 | 2.21 ± 0.43 | 15.51 ± 0.14 | 12 | 12.1 ± 2.1 |
| 600 | 5.5 ± 1.8 | 3.2 ± 1.0 | 1.80 ± 0.39 | 9.23 ± 0.08 | 8 | 10.5 ± 2.1 |
| 650 | 2.9 ± 1.2 | 1.14 ± 0.59 | 1.13 ± 0.31 | 4.964 ± 0.043 | 7 | 5.1 ± 1.3 |
| 750 | 2.9 ± 1.2 | 0.51 ± 0.36 | 0.99 ± 0.29 | 1.840 ± 0.015 | 6 | 4.4 ± 1.2 |
| 850 | 2.7 ± 1.1 | 0.51 ± 0.36 | 0.76 ± 0.23 | 0.6906 ± 0.0051 | 6 | 4.0 ± 1.2 |

The uncertainty on the estimate of the $t\bar{t}$ background in the $eejj$ and $\mu\mu jj$ channels is derived from the statistical uncertainty of the $e\mu jj$ data sample and the ratio of electron and muon reconstruction uncertainties, which is calculated to be 2% and 3%, respectively. In addition, an uncertainty of 7% is assigned based on the estimated contamination from sources other than $t\bar{t}$ in the data sample containing one electron and one muon. A 5.5% (5%) uncertainty on the normalization of the estimated $t\bar{t}$ background in the $e\nu jj$ ($\mu\nu jj$) channel is given by the statistical uncertainty on the value of $R_{t\bar{t}}$ after the initial selection requirements. A 10% (10%) uncertainty on the shape of the $t\bar{t}$ background distribution in the $e\nu jj$ ($\mu\nu jj$) channel is estimated by comparing the predictions of MADGRAPH samples produced with factorization or renormalization scales and matrix element-parton shower matching thresholds varied up and down by a factor of 2.

A systematic uncertainty of 50% (25%) on the QCD multijet background estimate for the $eejj$ ($e\nu jj$) channel is estimated from the difference between the number of observed data and the background prediction in a QCD multijet-enriched data sample with lower jet multiplicity.

PDF uncertainties on the theoretical cross section of leptoquark production and on the final selection acceptance have been calculated using the PDF4LHC [31] prescriptions, with PDF and α_s variations of the MSTW2008 [32], CTEQ6.6 [33], and NNPDF2.0 [34] PDF sets taken into account. Uncertainties on the cross section vary from 10% to 30% for leptoquarks in the mass range of 200–900 GeV, while the effect of the PDF uncertainties on signal acceptance varies from 1% to 3%. The PDF uncertainties are not considered for background sources with uncertainties determined from data. An uncertainty on the modeling of pileup interactions in the MC simulation is determined by varying the mean of the distribution of pileup interactions by 8%.

Energy and momentum scale uncertainties are estimated by assigning a 4% uncertainty on the jet energy scale, a 1% (3%) uncertainty on the electron energy scale for the barrel (end cap) region of ECAL, and a 1% uncertainty on the muon momentum scale. The effect of electron energy, muon momentum, and jet energy resolution on expected

signal and backgrounds is assessed by smearing the electron energy by 1% and 3% in the barrel and end caps, respectively, by smearing the muon momentum by 4%, and by varying the jet energy resolution by an η -dependent value in the range 5%–14%. In the $\ell\nu jj$ analyses, the uncertainty on the energy and momentum scales and resolutions is propagated to the measurement of E_T^{miss} . The effect of these uncertainties is calculated for the (minor) background sources for which no data rescaling is applied. For the background sources for which data rescaling is applied, residual uncertainties are calculated (i.e. relative to the initial selection used to derive the rescaling factor).

Recent measurements of the muon reconstruction, identification, trigger, and isolation efficiencies using $Z \rightarrow \mu\mu$ events show very good agreement between data and MC events [35]. An $\sim 1\%$ discrepancy is observed in the data-to-MC comparison of the muon trigger efficiency. This discrepancy is taken as a systematic uncertainty per muon, assigned to both signal and estimated background. The electron trigger and reconstruction and identification uncertainties contribute 3% (4%) to the uncertainty in both signal and estimated background for the $eejj$ ($e\nu jj$) channel.

The systematic uncertainties and their effects on signal and background are summarized in Table VIII for all channels, corresponding to the final selection optimized for $M_{LQ} = 600$ GeV.

VII. RESULTS

The number of observed events in data passing the full selection criteria is consistent with the SM background prediction in all decay channels. An upper limit on the leptoquark pair-production cross section is therefore set using the CL_s modified frequentist approach [17,18]. A log-normal probability function is used to integrate over the systematic uncertainties. Uncertainties of a statistical nature are described with Γ distributions with widths determined by the number of events simulated in MC samples or observed in data control regions.

The 95% CL upper limits on $\sigma \times \beta^2$ or $\sigma \times 2\beta(1 - \beta)$ as a function of leptoquark mass are shown together with the NLO predictions for the scalar leptoquark

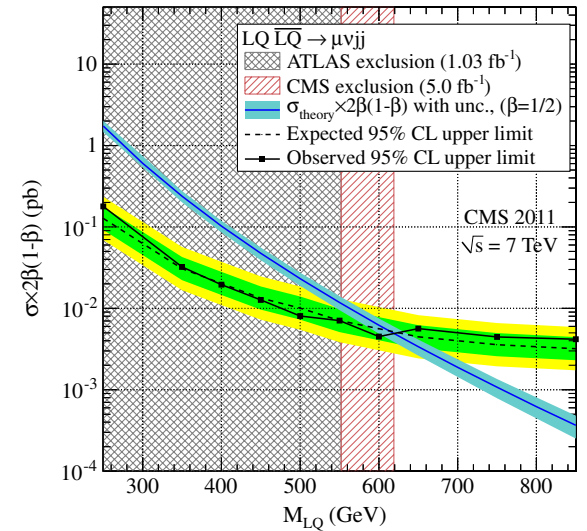
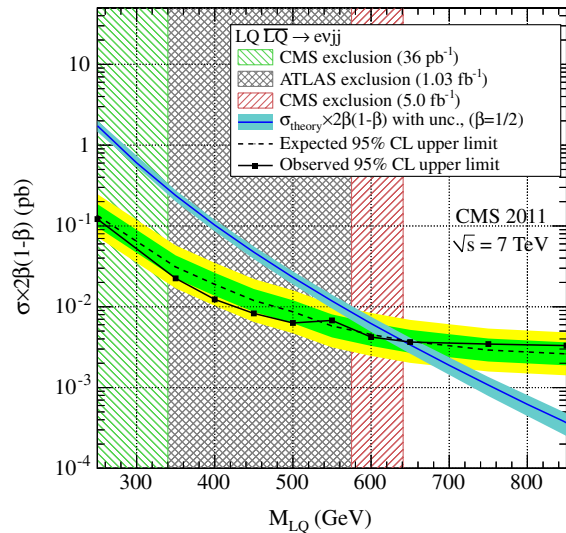
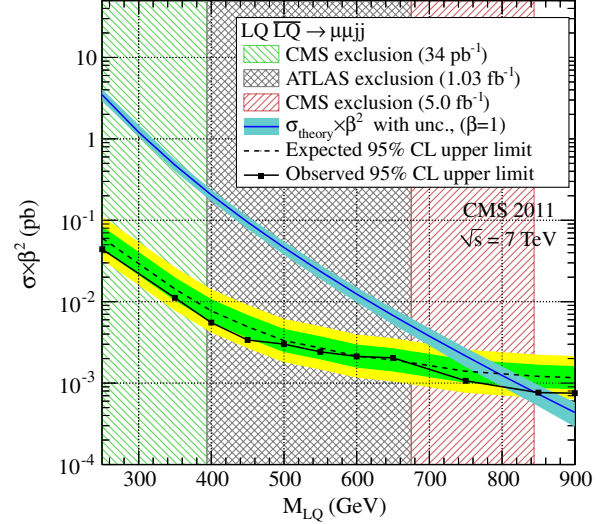
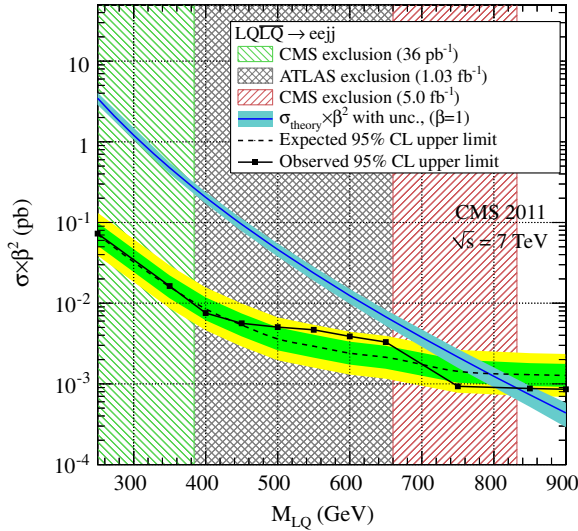


FIG. 10 (color online). Top (bottom) frame: the expected and observed upper limits at 95% CL on the leptoquark pair-production cross section times β^2 ($2\beta(1-\beta)$) as a function of the first-generation leptoquark mass obtained with the $eejj$ ($e\nu jj$) analysis. The expected limits and uncertainty bands represent the median expected limits and the 68% and 95% confidence intervals. The systematic uncertainties reported in Table VIII are included in the calculation. The left and middle shaded regions are excluded by the current ATLAS limit [15] and CMS limits [12,13] for $\beta = 1(0.5)$ in the $eejj$ ($e\nu jj$) channel. The right shaded regions are excluded by these results. The σ_{theory} curves and their bands represent, respectively, the theoretical scalar leptoquark pair-production cross section, and the uncertainties attributable to the choice of PDF and renormalization/factorization scales.

pair-production cross section in Figs. 10 and 11. The theoretical cross sections are represented for different values of the renormalization and factorization scale, μ , varied between half and twice the leptoquark mass (blue shaded region). The PDF uncertainties are taken into account in the theoretical cross section values.

FIG. 11 (color online). Top (bottom) frame: the expected and observed upper limits at 95% CL on the leptoquark pair-production cross section times β^2 ($2\beta(1-\beta)$) as a function of the second-generation leptoquark mass obtained with the $\mu\mu jj$ ($\mu\nu jj$) analysis. The expected limits and uncertainty bands represent the median expected limits and the 68% and 95% confidence intervals. The systematic uncertainties reported in Table VIII are included in the calculation. The left and middle shaded regions in the top frame are excluded by the current ATLAS limit [14] and CMS limit [11] for $\beta = 1$ in the $\mu\mu jj$ channel only. The left shaded region in the bottom frame is excluded by the current ATLAS limit [14] for $\beta = 0.5$ in the $\mu\nu jj$ channel only. The right shaded regions are excluded by these results. The σ_{theory} curves and their bands represent, respectively, the theoretical scalar leptoquark pair-production cross section, and the uncertainties attributable to the choice of PDF and renormalization/factorization scales.

