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

The CMS Collaboration

Abstract

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 $5.0 \, \text{fb}^{-1}$, collected by the CMS detector at the LHC. The search signatures involve either two charged leptons of the same-flavour (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.

Submitted to Physical Review D

*See Appendix A for the list of collaboration members
1 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]. LQs 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 $\lambda$, and it decays to a charged lepton and a quark with an unknown branching fraction $\beta$ or to a neutrino and a quark with branching fraction $1 - \beta$. In order to satisfy constraints from bounds on flavor-changing-neutral-currents and from rare pion and kaon decays [3, 8], it is assumed that LQs couple only to quarks and leptons of a single generation. LQs are classified as first-, second-, or third-generation, depending on the generation of leptons they couple to. The dominant mechanisms for the production of LQ 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 only depend 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 $\lambda$ of an LQ to a lepton and a quark is typically smaller.

This paper reports on a search for pair production of scalar leptoquarks. Several experiments have searched for pair-produced scalar LQs 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 (lljj) and the other with one high-$p_T$ electron or muon, large missing transverse energy ($E_T^{\text{miss}}$), and at least two high-$p_T$ jets (lvjj).

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 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 $\eta$ is defined as $\eta = -\ln[\tan(\theta/2)]$, and $\theta$ is the polar angle measured with respect to the $z$ axis. The crystal
Dataset and object reconstruction

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 endcaps ($|\eta| < 1.6$). 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 $lljj$ and $l\nu jj$ analyses are performed separately and the results are combined as a function of the branching fraction $\beta$ 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 Section 2. 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 $E_T^{\text{miss}}$ 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 in order 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 ($M_{lj}$), 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 ($M_{ll}$) in the $lljj$ channels or $E_T^{\text{miss}}$ in the $l\nu jj$ 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 LQ 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 $lljj$ and $l\nu jj$ channels are combined to further maximize the exclusion in $\beta$ 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 Section 2 of this paper, followed by a description of the signal modeling and background estimates in Section 3 and Section 4, respectively. Section 5 contains the final event selection, and Section 6 describes the systematic uncertainties. The results of the search are presented in Section 7 and summarized in Section 8.

2 Dataset 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 $evjj$ 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%.

Electron candidates [19] are required to have an electromagnetic cluster with $p_T > 40$ GeV and pseudorapidity $|\eta| < 2.5$ (2.2) for the $eejj$ ($evjj$) analysis, excluding the transition region between the barrel and the endcap detectors, $1.44 < |\eta| < 1.57$. The $evjj$ 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 acceptance. Electron candidates are 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 $E_T^{\text{miss}}$ are reconstructed using a particle-flow algorithm [21], which identifies and measures stable particles by combining information from all CMS sub-detectors. The $E_T^{\text{miss}}$ 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-$k_T$ algorithm with a distance parameter of $R = 0.5$. The jet energy is calibrated using $p_T$ balance of dijet and $\gamma +$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 $M_{ll} > 60$ (50) GeV. To reduce the combinatorial background, events with a scalar transverse energy $S_T^l = p_T(l_1) + p_T(l_2) + p_T(j_1) + p_T(j_2)$ below 250 GeV are rejected.

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 $E_T^{\text{miss}}$ vector is required to be $\Delta\phi(E_T^{\text{miss}}, j_1) > 0.5$ to reject events with misreconstructed $E_T^{\text{miss}}$. In order to
reduce the contribution from QCD multijet events, the lepton and the $E_T^{\text{miss}}$ are required to be separated by $\Delta \phi (E_T^{\text{miss}}, l) > 0.8$. In addition, events are rejected if the scalar transverse energy $S_T^{ll} = p_T(l) + E_T^{\text{miss}} + p_T(j_1) + p_T(j_2)$ is below 250 GeV.

The initial selection criteria are summarized in Table 1.