By comparing the observed upper limit with the theoretical cross section values, first-generation scalar leptoquarks with masses less than 830 (640) GeV are excluded with the assumption that $\beta = 1(0.5)$. Similarly,

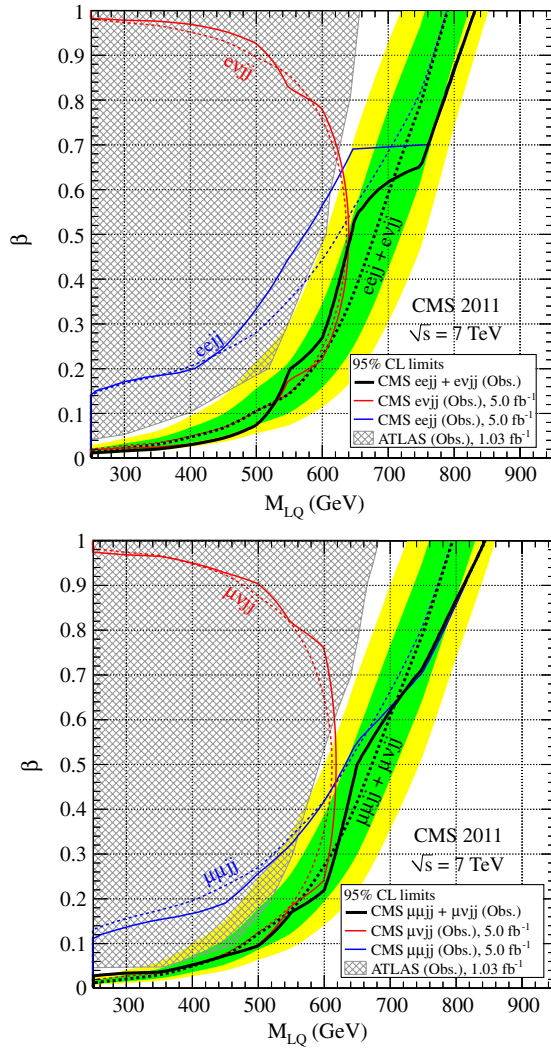


FIG. 12 (color online). Top (bottom) frame: the expected and observed exclusion limits at 95% CL on the first- (second-) generation leptoquark hypothesis in the β versus mass plane using the central value of signal cross section for the individual $eejj$ and $evjj$ ($\mu\mu jj$ and $\mu\nu jj$) channels and their combination. The dark green and light yellow expected limit uncertainty bands represent the 68% and 95% confidence intervals. Solid lines represent the observed limits in each channel, and dashed lines represent the expected limits. The systematic uncertainties reported in Table VIII are included in the calculation. The shaded region is excluded by the current ATLAS limits [14,15].

second-generation scalar leptoquarks with masses less than 840 (620) GeV are excluded for $\beta = 1(0.5)$. This is to be compared with median expected limits of 790 (640) GeV for first-generation scalar leptoquarks and 800 (610) GeV for second-generation scalar leptoquarks.

The observed and expected limits on the branching fraction β as a function of leptoquark mass can be further improved using the combination of the $\ell\ell jj$ and $\ell\nu jj$ channels, as shown in Fig. 12. These combinations lead to the exclusion of first- and second-generation scalar leptoquarks with masses less than 640 and 650 GeV for

$\beta = 0.5$, compared with median expected limits of 680 and 670 GeV.

VIII. SUMMARY

In summary, a search for pair production of first- and second-generation scalar leptoquarks has been performed in decay channels with either two charged leptons of the same flavor (electrons or muons) and at least two jets, or a single charged lepton (electron or muon), missing transverse energy, and at least two jets, using 7 TeV proton-proton collisions data corresponding to an integrated luminosity of 5 fb^{-1} . The selection criteria have been optimized for each leptoquark signal mass hypothesis. The number of observed candidates for each hypothesis agree with the estimated number of background events. The CL_s modified frequentist approach has been used to set limits on the leptoquark cross section times the branching fraction for the decay of a leptoquark pair. At 95% confidence level, the pair production of first- and second-generation leptoquarks is excluded with masses below 830 (640) GeV and 840 (650) GeV for $\beta = 1(0.5)$. These are the most stringent limits to date.

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S. Chatrchyan,¹ V. Khachatryan,¹ A. M. Sirunyan,¹ A. Tumasyan,¹ W. Adam,² E. Aguilo,² T. Bergauer,² M. Dragicevic,² J. Erö,² C. Fabjan,^{2,b} M. Friedl,² R. Frühwirth,^{2,b} V. M. Ghete,² J. Hammer,² N. Hörmann,² J. Hrubec,² M. Jeitler,^{2,b} W. Kiesenhofer,² V. Knünz,² M. Krammer,^{2,b} I. Krätschmer,² D. Liko,² I. Mikulec,² M. Pernicka,^{2,a} B. Rabbaran,² C. Rohringer,² H. Rohringer,² R. Schöfbeck,² J. Strauss,² A. Taurok,² W. Waltenberger,² G. Walzel,² E. Widl,² C.-E. Wulz,^{2,b} V. Mossolov,³ N. Shumeiko,³ J. Suarez Gonzalez,³ M. Bansal,⁴ S. Bansal,⁴ T. Cornelis,⁴ E. A. De Wolf,⁴ X. Janssen,⁴ S. Luyckx,⁴ L. Mucibello,⁴ S. Ochesanu,⁴ B. Roland,⁴ R. Rougny,⁴ M. Selvaggi,⁴ Z. Staykova,⁴ H. Van Haevermaet,⁴ P. Van Mechelen,⁴ N. Van Remortel,⁴ A. Van Spilbeeck,⁴ F. Blekman,⁵ S. Blyweert,⁵ J. D'Hondt,⁵ R. Gonzalez Suarez,⁵ A. Kalogeropoulos,⁵ M. Maes,⁵

A. Olbrechts,⁵ W. Van Doninck,⁵ P. Van Mulders,⁵ G. P. Van Onsem,⁵ I. Vilella,⁵ B. Clerbaux,⁶ G. De Lentdecker,⁶ V. Dero,⁶ A. P. R. Gay,⁶ T. Hreus,⁶ A. Léonard,⁶ P. E. Marage,⁶ T. Reis,⁶ L. Thomas,⁶ G. Vander Marcken,⁶ C. Vander Velde,⁶ P. Vanlaer,⁶ J. Wang,⁶ V. Adler,⁷ K. Beernaert,⁷ A. Cimmino,⁷ S. Costantini,⁷ G. Garcia,⁷ M. Grunewald,⁷ B. Klein,⁷ J. Lellouch,⁷ A. Marinov,⁷ J. McCartin,⁷ A. A. Ocampo Rios,⁷ D. Ryckbosch,⁷ N. Strobbe,⁷ F. Thyssen,⁷ M. Tytgat,⁷ P. Verwilligen,⁷ S. Walsh,⁷ E. Yazgan,⁷ N. Zaganidis,⁷ S. Basesmez,⁸ G. Bruno,⁸ R. Castello,⁸ L. Ceard,⁸ C. Delaere,⁸ T. du Pree,⁸ D. Favart,⁸ L. Forthomme,⁸ A. Giammanco,^{8,c} J. Hollar,⁸ V. Lemaitre,⁸ J. Liao,⁸ O. Militaru,⁸ C. Nuttens,⁸ D. Pagano,⁸ A. Pin,⁸ K. Piotrkowski,⁸ N. Schul,⁸ J. M. Vizan Garcia,⁸ N. Belyi,⁹ T. Caeberts,⁹ E. Daubie,⁹ G. H. Hammad,⁹ G. A. Alves,¹⁰ M. Correa Martins Junior,¹⁰ D. De Jesus Damiao,¹⁰ T. Martins,¹⁰ M. E. Pol,¹⁰ M. H. G. Souza,¹⁰ W. L. Aldá Júnior,¹¹ W. Carvalho,¹¹ A. Custódio,¹¹ E. M. Da Costa,¹¹ C. De Oliveira Martins,¹¹ S. Fonseca De Souza,¹¹ D. Matos Figueiredo,¹¹ L. Mundim,¹¹ H. Nogima,¹¹ V. Oguri,¹¹ W. L. Prado Da Silva,¹¹ A. Santoro,¹¹ L. Soares Jorge,¹¹ A. Sznajder,¹¹ T. S. Anjos,^{12,d} C. A. Bernardes,^{12,d} F. A. Dias,^{12,e} T. R. Fernandez Perez Tomei,¹² E. M. Gregores,^{12,d} C. Lagana,¹² F. Marinho,¹² P. G. Mercadante,^{12,d} S. F. Novaes,¹² Sandra S. Padula,¹² V. Genchev,^{13,f} P. Iaydjiev,^{13,f} S. Piperov,¹³ M. Rodozov,¹³ S. Stoykova,¹³ G. Sultanov,¹³ V. Tcholakov,¹³ R. Trayanov,¹³ M. Vutova,¹³ A. Dimitrov,¹⁴ R. Hadjiiska,¹⁴ V. Kozhuharov,¹⁴ L. Litov,¹⁴ B. Pavlov,¹⁴ P. Petkov,¹⁴ J. G. Bian,¹⁵ G. M. Chen,¹⁵ H. S. Chen,¹⁵ C. H. Jiang,¹⁵ D. Liang,¹⁵ S. Liang,¹⁵ X. Meng,¹⁵ J. Tao,¹⁵ J. Wang,¹⁵ X. Wang,¹⁵ Z. Wang,¹⁵ H. Xiao,¹⁵ M. Xu,¹⁵ J. Zang,¹⁵ Z. Zhang,¹⁵ C. Asawatangtrakuldee,¹⁶ Y. Ban,¹⁶ Y. Guo,¹⁶ W. Li,¹⁶ S. Liu,¹⁶ Y. Mao,¹⁶ S. J. Qian,¹⁶ H. Teng,¹⁶ D. Wang,¹⁶ L. Zhang,¹⁶ W. Zou,¹⁶ C. Avila,¹⁷ J. P. Gomez,¹⁷ B. Gomez Moreno,¹⁷ A. F. Osorio Oliveros,¹⁷ J. C. Sanabria,¹⁷ N. Godinovic,¹⁸ D. Lelas,¹⁸ R. Plestina,^{18,g} D. Polic,¹⁸ I. Puljak,^{18,f} Z. Antunovic,¹⁹ M. Kovac,¹⁹ V. Brigljevic,²⁰ S. Duric,²⁰ K. Kadija,²⁰ J. Luetic,²⁰ S. Morovic,²⁰ A. Attikis,²¹ M. Galanti,²¹ G. Mavromanolakis,²¹ J. Mousa,²¹ C. Nicolaou,²¹ F. Ptochos,²¹ P. A. Razis,²¹ M. Finger,²² M. Finger, Jr.,²² Y. Assran,^{23,h} S. Elgammal,^{23,i} A. Ellithi Kamel,^{23,j} S. Khalil,^{23,i} M. A. Mahmoud,^{23,k} A. Radi,^{23,l,m} M. Kadastik,²⁴ M. Müntel,²⁴ M. Raidal,²⁴ L. Rebane,²⁴ A. Tiko,²⁴ P. Eerola,²⁵ G. Fedi,²⁵ M. Voutilainen,²⁵ J. Härkönen,²⁶ A. Heikkinen,²⁶ V. Karimäki,²⁶ R. Kinnunen,²⁶ M. J. Kortelainen,²⁶ T. Lampén,²⁶ K. Lassila-Perini,²⁶ S. Lehti,²⁶ T. Lindén,²⁶ P. Luukka,²⁶ T. Mäenpää,²⁶ T. Peltola,²⁶ E. Tuominen,²⁶ J. Tuominiemi,²⁶ E. Tuovinen,²⁶ D. Ungaro,²⁶ L. Wendland,²⁶ K. Banzuzi,²⁷ A. Karjalainen,²⁷ A. Korpela,²⁷ T. Tuuva,²⁷ M. Besancon,²⁸ S. Choudhury,²⁸ M. Dejardin,²⁸ D. Denegri,²⁸ B. Fabbro,²⁸ J. L. Faure,²⁸ F. Ferri,²⁸ S. Ganjour,²⁸ A. Givernaud,²⁸ P. Gras,²⁸ G. Hamel de Monchenault,²⁸ P. Jarry,²⁸ E. Locci,²⁸ J. Malcles,²⁸ L. Millischer,²⁸ A. Nayak,²⁸ J. Rander,²⁸ A. Rosowsky,²⁸ I. Shreyber,²⁸ M. Titov,²⁸ S. Baffioni,²⁹ F. Beaudette,²⁹ L. Benhabib,²⁹ L. Bianchini,²⁹ M. Bluj,^{29,n} C. Broutin,²⁹ P. Busson,²⁹ C. Charlot,²⁹ N. Daci,²⁹ T. Dahms,²⁹ L. Dobrzynski,²⁹ R. Granier de Cassagnac,²⁹ M. Haguenaer,²⁹ P. Miné,²⁹ C. Mironov,²⁹ I. N. Naranjo,²⁹ M. Nguyen,²⁹ C. Ochando,²⁹ P. Paganini,²⁹ D. Sabes,²⁹ R. Salerno,²⁹ Y. Sirois,²⁹ C. Veelken,²⁹ A. Zabi,²⁹ J.-L. Agram,^{30,o} J. Andrea,³⁰ D. Bloch,³⁰ D. Bodin,³⁰ J.-M. Brom,³⁰ M. Cardaci,³⁰ E. C. Chabert,³⁰ C. Collard,³⁰ E. Conte,^{30,o} F. Drouhin,^{30,o} C. Ferro,³⁰ J.-C. Fontaine,^{30,o} D. Gelé,³⁰ U. Goerlach,³⁰ P. Juillot,³⁰ A.-C. Le Bihan,³⁰ P. Van Hove,³⁰ F. Fassi,³¹ D. Mercier,³¹ S. Beauceron,³² N. Beaupere,³² O. Bondu,³² G. Boudoul,³² J. Chasserat,³² R. Chierici,^{32,f} D. Contardo,³² P. Depasse,³² H. El Mamouni,³² J. Fay,³² S. Gascon,³² M. Gouzevitch,³² B. Ille,³² T. Kurca,³² M. Lethuillier,³² L. Mirabito,³² S. Perries,³² L. Sgandurra,³² V. Sordini,³² Y. Tschudi,³² P. Verdier,³² S. Viret,³² Z. Tsamalaidze,^{33,p} G. Anagnostou,³⁴ C. Autermann,³⁴ S. Beranek,³⁴ M. Edelhoff,³⁴ L. Feld,³⁴ N. Heracleous,³⁴ O. Hindrichs,³⁴ R. Jussen,³⁴ K. Klein,³⁴ J. Merz,³⁴ A. Ostapchuk,³⁴ A. Perieanu,³⁴ F. Raupach,³⁴ J. Sammet,³⁴ S. Schael,³⁴ D. Sprenger,³⁴ H. Weber,³⁴ B. Wittmer,³⁴ V. Zhukov,^{34,q} M. Ata,³⁵ J. Caudron,³⁵ E. Dietz-Laursonn,³⁵ D. Duchardt,³⁵ M. Erdmann,³⁵ R. Fischer,³⁵ A. Güth,³⁵ T. Hebbeker,³⁵ C. Heidemann,³⁵ K. Hoepfner,³⁵ D. Klingebiel,³⁵ P. Kreuzer,³⁵ M. Merschmeyer,³⁵ A. Meyer,³⁵ M. Olschewski,³⁵ P. Papacz,³⁵ H. Pieta,³⁵ H. Reithler,³⁵ S. A. Schmitz,³⁵ L. Sonnenschein,³⁵ J. Steggemann,³⁵ D. Teyssier,³⁵ M. Weber,³⁵ M. Bontenackels,³⁶ V. Cherepanov,³⁶ Y. Erdogan,³⁶ G. Flügge,³⁶ H. Geenen,³⁶ M. Geisler,³⁶ W. Haj Ahmad,³⁶ F. Hoehle,³⁶ B. Kargoll,³⁶ T. Kress,³⁶ Y. Kuessel,³⁶ J. Lingemann,^{36,f} A. Nowack,³⁶ L. Perchalla,³⁶ O. Pooth,³⁶ P. Sauerland,³⁶ A. Stahl,³⁶ M. Aldaya Martin,³⁷ J. Behr,³⁷ W. Behrenhoff,³⁷ U. Behrens,³⁷ M. Bergholz,^{37,r} A. Bethani,³⁷ K. Borras,³⁷ A. Burgmeier,³⁷ A. Cakir,³⁷ L. Calligaris,³⁷ A. Campbell,³⁷ E. Castro,³⁷ F. Costanza,³⁷ D. Dammann,³⁷ C. Diez Pardos,³⁷ G. Eckerlin,³⁷ D. Eckstein,³⁷ G. Flucke,³⁷ A. Geiser,³⁷ I. Glushkov,³⁷ P. Gunnellini,³⁷ S. Habib,³⁷ J. Hauk,³⁷ G. Hellwig,³⁷ H. Jung,³⁷ M. Kasemann,³⁷ P. Katsas,³⁷ C. Kleinwort,³⁷ H. Kluge,³⁷ A. Knutsson,³⁷ M. Krämer,³⁷ D. Krücker,³⁷ E. Kuznetsova,³⁷ W. Lange,³⁷ W. Lohmann,^{37,r} B. Lutz,³⁷ R. Mankel,³⁷ I. Marfin,³⁷ M. Marienfeld,³⁷ I.-A. Melzer-Pellmann,³⁷ A. B. Meyer,³⁷ J. Mnich,³⁷ A. Mussgiller,³⁷ S. Naumann-Emme,³⁷ O. Novgorodova,³⁷