Table 1: Initial selection criteria in the $eejj$, $\mu\mu jj$, $e\nu jj$, and $\mu\nu jj$ channels.

| Variable | $eejj$ | $\mu\mu jj$ | $e\nu jj$ | $\mu\nu jj$ |
|----------|--------|-------------|-----------|------------|
| $p_T(l_1)$ [GeV] | > 40 | > 40 | > 40 | > 40 |
| $p_T(l_2)$ [GeV] | > 40 | > 40 | — | — |
| $|\eta(l_1)|$ | < 2.5 | < 2.1 | < 2.2 | < 2.1 |
| $|\eta(l_2)|$ | < 2.5 | < 2.1 | — | — |
| $p_T(j_1)$ [GeV] | > 30 | > 30 | > 40 | > 40 |
| $p_T(j_2)$ [GeV] | > 30 | > 30 | > 40 | > 40 |
| $\Delta R(l, j)$ | > 0.3 | > 0.3 | > 0.3 | > 0.3 |
| $E_T^{\text{miss}}$ [GeV] | — | — | > 55 | > 55 |
| $|\Delta \phi(E_T^{\text{miss}}, j_1)|$ | — | — | > 0.5 | > 0.5 |
| $|\Delta \phi(E_T^{\text{miss}}, l)|$ | — | — | > 0.8 | > 0.8 |
| $M_{ll}$ [GeV] | > 60 | > 50 | — | — |
| $E_T^\gamma$ [GeV] | — | — | > 50 | > 50 |
| $S_T^{ll}$ [GeV] | > 250 | > 250 | — | — |
| $S_T^\nu$ [GeV] | — | — | > 250 | > 250 |

3 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 $\mu \approx M_{LQ}$. The MC generation uses the PYTHIA generator [24] (version 6.422) and CTEQ6.6 parton distribution functions (PDF). The MC samples used to estimate the contribution from SM background processes are $tt$+jets events, generated with MADGRAPH [25, 26]; single-top events ($s$, $t$, and $tW$ channels), generated with MADGRAPH; $Z/\gamma^\ast$+jets events and $W$+jets events, generated with SHERPA [27]; $VV$ events, where $V$ either represents 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 [28], and includes multiple collisions in a single bunch crossing corresponding to the luminosity profile of the LHC during the data taking periods of interest.

4 Background estimate

The main processes that can mimic the signature of a leptoquark signal in the $lljj$ channels are $Z/\gamma^\ast$+jets, $t\bar{t}$, $VV$+jets, $W$+jets, and QCD multijets. The $Z/\gamma^\ast$+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 ($70 < M_{ll} < 100$ GeV for electrons and $80 < M_{ll} < 100$ GeV for muons) and in the region of high (H) mass $M_{ll} > 100$ GeV. The low mass scaling factor $R_Z = N_L/N_L^{MC}$ is measured to be $1.27 \pm 0.02$ for both $eejj$ and $\mu\mu jj$ channels, 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:

$$N_H = R_{Z\gamma} N_{H}^{MC},$$

where $N_{H}^{MC}$ is the number of MC events with $M_H > 100$ GeV. The estimated number of $Z/\gamma^* + \text{jets}$ events is obtained with the selection criteria optimized for different LQ 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 is estimated from the number of data events that contain one electron and one muon. This type of background is expected to produce $ee$ plus $\mu\mu$ and $e\mu$ final state events with equal probability.

In the data the number of $ee$ or $\mu\mu$ events is estimated to be:

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

where $\epsilon_e$ and $\epsilon_{\mu}$ are the muon and electron reconstruction and identification efficiencies and $\epsilon_{\text{trig}}$ are the HLT efficiencies to select $ee$, $\mu\mu$, and $e\mu$ events.

No QCD multijet MC events pass the $\mu\mu jj$ final selection. A crosscheck 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 LQ 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 $\eta$ in a data sample with one and only one electron candidate, two or more jets and low $E_T^{\text{miss}}$. 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 $E_T^{\text{miss}}$), 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.

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

In the $l\nu jj$ channel, the main backgrounds come from three sources: processes that lead to the production of a genuine $W$ bosons 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 background, $W + \text{jets}$, 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 the $E_T^{\text{miss}}$.