- J. Olzem,³⁷ H. Perrey,³⁷ A. Petrukhin,³⁷ D. Pitzl,³⁷ A. Raspereza,³⁷ P. M. Ribeiro Cipriano,³⁷ C. Riedl,³⁷ E. Ron,³⁷ M. Rosin,³⁷ J. Salfeld-Nebgen,³⁷ R. Schmidt,^{37,r} T. Schoerner-Sadenius,³⁷ N. Sen,³⁷ A. Spiridonov,³⁷ M. Stein,³⁷ R. Walsh,³⁷ C. Wissing,³⁷ V. Blobel,³⁸ J. Draeger,³⁸ H. Enderle,³⁸ J. Erfle,³⁸ U. Gebbert,³⁸ M. Görner,³⁸ T. Hermanns,³⁸ R. S. Höing,³⁸ K. Kaschube,³⁸ G. Kaussen,³⁸ H. Kirschenmann,³⁸ R. Klanner,³⁸ J. Lange,³⁸ B. Mura,³⁸ F. Nowak,³⁸ T. Peiffer,³⁸ N. Pietsch,³⁸ D. Rathjens,³⁸ C. Sander,³⁸ H. Schettler,³⁸ P. Schleper,³⁸ E. Schlieckau,³⁸ A. Schmidt,³⁸ M. Schröder,³⁸ T. Schum,³⁸ M. Seidel,³⁸ V. Sola,³⁸ H. Stadie,³⁸ G. Steinbrück,³⁸ J. Thomsen,³⁸ L. Vanelderren,³⁸ C. Barth,³⁹ J. Berger,³⁹ C. Böser,³⁹ T. Chwalek,³⁹ W. De Boer,³⁹ A. Descroix,³⁹ A. Dierlamm,³⁹ M. Feindt,³⁹ M. Guthoff,^{39,f} C. Hackstein,³⁹ F. Hartmann,³⁹ T. Hauth,^{39,f} M. Heinrich,³⁹ H. Held,³⁹ K. H. Hoffmann,³⁹ U. Husemann,³⁹ I. Katkov,^{39,q} J. R. Komaragiri,³⁹ P. Lobelle Pardo,³⁹ D. Martschei,³⁹ S. Mueller,³⁹ Th. Müller,³⁹ M. Niegel,³⁹ A. Nürnberg,³⁹ O. Oberst,³⁹ A. Oehler,³⁹ J. Ott,³⁹ G. Quast,³⁹ K. Rabbertz,³⁹ F. Ratnikov,³⁹ N. Ratnikova,³⁹ S. Röcker,³⁹ F.-P. Schilling,³⁹ G. Schott,³⁹ H. J. Simonis,³⁹ F. M. Stober,³⁹ D. Troendle,³⁹ R. Ulrich,³⁹ J. Wagner-Kuhr,³⁹ S. Wayand,³⁹ T. Weiler,³⁹ M. Zeise,³⁹ G. Daskalakis,⁴⁰ T. Geralis,⁴⁰ S. Kesisoglou,⁴⁰ A. Kyriakis,⁴⁰ D. Loukas,⁴⁰ I. Manolakos,⁴⁰ A. Markou,⁴⁰ C. Markou,⁴⁰ C. Mavrommatis,⁴⁰ E. Ntomari,⁴⁰ L. Gouskos,⁴¹ T. J. Mertzimekis,⁴¹ A. Panagiotou,⁴¹ N. Saoulidou,⁴¹ I. Evangelou,⁴² C. Foudas,⁴² P. Kokkas,⁴² N. Manthos,⁴² I. Papadopoulos,⁴² V. Patras,⁴² G. Bencze,⁴³ C. Hajdu,⁴³ P. Hidas,⁴³ D. Horvath,^{43,s} F. Sikler,⁴³ V. Veszpremi,⁴³ G. Vesztergombi,^{43,t} N. Beni,⁴⁴ S. Czellar,⁴⁴ J. Molnar,⁴⁴ J. Palinkas,⁴⁴ Z. Szillasi,⁴⁴ J. Karancsi,⁴⁵ P. Raics,⁴⁵ Z. L. Trocsanyi,⁴⁵ B. Ujvari,⁴⁵ S. B. Beri,⁴⁶ V. Bhatnagar,⁴⁶ N. Dhingra,⁴⁶ R. Gupta,⁴⁶ M. Kaur,⁴⁶ M. Z. Mehta,⁴⁶ N. Nishu,⁴⁶ L. K. Saini,⁴⁶ A. Sharma,⁴⁶ J. B. Singh,⁴⁶ Ashok Kumar,⁴⁷ Arun Kumar,⁴⁷ S. Ahuja,⁴⁷ A. Bhardwaj,⁴⁷ B. C. Choudhary,⁴⁷ S. Malhotra,⁴⁷ M. Naimuddin,⁴⁷ K. Ranjan,⁴⁷ V. Sharma,⁴⁷ R. K. Shivpuri,⁴⁷ S. Banerjee,⁴⁸ S. Bhattacharya,⁴⁸ S. Dutta,⁴⁸ B. Gomber,⁴⁸ Sa. Jain,⁴⁸ Sh. Jain,⁴⁸ R. Khurana,⁴⁸ S. Sarkar,⁴⁸ M. Sharan,⁴⁸ A. Abdulsalam,⁴⁹ R. K. Choudhury,⁴⁹ D. Dutta,⁴⁹ S. Kailas,⁴⁹ V. Kumar,⁴⁹ P. Mehta,⁴⁹ A. K. Mohanty,^{49,f} L. M. Pant,⁴⁹ P. Shukla,⁴⁹ T. Aziz,⁵⁰ S. Ganguly,⁵⁰ M. Guchait,^{50,u} M. Maity,^{50,v} G. Majumder,⁵⁰ K. Mazumdar,⁵⁰ G. B. Mohanty,⁵⁰ B. Parida,⁵⁰ K. Sudhakar,⁵⁰ N. Wickramage,⁵⁰ S. Banerjee,⁵¹ S. Dugad,⁵¹ H. Arfaei,^{52,w} H. Bakhshiansohi,⁵² S. M. Etesami,^{52,x} A. Fahim,^{52,w} M. Hashemi,⁵² H. Hesari,⁵² A. Jafari,⁵² M. Khakzad,⁵² M. Mohammadi Najafabadi,⁵² S. Paktinat Mehdiabadi,⁵² B. Safarzadeh,^{52,y} M. Zeinali,⁵² M. Abbrescia,^{53a,53b} L. Barbone,^{53a,53b} C. Calabria,^{53a,53b,f} S. S. Chhibra,^{53a,53b} A. Colaleo,^{53a} D. Creanza,^{53a,53c} N. De Filippis,^{53a,53c,f} M. De Palma,^{53a,53b} L. Fiore,^{53a} G. Iaselli,^{53a,53c} L. Lusito,^{53a,53b} G. Maggi,^{53a,53c} M. Maggi,^{53a} B. Marangelli,^{53a,53b} S. My,^{53a,53c} S. Nuzzo,^{53a,53b} N. Pacifico,^{53a,53b} A. Pompili,^{53a,53b} G. Pugliese,^{53a,53c} G. Selvaggi,^{53a,53b} L. Silvestris,^{53a} G. Singh,^{53a,53b} R. Venditti,^{53a,53b} G. Zito,^{53a} G. Abbiendi,^{54a} A. C. Benvenuti,^{54a} D. Bonacorsi,^{54a,54b} S. Braibant-Giacomelli,^{54a,54b} L. Brigliadori,^{54a,54b} P. Capiluppi,^{54a,54b} A. Castro,^{54a,54b} F. R. Cavallo,^{54a} M. Cuffiani,^{54a,54b} G. M. Dallavalle,^{54a} F. Fabbri,^{54a} A. Fanfani,^{54a,54b} D. Fasanella,^{54a,54b,f} P. Giacomelli,^{54a} C. Grandi,^{54a} L. Guiducci,^{54a,54b} S. Marcellini,^{54a} G. Masetti,^{54a} M. Meneghelli,^{54a,54b,f} A. Montanari,^{54a} F. L. Navarria,^{54a,54b} F. Odoricci,^{54a} A. Perrotta,^{54a} F. Primavera,^{54a,54b} A. M. Rossi,^{54a,54b} T. Rovelli,^{54a,54b} G. Siroli,^{54a,54b} R. Travaglini,^{54a,54b} S. Albergo,^{55a,55b} G. Cappello,^{55a,55b} M. Chiorboli,^{55a,55b} S. Costa,^{55a,55b} R. Potenza,^{55a,55b} A. Tricoli,^{55a,55b} C. Tuve,^{55a,55b} G. Barbagli,^{56a} V. Ciulli,^{56a,56b} C. Civinini,^{56a} R. D'Alessandro,^{56a,56b} E. Focardi,^{56a,56b} S. Frosali,^{56a,56b} E. Gallo,^{56a} S. Gonzi,^{56a,56b} M. Meschini,^{56a} S. Paoletti,^{56a} G. Sguazzoni,^{56a} A. Tropiano,^{56a} L. Benussi,⁵⁷ S. Bianco,⁵⁷ S. Colafranceschi,^{57,z} F. Fabbri,⁵⁷ D. Piccolo,⁵⁷ P. Fabbricatore,⁵⁸ R. Musenich,⁵⁸ S. Tosi,⁵⁸ A. Benaglia,^{59a,59b} F. De Guio,^{59a,59b} L. Di Matteo,^{59a,59b,f} S. Fiorendi,^{59a,59b} S. Gennai,^{59a,f} A. Ghezzi,^{59a,59b} S. Malvezzi,^{59a} R. A. Manzoni,^{59a,59b} A. Martelli,^{59a,59b} A. Massironi,^{59a,59b,f} D. Menasce,^{59a} L. Moroni,^{59a} M. Paganoni,^{59a,59b} D. Pedrini,^{59a} S. Ragazzi,^{59a,59b} N. Redaelli,^{59a} S. Sala,^{59a} T. Tabarelli de Fatis,^{59a,59b} S. Buontempo,^{60a} C. A. Carrillo Montoya,^{60a} N. Cavallo,^{60a,aa} A. De Cosa,^{60a,60b,f} O. Dogangun,^{60a,60b} F. Fabozzi,^{60a,aa} A. O. M. Iorio,^{60a} L. Lista,^{60a} S. Meola,^{60a,bb} M. Merola,^{60a,60b} P. Paolucci,^{60a,f} P. Azzi,^{61a} N. Bacchetta,^{61a,f} P. Bellan,^{61a,61b} D. Bisello,^{61a,61b} A. Branca,^{61a,f} R. Carlin,^{61a,61b} P. Checchia,^{61a} T. Dorigo,^{61a} U. Dosselli,^{61a} F. Gasparini,^{61a,61b} U. Gasparini,^{61a,61b} A. Gozzelino,^{61a} K. Kanishchev,^{61a,61c} S. Lacaprara,^{61a} I. Lazzizzera,^{61a,61c} M. Margoni,^{61a,61b} A. T. Meneguzzo,^{61a,61b} M. Nespolo,^{61a,f} J. Pazzini,^{61a,61b} P. Ronchese,^{61a,61b} F. Simonetto,^{61a,61b} E. Torassa,^{61a} S. Vanini,^{61a,61b} P. Zotto,^{61a,61b} G. Zumerle,^{61a,61b} M. Gabusi,^{62a,62b} S. P. Ratti,^{62a,62b} C. Riccardi,^{62a,62b} P. Torre,^{62a,62b} P. Vitulo,^{62a,62b} M. Biasini,^{63a,63b} G. M. Bilei,^{63a} L. Fanò,^{63a,63b} P. Lariccia,^{63a,63b} G. Mantovani,^{63a,63b} M. Menichelli,^{63a} A. Nappi,^{63a,63b,a} F. Romeo,^{63a,63b} A. Saha,^{63a} A. Santocchia,^{63a,63b} A. Spiezia,^{63a,63b} S. Taroni,^{63a,63b} P. Azzurri,^{64a,64c} G. Bagliesi,^{64a} T. Boccali,^{64a} G. Broccolo,^{64a,64c} R. Castaldi,^{64a} R. T. D'Agnolo,^{64a,64c,f} R. Dell'Orso,^{64a} F. Fiori,^{64a,64b,f} L. Foà,^{64a,64c} A. Giassi,^{64a} A. Kraan,^{64a} F. Ligabue,^{64a,64c} T. Lomtadze,^{64a}

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Carrillo Moreno,⁷⁶ F. Vazquez Valencia,⁷⁶ H. A. Salazar Ibarguen,⁷⁷ E. Casimiro Linares,⁷⁸ A. Morelos Pineda,⁷⁸ M. A. Reyes-Santos,⁷⁸ D. Krofcheck,⁷⁹ A. J. Bell,⁸⁰ P. H. Butler,⁸⁰ R. Doesburg,⁸⁰ S. Reucroft,⁸⁰ H. Silverwood,⁸⁰ M. Ahmad,⁸¹ M. H. Ansari,⁸¹ M. I. Asghar,⁸¹ H. R. Hoorani,⁸¹ S. Khalid,⁸¹ W. A. Khan,⁸¹ T. Khurshid,⁸¹ S. Qazi,⁸¹ M. A. Shah,⁸¹ M. Shoaib,⁸¹ G. Brona,⁸² K. Bunkowski,⁸² M. Cwiok,⁸² W. Dominik,⁸² K. Doroba,⁸² A. Kalinowski,⁸² M. Konecki,⁸² J. Krolikowski,⁸² H. Bialkowska,⁸³ B. Boimska,⁸³ T. Frueboes,⁸³ R. Gokieli,⁸³ M. Górski,⁸³ M. Kazana,⁸³ K. Nawrocki,⁸³ K. Romanowska-Rybinska,⁸³ M. Szleper,⁸³ G. Wrochna,⁸³ P. Zalewski,⁸³ N. Almeida,⁸⁴ P. Bargassa,⁸⁴ A. David,⁸⁴ P. Faccioli,⁸⁴ P. G. Ferreira Parracho,⁸⁴ M. Gallinaro,⁸⁴ J. Seixas,⁸⁴ J. Varela,⁸⁴ P. Vischia,⁸⁴ I. Belotelov,⁸⁵ P. Bunin,⁸⁵ M. Gavrilenko,⁸⁵ I. Golutvin,⁸⁵ I. Gorbunov,⁸⁵ A. Kamenev,⁸⁵ V. Karjavin,⁸⁵ G. Kozlov,⁸⁵ A. Lanev,⁸⁵ A. Malakhov,⁸⁵ P. Moisez,⁸⁵ V. Palichik,⁸⁵ V. Perelygin,⁸⁵ S. Shmatov,⁸⁵ V. Smirnov,⁸⁵ A. Volodko,⁸⁵ A. Zarubin,⁸⁵ S. Evstyukhin,⁸⁶ V. Golovtsov,⁸⁶ Y. Ivanov,⁸⁶ V. Kim,⁸⁶ P. Levchenko,⁸⁶ V. Murzin,⁸⁶ V. Oreshkin,⁸⁶ I. Smirnov,⁸⁶ V. Sulimov,⁸⁶ L. Uvarov,⁸⁶ S. Vavilov,⁸⁶ A. Vorobyev,⁸⁶ An. Vorobyev,⁸⁶ Yu. Andreev,⁸⁷ A. Dermenev,⁸⁷ S. Gninenko,⁸⁷ N. Golubev,⁸⁷ M. Kirsanov,⁸⁷ N. Krasnikov,⁸⁷ V. Matveev,⁸⁷ A. Pashenkov,⁸⁷ D. Tlisov,⁸⁷ A. Toropin,⁸⁷ V. Epshteyn,⁸⁸ M. Erofeeva,⁸⁸ V. Gavrillov,⁸⁸ M. Kossov,⁸⁸ N. Lychkovskaya,⁸⁸ V. Popov,⁸⁸ G. Safronov,⁸⁸ S. Semenov,⁸⁸ V. Stolin,⁸⁸ E. Vlasov,⁸⁸ A. Zhokin,⁸⁸ A. Belyaev,⁸⁹ E. Boos,⁸⁹ M. Dubinin,^{89,e} L. Dudko,⁸⁹ A. Ershov,⁸⁹ A. Gribushin,⁸⁹ V. Klyukhin,⁸⁹ O. Kodolova,⁸⁹ I. Lokhtin,⁸⁹ A. Markina,⁸⁹ S. Obraztsov,⁸⁹ M. Perfilov,⁸⁹ S. Petrushanko,⁸⁹ A. Popov,⁸⁹ L. Sarycheva,^{89,a} V. Savrin,⁸⁹ A. Snigirev,⁸⁹ V. Andreev,⁹⁰ M. Azarkin,⁹⁰ I. Dremin,⁹⁰ M. Kirakosyan,⁹⁰ A. Leonidov,⁹⁰ G. Mesyats,⁹⁰ S. V. Rusakov,⁹⁰ A. Vinogradov,⁹⁰ I. Azhgirey,⁹¹ I. Bayshev,⁹¹ S. Bitioukov,⁹¹ V. Grishin,^{91,f} V. Kachanov,⁹¹ D. 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- R. Guida,⁹⁷ M. Hansen,⁹⁷ P. Harris,⁹⁷ C. Hartl,⁹⁷ J. Harvey,⁹⁷ B. Hegner,⁹⁷ A. Hinzmann,⁹⁷ V. Innocente,⁹⁷ P. Janot,⁹⁷ K. Kaadze,⁹⁷ E. Karavakis,⁹⁷ K. Kousouris,⁹⁷ P. Lecoq,⁹⁷ Y.-J. Lee,⁹⁷ P. Lenzi,⁹⁷ C. Lourenço,⁹⁷ N. Magini,⁹⁷ T. Mäki,⁹⁷ M. Malberti,⁹⁷ L. Malgeri,⁹⁷ M. Mannelli,⁹⁷ L. Masetti,⁹⁷ F. Meijers,⁹⁷ S. Mersi,⁹⁷ E. Meschi,⁹⁷ R. Moser,⁹⁷ M. U. Mozer,⁹⁷ M. Mulders,⁹⁷ P. Musella,⁹⁷ E. Nesvold,⁹⁷ T. Orimoto,⁹⁷ L. Orsini,⁹⁷ E. Palencia Cortezon,⁹⁷ E. Perez,⁹⁷ L. Perrozzi,⁹⁷ A. Petrilli,⁹⁷ A. Pfeiffer,⁹⁷ M. Pierini,⁹⁷ M. Pimiä,⁹⁷ D. Piparo,⁹⁷ G. Polese,⁹⁷ L. Quertenmont,⁹⁷ A. Racz,⁹⁷ W. Reece,⁹⁷ J. Rodrigues Antunes,⁹⁷ G. Rolandi,^{97,hh} C. Rovelli,^{97,ii} M. Rovere,⁹⁷ H. Sakulin,⁹⁷ F. Santanastasio,⁹⁷ C. Schäfer,⁹⁷ C. Schwick,⁹⁷ I. Segoni,⁹⁷ S. Sekmen,⁹⁷ A. Sharma,⁹⁷ P. Siegrist,⁹⁷ P. Silva,⁹⁷ M. Simon,⁹⁷ P. Spicas,^{97,ij} D. Spiga,⁹⁷ A. Tsirou,⁹⁷ G. I. Veres,^{97,t} J. R. Vlimant,⁹⁷ H. K. Wöhri,⁹⁷ S. D. Worm,^{97,kk} W. D. Zeuner,⁹⁷ W. Bertl,⁹⁸ K. Deiters,⁹⁸ W. 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Chang,¹⁰¹ K. H. Chen,¹⁰¹ C. M. Kuo,¹⁰¹ S. W. Li,¹⁰¹ W. Lin,¹⁰¹ Z. K. Liu,¹⁰¹ Y. J. Lu,¹⁰¹ D. Mekterovic,¹⁰¹ A. P. Singh,¹⁰¹ R. Volpe,¹⁰¹ S. S. Yu,¹⁰¹ P. Bartalini,¹⁰² P. Chang,¹⁰² Y. H. Chang,¹⁰² Y. W. Chang,¹⁰² Y. Chao,¹⁰² K. F. Chen,¹⁰² C. Dietz,¹⁰² U. Grundler,¹⁰² W.-S. Hou,¹⁰² Y. Hsiung,¹⁰² K. Y. Kao,¹⁰² Y. J. Lei,¹⁰² R.-S. Lu,¹⁰² D. Majumder,¹⁰² E. Petrakou,¹⁰² X. Shi,¹⁰² J. G. Shiu,¹⁰² Y. M. Tzeng,¹⁰² X. Wan,¹⁰² M. Wang,¹⁰² B. Asavapibhop,¹⁰³ N. Srimanobhas,¹⁰³ A. Adiguzel,¹⁰⁴ M. N. Bakirci,^{104,oo} S. Cerci,^{104,pp} C. Dozen,¹⁰⁴ I. Dumanoglu,¹⁰⁴ E. Eskut,¹⁰⁴ S. Girgis,¹⁰⁴ G. Gokbulut,¹⁰⁴ E. Garpinar,¹⁰⁴ I. Hos,¹⁰⁴ E. E. Kangal,¹⁰⁴ T. Karaman,¹⁰⁴ G. Karapinar,^{104,qq} A. Kayis Topaksu,¹⁰⁴ G. Onengut,¹⁰⁴ K. Ozdemir,¹⁰⁴ S. Ozturk,^{104,rr} A. Polatoz,¹⁰⁴ K. Sogut,^{104,ss} D. Sunar Cerci,^{104,pp} B. Tali,^{104,pp} H. Topakli,^{104,oo} L. N. Vergili,¹⁰⁴ M. Vergili,¹⁰⁴ I. V. Akin,¹⁰⁵ T. Aliiev,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 E. Gülmez,¹⁰⁶ B. Isildak,^{106,tt} M. Kaya,^{106,uu} O. Kaya,^{106,uu} S. Ozkorucuklu,^{106,vv} N. Sonmez,^{106,ww} K. Cankocak,¹⁰⁷ L. Levchuk,¹⁰⁸ F. Bostock,¹⁰⁹ J. J. Brooke,¹⁰⁹ E. Clement,¹⁰⁹ D. Cussans,¹⁰⁹ H. Flacher,¹⁰⁹ R. Frazier,¹⁰⁹ J. Goldstein,¹⁰⁹ M. Grimes,¹⁰⁹ G. P. Heath,¹⁰⁹ H. F. Heath,¹⁰⁹ L. Kreczko,¹⁰⁹ S. Metson,¹⁰⁹ D. M. Newbold,^{109,kk} K. Nirunpong,¹⁰⁹ A. Poll,¹⁰⁹ S. Senkin,¹⁰⁹ V. J. Smith,¹⁰⁹ T. Williams,¹⁰⁹ L. Basso,^{110,xx} K. W. Bell,¹¹⁰ A. Belyaev,^{110,xx} C. Brew,¹¹⁰ R. M. Brown,¹¹⁰ D. J. A. Cockerill,¹¹⁰ J. A. Coughlan,¹¹⁰ K. Harder,¹¹⁰ S. Harper,¹¹⁰ J. Jackson,¹¹⁰ B. W. Kennedy,¹¹⁰ E. Olaiya,¹¹⁰ D. Petyt,¹¹⁰ B. C. Radburn-Smith,¹¹⁰ C. H. Shepherd-Themistocleous,¹¹⁰ I. R. Tomalin,¹¹⁰ W. J. Womersley,¹¹⁰ R. Bainbridge,¹¹¹ G. Ball,¹¹¹ R. Beuselinck,¹¹¹ O. Buchmuller,¹¹¹ D. Colling,¹¹¹ N. Cripps,¹¹¹ M. Cutajar,¹¹¹ P. Dauncey,¹¹¹ G. Davies,¹¹¹ M. Della Negra,¹¹¹ W. Ferguson,¹¹¹ J. Fulcher,¹¹¹ D. Futyan,¹¹¹ A. Gilbert,¹¹¹ A. Guleratne Bryer,¹¹¹ G. Hall,¹¹¹ Z. Hatherell,¹¹¹ J. Hays,¹¹¹ G. Iles,¹¹¹ M. Jarvis,¹¹¹ G. Karapostoli,¹¹¹ L. Lyons,¹¹¹ A.-M. Magnan,¹¹¹ J. Marrouche,¹¹¹ B. Mathias,¹¹¹ R. Nandi,¹¹¹ J. Nash,¹¹¹ A. Nikitenko,^{111,nn} A. Papageorgiou,¹¹¹ J. Pela,¹¹¹ M. Pesaresi,¹¹¹ K. Petridis,¹¹¹ M. Pioppi,^{111,yy} D. M. Raymond,¹¹¹ S. Rogerson,¹¹¹ A. Rose,¹¹¹ M. J. Ryan,¹¹¹ C. Seez,¹¹¹ P. Sharp,^{111,aa} A. Sparrow,¹¹¹ M. Stoye,¹¹¹ A. Tapper,¹¹¹ M. Vazquez Acosta,¹¹¹ T. Virdee,¹¹¹ S. Wakefield,¹¹¹ N. Wardle,¹¹¹ T. Whyntie,¹¹¹ M. Chadwick,¹¹² J. E. Cole,¹¹² P. R. Hobson,¹¹² A. Khan,¹¹² P. Kyberd,¹¹² D. Leggat,¹¹² D. Leslie,¹¹² W. Martin,¹¹² I. D. Reid,¹¹² P. Symonds,¹¹² L. Teodorescu,¹¹² M. Turner,¹¹² K. Hatakeyama,¹¹³ H. Liu,¹¹³ T. Scarborough,¹¹³ O. Charaf,¹¹⁴ C. Henderson,¹¹⁴ P. Rumerio,¹¹⁴ A. Avetisyan,¹¹⁵ T. Bose,¹¹⁵ C. Fantasia,¹¹⁵ A. Heister,¹¹⁵ J. St. John,¹¹⁵ P. Lawson,¹¹⁵ D. Lazic,¹¹⁵ J. Rohlf,¹¹⁵ D. Sperka,¹¹⁵ L. Sulak,¹¹⁵ J. Alimena,¹¹⁶ S. Bhattacharya,¹¹⁶ D. Cutts,¹¹⁶ A. Ferapontov,¹¹⁶ U. Heintz,¹¹⁶ S. Jabeen,¹¹⁶ G. Kukartsev,¹¹⁶ E. Laird,¹¹⁶ G. Landsberg,¹¹⁶ M. Luk,¹¹⁶ M. Narain,¹¹⁶ D. Nguyen,¹¹⁶ M. Segala,¹¹⁶ T. Sinthuprasith,¹¹⁶ T. Speer,¹¹⁶ K. V. Tsang,¹¹⁶ R. Breedon,¹¹⁷ G. Breto,¹¹⁷ M. Calderon De La Barca Sanchez,¹¹⁷ S. Chauhan,¹¹⁷ M. Chertok,¹¹⁷ J. Conway,¹¹⁷ R. Conway,¹¹⁷ P. T. Cox,¹¹⁷ J. Dolen,¹¹⁷ R. Erbacher,¹¹⁷ M. Gardner,¹¹⁷ R. Houtz,¹¹⁷ W. Ko,¹¹⁷ A. Kopecky,¹¹⁷ R. Lander,¹¹⁷ O. Mall,¹¹⁷ T. Miceli,¹¹⁷ D. Pellett,¹¹⁷ F. Ricci-tam,¹¹⁷ B. Rutherford,¹¹⁷ M. Searle,¹¹⁷ J. Smith,¹¹⁷ M. Squires,¹¹⁷ M. Tripathi,¹¹⁷ R. Vasquez Sierra,¹¹⁷ V. Andreev,¹¹⁸ D. Cline,¹¹⁸ R. Cousins,¹¹⁸ J. Duris,¹¹⁸ S. Erhan,¹¹⁸ P. Everaerts,¹¹⁸ C. Farrell,¹¹⁸ J. Hauser,¹¹⁸ M. Ignatenko,¹¹⁸