In the $evjj$ analysis, 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:

$$\begin{align*}
N_1 &= R_{t\bar{t}} N_{1,t\bar{t}} + R_W N_{1,W} + N_{1,QCD} + N_{1,O} \\
N_2 &= R_{t\bar{t}} N_{2,t\bar{t}} + R_W N_{2,W} + N_{2,QCD} + N_{2,O}.
\end{align*}$$

(3)
where $N_i$, $N_{iW}$, $N_{iO}$, $N_{it}$, and $N_{iQCD}$ are the number of events in data, W+jets, other MC backgrounds, t\(\bar{t}\)-MC, and QCD multijet events obtained from data, passing selection $i$. The solution of the system yields the following normalization factors:

$R_{tt} = 0.82 \pm 0.04 \text{ (stat.)} \pm 0.02 \text{ (syst.)}$

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 W+jets normalization factor is calculated in the region $50 < M_T < 110 \text{ GeV}$ as:

$$R_{W} = \frac{N - (N_{tt} + R_{Z}N_{Z} + N_{O})}{N_{W}}$$

where $N$, $N_{tt}$, $N_{Z}$, $N_{O}$, and $N_{W}$ are the number of events in data, t\(\bar{t}\), Z/\(\gamma^*\)+jets, other backgrounds (QCD, diboson, single top production), and W+jets MC samples, normalized to the integrated luminosity of the data sample. $R_{W}$ is measured to be $1.21 \pm 0.01 \text{ (stat.)}$. To estimate the total t\(\bar{t}\) background in the $\mu\nu jj$ analysis, the MC prediction is compared with data in a control sample enriched with t\(\bar{t}\) events ($50 < M_T < 110 \text{ GeV}$, $E_{miss}^T > 55 \text{ GeV}$, and at least four jets). The normalization factor of the t\(\bar{t}\) background,

$$R_{tt} = \frac{N - (N_{W} + R_{Z}N_{Z} + N_{O})}{N_{tt}}$$

is calculated to be $0.88 \pm 0.02 \text{ (stat.)}$. The calculation of the normalization factors $R_{W}$ and $R_{tt}$ is repeated using an iterative procedure.

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. However, as multijet processes are difficult to accurately model by MC simulation, several crosschecks 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 $ev jj$ analysis is similar to the one used for the eejj channel.

### 5 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 $lljj$ channels: $M_{ll}$, $S_T^l$, and $M_{lj}^{\text{min}}$. The invariant mass of the dilepton pair, $M_{ll}$, is used to remove the majority of the contribution from the Z/\(\gamma^*\)+jets background. The variable $M_{lj}^{\text{min}}$ is defined as the smaller lepton-jet invariant mass for the assignment of jets and leptons to LQs which minimizes the LQ - LQ invariant mass difference.

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

The resulting optimized thresholds are summarized in Tables 2 and 3 for the $lljj$ and the $lv jj$ channels, respectively.
Table 2: Optimized thresholds for different mass hypothesis of the $lljj$ signal.

| $M_{LQ}$ (GeV) | 250 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 750 | 850 | 900 |
|---------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $S^l_T > (GeV)$ | 330 | 450 | 530 | 610 | 690 | 720 | 770 | 810 | 880 | 900 | 920 |
| $M_{ll} > (GeV)$ | 100 | 110 | 120 | 130 | 130 | 130 | 140 | 150 | 150 | 150 | 150 |
| $M_{min}lj > (GeV)$ | 60 | 160 | 200 | 250 | 300 | 340 | 370 | 400 | 470 | 500 | 520 |

Table 3: Optimized thresholds for different mass hypotheses of the $l\nu jj$ signal.

| $M_{LQ}$ (GeV) | 250 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 750 | 850 | 890 | 970 | 1000 | 1000 | 2400 |
|---------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $S^l_{\nu}T > (GeV)$ | 450 | 570 | 650 | 700 | 800 | 850 | 890 | 970 | 1000 | 1000 | 1000 | 1000 | 2400 | 2400 |
| $E_T^{miss} > (GeV)$ | 100 | 120 | 120 | 140 | 160 | 160 | 180 | 180 | 220 | 220 | 220 | 220 | 220 | 220 |
| $M_{lj} > (GeV)$ | 150 | 300 | 360 | 360 | 360 | 480 | 480 | 540 | 540 | 540 | 540 | 540 | 540 | 540 | 540 |

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.

Figure 2: $eejj$ channel: the distributions of $S^{ee_T}$ (left) and of $M_{ej}$ for each of the two electron-jet pairs (right) 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 LQ signal with $M_{LQ} = 400$ GeV is also shown.

Figure 3: $evjj$ channel: the distributions of $S^{ev_T}$ (left) and of $M_{ej}$ (right) 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 LQ signal with $M_{LQ} = 400$ GeV is also shown.

The number of events selected in data and estimated backgrounds are then compared at different stages of selection. This information is shown in Tables 4–7 for the initial selection and for
5 Event selection optimization

Figure 4: $\mu\mu jj$ channel: the distributions of $S_T^{\mu\mu}$ (left) and of $M_{\mu j}$ (right) for each of the two muon-jet pairs (right) 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 LQ signal with $M_{LQ} = 400$ GeV is also shown.

Figure 5: $\mu\nu jj$ channel: the distributions of $S_T^{\mu\nu}$ (left) and of $M_{\mu j}$ (right) 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 LQ signal with $M_{LQ} = 400$ GeV is also shown.
the final selection for each channel separately.

Table 4: 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+jets, γ+jets, and VV+jets. Only statistical uncertainties are reported.

| \( M_{LQ} \) | Z+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 |
| 450       | 15.2 ± 1.1 | 7.8 ± 2.0 | 0.310 ± 0.013 | 1.92 ± 0.60 | 225.6 ± 1.0 | 26 | 25.2 ± 2.3 |
| 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 | 3.34 ± 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 | 0.0001 ± 0.56 | 0.0092 ± 0.0020 | 0.41 ± 0.40 | 5.526 ± 0.023 | 0 | 1.45 ± 0.47 |
| 850       | 0.81 ± 0.23 | 0.0001 ± 0.56 | 0.00101 ± 0.00022 | 0.40 ± 0.40 | 1.9679 ± 0.0078 | 0 | 1.21 ± 0.46 |

Table 5: Individual background (BG) sources, expected signal, data, and total background event yields after the initial (first row) and final selections for the \( e\mu jj \) analysis. Other BG includes single top, Z+jets, γ+jets, and VV+jets. Only statistical uncertainties are reported.

| \( M_{LQ} \) | W+jets | \( t\bar{t} \) | QCD | Other | LQ Signal | Data | Total BG |
|-----------|--------|---------|-----|-------|-----------|------|----------|
| \(-\)     | 20108 ± 99 | 930 ± 42 | 3267 ± 26 | 1913 ± 53 | -- | 34135 | 34590 ± 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 |
| 450       | 19.7 ± 2.9 | 12.2 ± 1.5 | 3.01 ± 0.31 | 4.13 ± 0.44 | 68.38 ± 0.43 | 29 | 39.1 ± 3.3 |
| 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 |

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

## 6 Systematics Uncertainties

The uncertainty on the integrated luminosity is taken as 2.2% [29].

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 two.

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.
Figure 6: eejj channel: the distributions of $S_T^{ee}$ (left) and of $M_{ej}$ for each of the two electron-jet pairs (right) for events that pass the final selection criteria optimized for a signal LQ 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 LQ signal with $M_{LQ} = 600$ GeV is also shown.

Figure 7: evjj channel: the distributions of $S_T^{ev}$ (left) and of $M_{ej}$ (right) for events that pass the final selection criteria optimized for a signal LQ 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 LQ signal with $M_{LQ} = 600$ GeV is also shown.