C. Jarvis,¹¹⁸ C. Plager,¹¹⁸ G. Rakness,¹¹⁸ P. Schlein,^{118,a} P. Traczyk,¹¹⁸ V. Valuev,¹¹⁸ M. Weber,¹¹⁸ J. Babb,¹¹⁹ R. Clare,¹¹⁹ M. E. Dinardo,¹¹⁹ J. Ellison,¹¹⁹ J. W. Gary,¹¹⁹ F. Giordano,¹¹⁹ G. Hanson,¹¹⁹ G. Y. Jeng,^{119,zz} H. Liu,¹¹⁹ O. R. Long,¹¹⁹ A. Luthra,¹¹⁹ H. Nguyen,¹¹⁹ S. Paramesvaran,¹¹⁹ J. Sturdy,¹¹⁹ S. Sumowidagdo,¹¹⁹ R. Wilken,¹¹⁹ S. Wimpenny,¹¹⁹ W. Andrews,¹²⁰ J. G. Branson,¹²⁰ G. B. Cerati,¹²⁰ S. Cittolin,¹²⁰ D. Evans,¹²⁰ F. Golf,¹²⁰ A. Holzner,¹²⁰ R. Kelley,¹²⁰ M. Lebourgeois,¹²⁰ J. Letts,¹²⁰ I. Macneill,¹²⁰ B. Mangano,¹²⁰ S. Padhi,¹²⁰ C. Palmer,¹²⁰ G. Petrucciani,¹²⁰ M. Pieri,¹²⁰ M. Sani,¹²⁰ V. Sharma,¹²⁰ S. Simon,¹²⁰ E. Sudano,¹²⁰ M. Tadel,¹²⁰ Y. Tu,¹²⁰ A. Vartak,¹²⁰ S. Wasserbaech,^{120,aaa} F. Würthwein,¹²⁰ A. Yagil,¹²⁰ J. Yoo,¹²⁰ D. Barge,¹²¹ R. Bellan,¹²¹ C. Campagnari,¹²¹ M. D'Alfonso,¹²¹ T. Danielson,¹²¹ K. Flowers,¹²¹ P. Geffert,¹²¹ J. Incandela,¹²¹ C. Justus,¹²¹ P. Kalavase,¹²¹ S. A. Koay,¹²¹ D. Kovalskyi,¹²¹ V. Krutelyov,¹²¹ S. Lowette,¹²¹ N. Mccoll,¹²¹ V. Pavlunin,¹²¹ F. Rebassoo,¹²¹ J. Ribnik,¹²¹ J. Richman,¹²¹ R. Rossin,¹²¹ D. Stuart,¹²¹ W. To,¹²¹ C. West,¹²¹ A. Apresyan,¹²² A. Bornheim,¹²² Y. Chen,¹²² E. Di Marco,¹²² J. Duarte,¹²² M. Gataullin,¹²² Y. Ma,¹²² A. Mott,¹²² H. B. Newman,¹²² C. Rogan,¹²² M. Spiropulu,¹²² V. Timciuc,¹²² J. Veverka,¹²² R. Wilkinson,¹²² S. Xie,¹²² Y. Yang,¹²² R. Y. Zhu,¹²² B. Akgun,¹²³ V. Azzolini,¹²³ A. Calamba,¹²³ R. Carroll,¹²³ T. Ferguson,¹²³ Y. Iiyama,¹²³ D. W. Jang,¹²³ Y. F. Liu,¹²³ M. Paulini,¹²³ H. Vogel,¹²³ I. Vorobiev,¹²³ J. P. Cumalat,¹²⁴ B. R. Drell,¹²⁴ W. T. Ford,¹²⁴ A. Gaz,¹²⁴ E. Luiggi Lopez,¹²⁴ J. G. Smith,¹²⁴ K. Stenson,¹²⁴ K. A. Ulmer,¹²⁴ S. R. Wagner,¹²⁴ J. Alexander,¹²⁵ A. Chatterjee,¹²⁵ N. Eggert,¹²⁵ L. K. Gibbons,¹²⁵ B. Heltsley,¹²⁵ A. Khukhunaishvili,¹²⁵ B. Kreis,¹²⁵ N. Mirman,¹²⁵ G. Nicolas Kaufman,¹²⁵ J. R. Patterson,¹²⁵ A. Ryd,¹²⁵ E. Salvati,¹²⁵ W. Sun,¹²⁵ W. D. Teo,¹²⁵ J. Thom,¹²⁵ J. Thompson,¹²⁵ J. Tucker,¹²⁵ J. Vaughan,¹²⁵ Y. Weng,¹²⁵ L. Winstrom,¹²⁵ P. Wittich,¹²⁵ D. Winn,¹²⁶ S. Abdullin,¹²⁷ M. Albrow,¹²⁷ J. Anderson,¹²⁷ L. A. T. Bauerdick,¹²⁷ A. Beretvas,¹²⁷ J. Berryhill,¹²⁷ P. C. Bhat,¹²⁷ I. Bloch,¹²⁷ K. Burkett,¹²⁷ J. N. Butler,¹²⁷ V. Chetluru,¹²⁷ H. W. K. Cheung,¹²⁷ F. Chlebana,¹²⁷ V. D. Elvira,¹²⁷ I. Fisk,¹²⁷ J. Freeman,¹²⁷ Y. Gao,¹²⁷ D. Green,¹²⁷ O. Gutsche,¹²⁷ J. Hanlon,¹²⁷ R. M. Harris,¹²⁷ J. Hirschauer,¹²⁷ B. Hooberman,¹²⁷ S. Jindariani,¹²⁷ M. Johnson,¹²⁷ U. Joshi,¹²⁷ B. Kilminster,¹²⁷ B. Klima,¹²⁷ S. Kunori,¹²⁷ S. Kwan,¹²⁷ C. Leonidopoulos,¹²⁷ J. Linacre,¹²⁷ D. Lincoln,¹²⁷ R. Lipton,¹²⁷ J. Lykken,¹²⁷ K. Maeshima,¹²⁷ J. M. Marraffino,¹²⁷ S. Maruyama,¹²⁷ D. Mason,¹²⁷ P. McBride,¹²⁷ K. Mishra,¹²⁷ S. Mrenna,¹²⁷ Y. Musienko,^{127,bbb} C. Newman-Holmes,¹²⁷ V. O'Dell,¹²⁷ O. Prokofyev,¹²⁷ E. Sexton-Kennedy,¹²⁷ S. Sharma,¹²⁷ W. J. Spalding,¹²⁷ L. Spiegel,¹²⁷ L. Taylor,¹²⁷ S. Tkaczyk,¹²⁷ N. V. Tran,¹²⁷ L. Uplegger,¹²⁷ E. W. Vaandering,¹²⁷ R. Vidal,¹²⁷ J. Whitmore,¹²⁷ W. Wu,¹²⁷ F. Yang,¹²⁷ F. Yumiceva,¹²⁷ J. C. Yun,¹²⁷ D. Acosta,¹²⁸ P. Avery,¹²⁸ D. Bourilkov,¹²⁸ M. Chen,¹²⁸ T. Cheng,¹²⁸ S. Das,¹²⁸ M. De Gruttola,¹²⁸ G. P. Di Giovanni,¹²⁸ D. Dobur,¹²⁸ A. Drozdetskiy,¹²⁸ R. D. Field,¹²⁸ M. Fisher,¹²⁸ Y. Fu,¹²⁸ I. K. Furic,¹²⁸ J. Gartner,¹²⁸ J. Hugon,¹²⁸ B. Kim,¹²⁸ J. Konigsberg,¹²⁸ A. Korytov,¹²⁸ A. Kropivnitskaya,¹²⁸ T. Kypreos,¹²⁸ J. F. Low,¹²⁸ K. Matchev,¹²⁸ P. Milenovic,^{128,ccc} G. Mitselmakher,¹²⁸ L. Muniz,¹²⁸ M. Park,¹²⁸ R. Remington,¹²⁸ A. Rinkevicius,¹²⁸ P. Sellers,¹²⁸ N. Skhirtladze,¹²⁸ M. Snowball,¹²⁸ J. Yelton,¹²⁸ M. Zakaria,¹²⁸ V. Gaultney,¹²⁹ S. Hewamanage,¹²⁹ L. M. Lebolo,¹²⁹ S. Linn,¹²⁹ P. Markowitz,¹²⁹ G. Martinez,¹²⁹ J. L. Rodriguez,¹²⁹ T. Adams,¹³⁰ A. Askew,¹³⁰ J. Bochenek,¹³⁰ J. Chen,¹³⁰ B. Diamond,¹³⁰ S. V. Gleyzer,¹³⁰ J. Haas,¹³⁰ S. Hagopian,¹³⁰ V. Hagopian,¹³⁰ M. Jenkins,¹³⁰ K. F. Johnson,¹³⁰ H. Prosper,¹³⁰ V. Veeraraghavan,¹³⁰ M. Weinberg,¹³⁰ M. M. Baarmand,¹³¹ B. Dorney,¹³¹ M. Hohlmann,¹³¹ H. Kalakhety,¹³¹ I. Vodopiyarov,¹³¹ M. R. Adams,¹³² I. M. Anghel,¹³² L. Apanasevich,¹³² Y. Bai,¹³² V. E. Bazterra,¹³² R. R. Betts,¹³² I. Bucinskaite,¹³² J. Callner,¹³² R. Cavanaugh,¹³² O. Evdokimov,¹³² L. Gauthier,¹³² C. E. Gerber,¹³² D. J. Hofman,¹³² S. Khalatyan,¹³² F. Lacroix,¹³² M. Malek,¹³² C. O'Brien,¹³² C. Silkworth,¹³² D. Strom,¹³² P. Turner,¹³² N. Varelas,¹³² U. Akgun,¹³³ E. A. Albayrak,¹³³ B. Bilki,^{133,ddd} W. Clarida,¹³³ F. Duru,¹³³ S. Griffiths,¹³³ J.-P. Merlo,¹³³ H. Mermerkaya,^{133,eee} A. Mestvirishvili,¹³³ A. Moeller,¹³³ J. Nachtman,¹³³ C. R. Newsom,¹³³ E. Norbeck,¹³³ Y. Onel,¹³³ F. Ozok,^{133,fff} S. Sen,¹³³ P. Tan,¹³³ E. Tiras,¹³³ J. Wetzel,¹³³ T. Yetkin,¹³³ K. Yi,¹³³ B. A. Barnett,¹³⁴ B. Blumenfeld,¹³⁴ S. Bolognesi,¹³⁴ D. Fehling,¹³⁴ G. Giurgiu,¹³⁴ A. V. Gritsan,¹³⁴ Z. J. Guo,¹³⁴ G. Hu,¹³⁴ P. Maksimovic,¹³⁴ S. Rappoccio,¹³⁴ M. Swartz,¹³⁴ A. Whitbeck,¹³⁴ P. Baringer,¹³⁵ A. Bean,¹³⁵ G. Benelli,¹³⁵ R. P. Kenny Iii,¹³⁵ M. Murray,¹³⁵ D. Noonan,¹³⁵ S. Sanders,¹³⁵ R. Stringer,¹³⁵ G. Tinti,¹³⁵ J. S. Wood,¹³⁵ V. Zhukova,¹³⁵ A. F. Barfuss,¹³⁶ T. Bolton,¹³⁶ I. Chakaberia,¹³⁶ A. Ivanov,¹³⁶ S. Khalil,¹³⁶ M. Makouski,¹³⁶ Y. Maravin,¹³⁶ S. Shrestha,¹³⁶ I. Svintradze,¹³⁶ J. Gronberg,¹³⁷ D. Lange,¹³⁷ D. Wright,¹³⁷ A. Baden,¹³⁸ M. Boutemour,¹³⁸ B. Calvert,¹³⁸ S. C. Eno,¹³⁸ J. A. Gomez,¹³⁸ N. J. Hadley,¹³⁸ R. G. Kellogg,¹³⁸ M. Kirn,¹³⁸ T. Kolberg,¹³⁸ Y. Lu,¹³⁸ M. Marionneau,¹³⁸ A. C. Mignerey,¹³⁸ K. Pedro,¹³⁸ A. Peterman,¹³⁸ A. Skuja,¹³⁸ J. Temple,¹³⁸ M. B. Tonjes,¹³⁸ S. C. Tonwar,¹³⁸ E. Twedt,¹³⁸ A. Apyan,¹³⁹ G. Bauer,¹³⁹ J. Bendavid,¹³⁹ W. Busza,¹³⁹ E. Butz,¹³⁹ I. A. Cali,¹³⁹ M. Chan,¹³⁹ V. Dutta,¹³⁹ G. Gomez Ceballos,¹³⁹ M. Goncharov,¹³⁹ K. A. Hahn,¹³⁹ Y. Kim,¹³⁹ M. Klute,¹³⁹ K. Krajczar,^{139,ggg} P. D. Luckey,¹³⁹ T. Ma,¹³⁹ S. Nahn,¹³⁹