Figure 8: µµjj channel: the distributions of $S_T^{µµ}$ (left) and of $M_{µj}$ for each of the two muon-jet pairs (right) for events that pass the final selection criteria optimized for a signal LQ 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 LQ signal with $M_{LQ} = 600$ GeV is also shown.
Table 6: 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, W+jets, and $VV$+jets. Only statistical uncertainties are reported.

| $M_{LQ}$ (GeV) | Z+jets | $t\bar{t}$ | Other BG | LQ Signal | Data | Total BG |
|----------------|--------|-----------|----------|-----------|------|----------|
| $-$            | 8413   | 1028      | 197.9    | -         | 9725 | 9638     |
| 400            | 45.9 ± 2.4 | 24.3 ± 4.1 | 3.54 ± 0.69 | 629.3 ± 4.0 | 68   | 73.8 ± 4.8 |
| 500            | 10.3 ± 1.1 | 4.2 ± 1.7  | 0.88 ± 0.60 | 136.70 ± 0.86 | 14   | 15.3 ± 2.0 |
| 550            | 7.18 ± 0.92 | 2.1 ± 1.2   | 0.53 ± 0.58 | 70.49 ± 0.40 | 9    | 9.8 ± 1.6 |
| 600            | 4.95 ± 0.74 | 0.69 ± 0.69 | 0.47 ± 0.58 | 37.39 ± 0.22 | 6    | 6.1 ± 1.2 |
| 650            | 3.76 ± 0.64 | 0.69 ± 0.69 | 0.24 ± 0.57 | 20.56 ± 0.13 | 5    | 4.7 ± 1.0 |
| 750            | 2.00 ± 0.46 | 0.00 ± 0.79 | 0.09 ± 0.57 | 5.875 ± 0.036 | 1    | 2.1 ± 1.1 |
| 850            | 1.53 ± 0.41 | 0.00 ± 0.79 | 0.08 ± 0.57 | 2.327 ± 0.014 | 0    | 1.6 ± 1.1 |

Table 7: 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.

| $M_{LQ}$ (GeV) | W+jets | $t\bar{t}$ | Other BG | LQ Signal | Data | Total BG |
|----------------|--------|-----------|----------|-----------|------|----------|
| $-$            | 23000 | 13066     | 2106     | -         | 39287 | 38170     |
| 400            | 30.2 ± 4.2 | 25.7 ± 2.8 | 5.88 ± 0.64 | 118.4 ± 1.2 | 61   | 61.8 ± 5.1 |
| 500            | 17.0 ± 3.1 | 10.3 ± 1.8 | 3.40 ± 0.51 | 34.02 ± 0.28 | 26   | 30.6 ± 3.6 |
| 550            | 5.6 ± 1.7 | 4.5 ± 1.2  | 2.16 ± 0.42 | 15.53 ± 0.14 | 12   | 12.3 ± 2.1 |
| 600            | 5.4 ± 1.7 | 3.5 ± 1.1  | 1.78 ± 0.38 | 9.245 ± 0.077 | 8    | 10.7 ± 2.0 |
| 650            | 2.8 ± 1.1 | 1.20 ± 0.62 | 1.12 ± 0.30 | 4.483 ± 0.040 | 7    | 5.1 ± 1.3 |
| 750            | 2.8 ± 1.1 | 0.54 ± 0.38 | 0.98 ± 0.28 | 1.844 ± 0.015 | 6    | 4.3 ± 1.2 |
| 850            | 2.7 ± 1.1 | 0.54 ± 0.38 | 0.75 ± 0.23 | 0.6934 ± 0.0052 | 6    | 3.9 ± 1.2 |

Figure 9: $\mu\nu jj$ 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 LQ mass of 600GeV. The data are indicated by the points, and the SM backgrounds are given as cumulative histograms. The expected contribution from a LQ signal with $M_{LQ} = 600$GeV is also shown.
reconstruction uncertainties, which is calculated to be 2% and 3%, respectively. A 5.5% (5%) uncertainty on the normalization of the estimated $t\bar{t}$ background in the $evjj$ ($\mu vjj$) channel is given by the statistical uncertainty on the value of $R_{t\ell}$ after the initial selection requirements. A 10% (10%) uncertainty on the shape of the $t\bar{t}$ background distribution in the $evjj$ ($\mu vjj$) 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 two.