C. Paus,¹³⁹ D. Ralph,¹³⁹ C. Roland,¹³⁹ G. Roland,¹³⁹ M. Rudolph,¹³⁹ G. S. F. Stephans,¹³⁹ F. Stöckli,¹³⁹
 K. Sumorok,¹³⁹ K. Sung,¹³⁹ D. Velicanu,¹³⁹ E. A. Wenger,¹³⁹ R. Wolf,¹³⁹ B. Wyslouch,¹³⁹ M. Yang,¹³⁹ Y. Yilmaz,¹³⁹
 A. S. Yoon,¹³⁹ M. Zanetti,¹³⁹ S. I. Cooper,¹⁴⁰ B. Dahmes,¹⁴⁰ A. De Benedetti,¹⁴⁰ G. Franzoni,¹⁴⁰ A. Gude,¹⁴⁰
 S. C. Kao,¹⁴⁰ K. Klapoetke,¹⁴⁰ Y. Kubota,¹⁴⁰ J. Mans,¹⁴⁰ N. Pastika,¹⁴⁰ R. Rusack,¹⁴⁰ M. Sasseville,¹⁴⁰
 A. Singovsky,¹⁴⁰ N. Tamba,¹⁴⁰ J. Turkewitz,¹⁴⁰ L. M. Cremaldi,¹⁴¹ R. Kroeger,¹⁴¹ L. Perera,¹⁴¹ R. Rahmat,¹⁴¹
 D. A. Sanders,¹⁴¹ E. Avdeeva,¹⁴² K. Bloom,¹⁴² S. Bose,¹⁴² J. Butt,¹⁴² D. R. Claes,¹⁴² A. Dominguez,¹⁴² M. Eads,¹⁴²
 J. Keller,¹⁴² I. Kravchenko,¹⁴² J. Lazo-Flores,¹⁴² H. Malbouisson,¹⁴² S. Malik,¹⁴² G. R. Snow,¹⁴² U. Baur,¹⁴³
 A. Godshalk,¹⁴³ I. Iashvili,¹⁴³ S. Jain,¹⁴³ A. Kharchilava,¹⁴³ A. Kumar,¹⁴³ S. P. Shipkowski,¹⁴³ K. Smith,¹⁴³
 G. Alverson,¹⁴⁴ E. Barberis,¹⁴⁴ D. Baumgartel,¹⁴⁴ M. Chasco,¹⁴⁴ J. Haley,¹⁴⁴ D. Nash,¹⁴⁴ D. Trocino,¹⁴⁴ D. Wood,¹⁴⁴
 J. Zhang,¹⁴⁴ A. Anastassov,¹⁴⁵ A. Kubik,¹⁴⁵ N. Mucia,¹⁴⁵ N. Odell,¹⁴⁵ R. A. Ofierzynski,¹⁴⁵ B. Pollack,¹⁴⁵
 A. Pozdnyakov,¹⁴⁵ M. Schmitt,¹⁴⁵ S. Stoynev,¹⁴⁵ M. Velasco,¹⁴⁵ S. Won,¹⁴⁵ L. Antonelli,¹⁴⁶ D. Berry,¹⁴⁶
 A. Brinkerhoff,¹⁴⁶ K. M. Chan,¹⁴⁶ M. Hildreth,¹⁴⁶ C. Jessop,¹⁴⁶ D. J. Karmgard,¹⁴⁶ J. Kolb,¹⁴⁶ K. Lannon,¹⁴⁶
 W. Luo,¹⁴⁶ S. Lynch,¹⁴⁶ N. Marinelli,¹⁴⁶ D. M. Morse,¹⁴⁶ T. Pearson,¹⁴⁶ M. Planer,¹⁴⁶ R. Ruchti,¹⁴⁶ J. Slaunwhite,¹⁴⁶
 N. Valls,¹⁴⁶ M. Wayne,¹⁴⁶ M. Wolf,¹⁴⁶ B. Bylsma,¹⁴⁷ L. S. Durkin,¹⁴⁷ C. Hill,¹⁴⁷ R. Hughes,¹⁴⁷ K. Kotov,¹⁴⁷
 T. Y. Ling,¹⁴⁷ D. Puigh,¹⁴⁷ M. Rodenburg,¹⁴⁷ C. Vuosalo,¹⁴⁷ G. Williams,¹⁴⁷ B. L. Winer,¹⁴⁷ N. Adam,¹⁴⁸ E. Berry,¹⁴⁸
 P. Elmer,¹⁴⁸ D. Gerbaudo,¹⁴⁸ V. Halyo,¹⁴⁸ P. Hebda,¹⁴⁸ J. Hegeman,¹⁴⁸ A. Hunt,¹⁴⁸ P. Jindal,¹⁴⁸ D. Lopes Pegna,¹⁴⁸
 P. Lujan,¹⁴⁸ D. Marlow,¹⁴⁸ T. Medvedeva,¹⁴⁸ M. Mooney,¹⁴⁸ J. Olsen,¹⁴⁸ P. Piroué,¹⁴⁸ X. Quan,¹⁴⁸ A. Raval,¹⁴⁸
 B. Safdi,¹⁴⁸ H. Saka,¹⁴⁸ D. Stickland,¹⁴⁸ C. Tully,¹⁴⁸ J. S. Werner,¹⁴⁸ A. Zuranski,¹⁴⁸ E. Brownson,¹⁴⁹ A. Lopez,¹⁴⁹
 H. Mendez,¹⁴⁹ J. E. Ramirez Vargas,¹⁴⁹ E. Alagoz,¹⁵⁰ V. E. Barnes,¹⁵⁰ D. Benedetti,¹⁵⁰ G. Bolla,¹⁵⁰ D. Bortoletto,¹⁵⁰
 M. De Mattia,¹⁵⁰ A. Everett,¹⁵⁰ Z. Hu,¹⁵⁰ M. Jones,¹⁵⁰ O. Koybasi,¹⁵⁰ M. Kress,¹⁵⁰ A. T. Laasanen,¹⁵⁰
 N. Leonardo,¹⁵⁰ V. Maroussov,¹⁵⁰ P. Merkel,¹⁵⁰ D. H. Miller,¹⁵⁰ N. Neumeister,¹⁵⁰ I. Shipsey,¹⁵⁰ D. Silvers,¹⁵⁰
 A. Svyatkovskiy,¹⁵⁰ M. Vidal Marono,¹⁵⁰ H. D. Yoo,¹⁵⁰ J. Zablocki,¹⁵⁰ Y. Zheng,¹⁵⁰ S. Guragain,¹⁵¹ N. Parashar,¹⁵¹
 A. Adair,¹⁵² C. Boulahouache,¹⁵² K. M. Ecklund,¹⁵² F. J. M. Geurts,¹⁵² W. Li,¹⁵² B. P. Padley,¹⁵² R. Redjimi,¹⁵²
 J. Roberts,¹⁵² J. Zabel,¹⁵² B. Betchart,¹⁵³ A. Bodek,¹⁵³ Y. S. Chung,¹⁵³ R. Covarelli,¹⁵³ P. de Barbaro,¹⁵³
 R. Demina,¹⁵³ Y. Eshaq,¹⁵³ T. Ferbel,¹⁵³ A. Garcia-Bellido,¹⁵³ P. Goldenzweig,¹⁵³ J. Han,¹⁵³ A. Harel,¹⁵³
 D. C. Miner,¹⁵³ D. Vishnevskiy,¹⁵³ M. Zielinski,¹⁵³ A. Bhatti,¹⁵⁴ R. Ciesielski,¹⁵⁴ L. Demortier,¹⁵⁴ K. Goulios,¹⁵⁴
 G. Lungu,¹⁵⁴ S. Malik,¹⁵⁴ C. Mesropian,¹⁵⁴ S. Arora,¹⁵⁵ A. Barker,¹⁵⁵ J. P. Chou,¹⁵⁵ C. Contreras-Campana,¹⁵⁵
 E. Contreras-Campana,¹⁵⁵ D. Duggan,¹⁵⁵ D. Ferencek,¹⁵⁵ Y. Gershtein,¹⁵⁵ R. Gray,¹⁵⁵ E. Halkiadakis,¹⁵⁵
 D. Hidas,¹⁵⁵ A. Lath,¹⁵⁵ S. Panwalkar,¹⁵⁵ M. Park,¹⁵⁵ R. Patel,¹⁵⁵ V. Rekovic,¹⁵⁵ J. Robles,¹⁵⁵ K. Rose,¹⁵⁵ S. Salur,¹⁵⁵
 S. Schnetzer,¹⁵⁵ C. Seitz,¹⁵⁵ S. Somalwar,¹⁵⁵ R. Stone,¹⁵⁵ S. Thomas,¹⁵⁵ G. Cerizza,¹⁵⁶ M. Hollingsworth,¹⁵⁶
 S. Spanier,¹⁵⁶ Z. C. Yang,¹⁵⁶ A. York,¹⁵⁶ R. Eusebi,¹⁵⁷ W. Flanagan,¹⁵⁷ J. Gilmore,¹⁵⁷ T. Kamon,^{157, hhh}
 V. Khotilovich,¹⁵⁷ R. Montalvo,¹⁵⁷ I. Osipenko,¹⁵⁷ Y. Pakhotin,¹⁵⁷ A. Perloff,¹⁵⁷ J. Roe,¹⁵⁷ A. Safonov,¹⁵⁷
 T. Sakuma,¹⁵⁷ S. Sengupta,¹⁵⁷ I. Suarez,¹⁵⁷ A. Tatarinov,¹⁵⁷ D. Toback,¹⁵⁷ N. Akchurin,¹⁵⁸ J. Damgov,¹⁵⁸
 C. Dragoiu,¹⁵⁸ P. R. Duderu,¹⁵⁸ C. Jeong,¹⁵⁸ K. Kovitanggoon,¹⁵⁸ S. W. Lee,¹⁵⁸ T. Libeiro,¹⁵⁸ Y. Roh,¹⁵⁸
 I. Volobouev,¹⁵⁸ E. Appelt,¹⁵⁹ A. G. Delannoy,¹⁵⁹ C. Florez,¹⁵⁹ S. Greene,¹⁵⁹ A. Gurrola,¹⁵⁹ W. Johns,¹⁵⁹
 C. Johnston,¹⁵⁹ P. Kurt,¹⁵⁹ C. Maguire,¹⁵⁹ A. Melo,¹⁵⁹ M. Sharma,¹⁵⁹ P. Sheldon,¹⁵⁹ B. Snook,¹⁵⁹ S. Tuo,¹⁵⁹
 J. Velkovska,¹⁵⁹ M. W. Arenton,¹⁶⁰ M. Balazs,¹⁶⁰ S. Boutle,¹⁶⁰ B. Cox,¹⁶⁰ B. Francis,¹⁶⁰ J. Goodell,¹⁶⁰ R. Hirosky,¹⁶⁰
 A. Ledovskoy,¹⁶⁰ C. Lin,¹⁶⁰ C. Neu,¹⁶⁰ J. Wood,¹⁶⁰ R. Yohay,¹⁶⁰ S. Gollapinni,¹⁶¹ R. Harr,¹⁶¹ P. E. Karchin,¹⁶¹
 C. Kottachchi Kankanamge Don,¹⁶¹ P. Lamichhane,¹⁶¹ A. Sakharov,¹⁶¹ M. Anderson,¹⁶² D. Belknap,¹⁶²
 L. Borrello,¹⁶² D. Carlsmith,¹⁶² M. Cepeda,¹⁶² S. Dasu,¹⁶² L. Gray,¹⁶² K. S. Grogg,¹⁶² M. Grothe,¹⁶²
 R. Hall-Wilton,¹⁶² M. Herndon,¹⁶² A. Hervé,¹⁶² P. Klabbers,¹⁶² J. Klukas,¹⁶² A. Lanaro,¹⁶² C. Lazaridis,¹⁶²
 J. Leonard,¹⁶² R. Loveless,¹⁶² A. Mohapatra,¹⁶² I. Ojalvo,¹⁶² F. Palmonari,¹⁶² G. A. Pierro,¹⁶² I. Ross,¹⁶² A. Savin,¹⁶²
 W. H. Smith,¹⁶² and J. Swanson¹⁶²

(CMS Collaboration)

¹Yerevan Physics Institute, Yerevan, Armenia²Institut für Hochenergiephysik der OeAW, Wien, Austria³National Centre for Particle and High Energy Physics, Minsk, Belarus⁴Universiteit Antwerpen, Antwerpen, Belgium⁵Vrije Universiteit Brussel, Brussel, Belgium⁶Université Libre de Bruxelles, Bruxelles, Belgium

- ⁷*Ghent University, Ghent, Belgium*
- ⁸*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*
- ⁹*Université de Mons, Mons, Belgium*
- ¹⁰*Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*
- ¹¹*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
- ¹²*Instituto de Física Teórica, Universidade Estadual Paulista, Sao Paulo, Brazil*
- ¹³*Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria*
- ¹⁴*University of Sofia, Sofia, Bulgaria*
- ¹⁵*Institute of High Energy Physics, Beijing, China*
- ¹⁶*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
- ¹⁷*Universidad de Los Andes, Bogota, Colombia*
- ¹⁸*Technical University of Split, Split, Croatia*
- ¹⁹*University of Split, Split, Croatia*
- ²⁰*Institute Rudjer Boskovic, Zagreb, Croatia*
- ²¹*University of Cyprus, Nicosia, Cyprus*
- ²²*Charles University, Prague, Czech Republic*
- ²³*Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt*
- ²⁴*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*
- ²⁵*Department of Physics, University of Helsinki, Helsinki, Finland*
- ²⁶*Helsinki Institute of Physics, Helsinki, Finland*
- ²⁷*Lappeenranta University of Technology, Lappeenranta, Finland*
- ²⁸*DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France*
- ²⁹*Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France*
- ³⁰*Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France*
- ³¹*Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France*
- ³²*Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France*
- ³³*Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia*
- ³⁴*RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*
- ³⁵*RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
- ³⁶*RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*
- ³⁷*Deutsches Elektronen-Synchrotron, Hamburg, Germany*
- ³⁸*University of Hamburg, Hamburg, Germany*
- ³⁹*Institut für Experimentelle Kernphysik, Karlsruhe, Germany*
- ⁴⁰*Institute of Nuclear Physics "Demokritos", Aghia Paraskevi, Greece*
- ⁴¹*University of Athens, Athens, Greece*
- ⁴²*University of Ioánnina, Ioánnina, Greece*
- ⁴³*KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary*
- ⁴⁴*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*
- ⁴⁵*University of Debrecen, Debrecen, Hungary*
- ⁴⁶*Panjab University, Chandigarh, India*
- ⁴⁷*University of Delhi, Delhi, India*
- ⁴⁸*Saha Institute of Nuclear Physics, Kolkata, India*
- ⁴⁹*Bhabha Atomic Research Centre, Mumbai, India*
- ⁵⁰*Tata Institute of Fundamental Research-EHEP, Mumbai, India*
- ⁵¹*Tata Institute of Fundamental Research-HECR, Mumbai, India*
- ⁵²*Institute for Research in Fundamental Sciences (IPM), Tehran, Iran*
- ^{53a}*INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy*
- ^{53b}*INFN Sezione di Bari, Bari, Italy*
- ^{53c}*Università di Bari, Bari, Italy*
- ^{53d}*Politecnico di Bari, Bari, Italy*
- ^{54a}*INFN Sezione di Bologna, Università di Bologna, Bologna, Italy*
- ^{54b}*INFN Sezione di Bologna, Bologna, Italy*
- ^{54c}*Università di Bologna, Bologna, Italy*
- ^{55a}*INFN Sezione di Catania, Università di Catania, Catania, Italy*
- ^{55b}*INFN Sezione di Catania, Catania, Italy*
- ^{55c}*Università di Catania, Catania, Italy*
- ^{56a}*INFN Sezione di Firenze, Università di Firenze, Firenze, Italy*
- ^{56b}*INFN Sezione di Firenze, Firenze, Italy*
- ^{56c}*Università di Firenze, Firenze, Italy*

- ⁵⁷*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
- ⁵⁸*INFN Sezione di Genova, Genova, Italy*
- ^{59a}*INFN Sezione di Milano-Bicocca, Università di Milano-Bicocca, Milano, Italy*
- ^{59b}*INFN Sezione di Milano-Bicocca, Milano, Italy*
- ^{59c}*Università di Milano-Bicocca, Milano, Italy*
- ^{60a}*INFN Sezione di Napoli, Università di Napoli “Federico II”, Napoli, Italy*
- ^{60b}*INFN Sezione di Napoli, Napoli, Italy*
- ^{60c}*Università di Napoli “Federico II”, Napoli, Italy*
- ^{61a}*INFN Sezione di Padova, Università di Padova, Università di Trento (Trento), Padova, Italy*
- ^{61b}*INFN Sezione di Padova, Padova, Italy*
- ^{61c}*Università di Padova, Padova, Italy*
- ^{61d}*Università di Trento (Trento), Padova, Italy*
- ^{62a}*INFN Sezione di Pavia, Università di Pavia, Pavia, Italy*
- ^{62b}*INFN Sezione di Pavia, Pavia, Italy*
- ^{62c}*Università di Pavia, Pavia, Italy*
- ^{63a}*INFN Sezione di Perugia, Università di Perugia, Perugia, Italy*
- ^{63b}*INFN Sezione di Perugia, Perugia, Italy*
- ^{63c}*Università di Perugia, Perugia, Italy*
- ^{64a}*INFN Sezione di Pisa, Università di Pisa, Scuola Normale Superiore di Pisa, Pisa, Italy*
- ^{64b}*INFN Sezione di Pisa, Pisa, Italy*
- ^{64c}*Università di Pisa, Pisa, Italy*
- ^{64d}*Scuola Normale Superiore di Pisa, Pisa, Italy*
- ^{65a}*INFN Sezione di Roma, Università di Roma “La Sapienza”, Roma, Italy*
- ^{65b}*INFN Sezione di Roma, Roma, Italy*
- ^{65c}*Università di Roma “La Sapienza”, Roma, Italy*
- ^{66a}*INFN Sezione di Torino, Università di Torino, Università del Piemonte Orientale (Novara), Torino, Italy*
- ^{66b}*INFN Sezione di Torino, Torino, Italy*
- ^{66c}*Università di Torino, Torino, Italy*
- ^{66d}*Università del Piemonte Orientale (Novara), Torino, Italy*
- ^{67a}*INFN Sezione di Trieste, Università di Trieste, Trieste, Italy*
- ^{67b}*INFN Sezione di Trieste, Trieste, Italy*
- ^{67c}*Università di Trieste, Trieste, Italy*
- ⁶⁸*Kangwon National University, Chunchon, Korea*
- ⁶⁹*Kyungpook National University, Daegu, Korea*
- ⁷⁰*Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea*
- ⁷¹*Korea University, Seoul, Korea*
- ⁷²*University of Seoul, Seoul, Korea*
- ⁷³*Sungkyunkwan University, Suwon, Korea*
- ⁷⁴*Vilnius University, Vilnius, Lithuania*
- ⁷⁵*Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico*
- ⁷⁶*Universidad Iberoamericana, Mexico City, Mexico*
- ⁷⁷*Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*
- ⁷⁸*Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico*
- ⁷⁹*University of Auckland, Auckland, New Zealand*
- ⁸⁰*University of Canterbury, Christchurch, New Zealand*
- ⁸¹*National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*
- ⁸²*Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*
- ⁸³*Soltan Institute for Nuclear Studies, Warsaw, Poland*
- ⁸⁴*Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal*
- ⁸⁵*Joint Institute for Nuclear Research, Dubna, Russia*
- ⁸⁶*Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia*
- ⁸⁷*Institute for Nuclear Research, Moscow, Russia*
- ⁸⁸*Institute for Theoretical and Experimental Physics, Moscow, Russia*
- ⁸⁹*Moscow State University, Moscow, Russia*
- ⁹⁰*P.N. Lebedev Physical Institute, Moscow, Russia*
- ⁹¹*State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia*
- ⁹²*University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia*
- ⁹³*Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*
- ⁹⁴*Universidad Autónoma de Madrid, Madrid, Spain*
- ⁹⁵*Universidad de Oviedo, Oviedo, Spain*
- ⁹⁶*Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain*

- ⁹⁷*CERN, European Organization for Nuclear Research, Geneva, Switzerland*
- ⁹⁸*Paul Scherrer Institut, Villigen, Switzerland*
- ⁹⁹*Institute for Particle Physics, ETH Zurich, Zurich, Switzerland*
- ¹⁰⁰*Universität Zürich, Zurich, Switzerland*
- ¹⁰¹*National Central University, Chung-Li, Taiwan*
- ¹⁰²*National Taiwan University (NTU), Taipei, Taiwan*
- ¹⁰³*Chulalongkorn University, Bangkok, Thailand*
- ¹⁰⁴*Cukurova University, Adana, Turkey*
- ¹⁰⁵*Middle East Technical University, Physics Department, Ankara, Turkey*
- ¹⁰⁶*Bogazici University, Istanbul, Turkey*
- ¹⁰⁷*Istanbul Technical University, Istanbul, Turkey*
- ¹⁰⁸*National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine*
- ¹⁰⁹*University of Bristol, Bristol, United Kingdom*
- ¹¹⁰*Rutherford Appleton Laboratory, Didcot, United Kingdom*
- ¹¹¹*Imperial College, London, United Kingdom*
- ¹¹²*Brunel University, Uxbridge, United Kingdom*
- ¹¹³*Baylor University, Waco, Texas, USA*
- ¹¹⁴*The University of Alabama, Tuscaloosa, Alabama, USA*
- ¹¹⁵*Boston University, Boston, Massachusetts, USA*
- ¹¹⁶*Brown University, Providence, Rhode Island, USA*
- ¹¹⁷*University of California, Davis, Davis, California, USA*
- ¹¹⁸*University of California, Los Angeles, Los Angeles, California, USA*
- ¹¹⁹*University of California, Riverside, Riverside, California, USA*
- ¹²⁰*University of California, San Diego, La Jolla, California, USA*
- ¹²¹*University of California, Santa Barbara, Santa Barbara, California, USA*
- ¹²²*California Institute of Technology, Pasadena, California, USA*
- ¹²³*Carnegie Mellon University, Pittsburgh, Pennsylvania, USA*
- ¹²⁴*University of Colorado at Boulder, Boulder, Colorado, USA*
- ¹²⁵*Cornell University, Ithaca, New York, USA*
- ¹²⁶*Fairfield University, Fairfield, Connecticut, USA*
- ¹²⁷*Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
- ¹²⁸*University of Florida, Gainesville, Florida, USA*
- ¹²⁹*Florida International University, Miami, Florida, USA*
- ¹³⁰*Florida State University, Tallahassee, Florida, USA*
- ¹³¹*Florida Institute of Technology, Melbourne, Florida, USA*
- ¹³²*University of Illinois at Chicago (UIC), Chicago, Illinois, USA*
- ¹³³*The University of Iowa, Iowa City, Iowa, USA*
- ¹³⁴*Johns Hopkins University, Baltimore, Maryland, USA*
- ¹³⁵*The University of Kansas, Lawrence, Kansas, USA*
- ¹³⁶*Kansas State University, Manhattan, Kansas, USA*
- ¹³⁷*Lawrence Livermore National Laboratory, Livermore, California, USA*
- ¹³⁸*University of Maryland, College Park, Maryland, USA*
- ¹³⁹*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
- ¹⁴⁰*University of Minnesota, Minneapolis, Minnesota, USA*
- ¹⁴¹*University of Mississippi, University, Mississippi, USA*
- ¹⁴²*University of Nebraska-Lincoln, Lincoln, Nebraska, USA*
- ¹⁴³*State University of New York at Buffalo, Buffalo, New York, USA*
- ¹⁴⁴*Northeastern University, Boston, Massachusetts, USA*
- ¹⁴⁵*Northwestern University, Evanston, Illinois, USA*
- ¹⁴⁶*University of Notre Dame, Notre Dame, Indiana, USA*
- ¹⁴⁷*The Ohio State University, Columbus, Ohio, USA*
- ¹⁴⁸*Princeton University, Princeton, New Jersey, USA*
- ¹⁴⁹*University of Puerto Rico, Mayaguez, Puerto Rico, USA*
- ¹⁵⁰*Purdue University, West Lafayette, Indiana, USA*
- ¹⁵¹*Purdue University Calumet, Hammond, Indiana, USA*
- ¹⁵²*Rice University, Houston, Texas, USA*
- ¹⁵³*University of Rochester, Rochester, New York, USA*
- ¹⁵⁴*The Rockefeller University, New York, USA*
- ¹⁵⁵*Rutgers, the State University of New Jersey, Piscataway, New Jersey, USA*
- ¹⁵⁶*University of Tennessee, Knoxville, Tennessee, USA*
- ¹⁵⁷*Texas A&M University, College Station, Texas, USA*

¹⁵⁸*Texas Tech University, Lubbock, Texas, USA*¹⁵⁹*Vanderbilt University, Nashville, Tennessee, USA*¹⁶⁰*University of Virginia, Charlottesville, Virginia, USA*¹⁶¹*Wayne State University, Detroit, Michigan, USA*¹⁶²*University of Wisconsin, Madison, Wisconsin, USA*^aDeceased.^bAlso at Vienna University of Technology, Vienna, Austria.^cAlso at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.^dAlso at Universidade Federal do ABC, Santo Andre, Brazil.^eAlso at California Institute of Technology, Pasadena, CA, USA.^fAlso at CERN, European Organization for Nuclear Research, Geneva, Switzerland.^gAlso at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.^hAlso at Suez Canal University, Suez, Egypt.ⁱAlso at Zewail City of Science and Technology, Zewail, Egypt.^jAlso at Cairo University, Cairo, Egypt.^kAlso at Fayoum University, El-Fayoum, Egypt.^lAlso at British University, Cairo, Egypt.^mNow at Ain Shams University, Cairo, Egypt.ⁿAlso at Soltan Institute for Nuclear Studies, Warsaw, Poland.^oAlso at Université de Haute-Alsace, Mulhouse, France.^pNow at Joint Institute for Nuclear Research, Dubna, Russia.^qAlso at Moscow State University, Moscow, Russia.^rAlso at Brandenburg University of Technology, Cottbus, Germany.^sAlso at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.^tAlso at Eötvös Loránd University, Budapest, Hungary.^uAlso at Tata Institute of Fundamental Research—HECR, Mumbai, India.^vAlso at University of Visva-Bharati, Santiniketan, India.^wAlso at Sharif University of Technology, Tehran, Iran.^xAlso at Isfahan University of Technology, Isfahan, Iran.^yAlso at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Teheran, Iran.^zAlso at Facoltà Ingegneria Università di Roma, Roma, Italy.^{aa}Also at Università della Basilicata, Potenza, Italy.^{bb}Also at Università degli Studi Guglielmo Marconi, Roma, Italy.^{cc}Also at Università degli Studi di Siena, Siena, Italy.^{dd}Also at University of Bucharest, Faculty of Physics, Bucuresti-Magurele, Romania.^{ee}Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia.^{ff}Also at University of Florida, Gainesville, FL, USA.^{gg}Also at University of California, Los Angeles, Los Angeles, CA, USA.^{hh}Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy.ⁱⁱAlso at INFN Sezione di Roma, Università di Roma "La Sapienza," Roma, Italy.^{jj}Also at University of Athens, Athens, Greece.^{kk}Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.^{ll}Also at The University of Kansas, Lawrence, KS, USA.^{mm}Also at Paul Scherrer Institut, Villigen, Switzerland.ⁿⁿAlso at Institute for Theoretical and Experimental Physics, Moscow, Russia.^{oo}Also at Gaziosmanpasa University, Tokat, Turkey.^{pp}Also at Adiyaman University, Adiyaman, Turkey.^{qq}Also at Izmir Institute of Technology, Izmir, Turkey.^{rr}Also at The University of Iowa, Iowa City, IA, USA.^{ss}Also at Mersin University, Mersin, Turkey.^{tt}Also at Ozyegin University, Istanbul, Turkey.^{uu}Also at Kafkas University, Kars, Turkey.^{vv}Also at Suleyman Demirel University, Isparta, Turkey.^{ww}Also at Ege University, Izmir, Turkey.^{xx}Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.

^{yy}Also at INFN Sezione di Perugia, Università di Perugia, Perugia, Italy.

^{zz}Also at University of Sydney, Sydney, Australia.

^{aaa}Also at Utah Valley University, Orem, UT, USA.

^{bbb}Also at Institute for Nuclear Research, Moscow, Russia.

^{ccc}Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.

^{ddd}Also at Argonne National Laboratory, Argonne, IL, USA.

^{eee}Also at Erzincan University, Erzincan, Turkey.

^{fff}Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.

^{ggg}Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.

^{hhh}Also at Kyungpook National University, Daegu, Korea.