A systematic uncertainty of 50% (25%) on the QCD multijet background estimate for the $eejj$ ($evjj$) 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 LQ production and on the final selection acceptance have been calculated using the PDF4LHC [30] prescriptions. 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 (endcap) 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 endcaps, respectively, the muon momentum by 4%, and by varying the jet energy resolution by an $\eta$-dependent value in the range 5-14%. In the $lvjj$ analyses, the uncertainty on the energy and momentum scales and resolutions are 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 [31]. A $\sim 1\%$ 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 $eejj$ ($evjj$) channel.

The systematic uncertainties, and their effects on signal and background are summarized in Table 8 for all channels, corresponding to the final selection optimized for $M_{LQ} = 600$ GeV.

7 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 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 statistical nature are described with $\Gamma$ 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 pair production cross section in Figs. 10 and 11. The theoretical cross sections are represented for different values of the renormalization and factorization scale, $\mu$, varied between half and twice the LQ mass (blue shaded region). The PDF uncertainties are taken into account in the theoretical cross section values.

By comparing the observed upper limit with the theoretical cross section values, first- and second-generation scalar leptoquarks with masses less than 830 (640) GeV and 840 (620) GeV, respectively, are excluded with the assumption that $\beta = 1$ (0.5). This is to be compared with median expected limits of 790 (640) GeV and 780 (610) GeV.

The observed and expected limits on the branching fraction $\beta$ as a function of leptoquark mass can be further improved using the combination of the $lljj$ and $l\nu jj$ channels, as shown in Figure 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 660 GeV.

## 8 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-flavour (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.
Figure 10: Left (right) frame: the expected and observed upper limits at 95% CL on the leptoquark pair production cross section times $\beta (2\beta(1-\beta))$ as a function of the first-generation leptoquark mass obtained with the eejj (evjj) 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 8 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 (evjj) channel only. The right shaded regions are excluded by these results. The $\sigma_{\text{theory}}$ curves and their bands represent, respectively, the theoretical scalar leptoquark pair production cross section and the uncertainties due to the choice of PDF and renormalization/factorization scales.
Figure 11: Left (right) frame: the expected and observed upper limits at 95% CL on the leptoquark pair production cross section times \( \beta \) \((2\beta(1-\beta))\) 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 8 are included in the calculation. The left and middle shaded regions in the left 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 right 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 \( \sigma_{\text{theory}} \) curves and their bands represent, respectively, the theoretical scalar leptoquark pair production cross section and the uncertainties due to the choice of PDF and renormalization/factorization scales.
Figure 12: Left (right) frame: the expected and observed exclusion limits at 95% CL on the first- (second-)generation leptoquark hypothesis in the $\beta$ 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 8 are included in the calculation. The shaded region is excluded by the current ATLAS limits [14][15].

Acknowledgements

We extend our thanks to Michael Krämer for providing the tools for calculation of the leptoquark theoretical cross section and PDF uncertainty.

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC machine. We thank the technical and administrative staff at CERN and other CMS institutes, and acknowledge support from: BMWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); MoER, SF0690030s09 and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MSI (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MON, RosAtom, RAS and RFBR (Russia); MSTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); TUBITAK and TAEK (Turkey); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie programme and the European Research Council (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Austrian Science Fund (FWF); the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l’Industrie et dans l’Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Council of Science and Industrial Research, India; the Compagnia di San Paolo (Torino); and the HOMING PLUS programme of Foundation for Polish Science, co-
financed from European Union, Regional Development Fund.

References

[1] J. C. Pati and A. Salam, “Lepton Number as the Fourth Color”, Phys. Rev. D 10 (1974) 275, doi:10.1103/PhysRevD.10.275.

[2] H. Georgi and S. Glashow, “Unity of All Elementary-Particle Forces”, Phys. Rev. Lett. 32 (1974) 438, doi:10.1103/PhysRevLett.32.438.

[3] W. Buchmüller and D. Wyler, “Constraints on SU(5)-type Leptoquarks”, Phys. Lett. B 177 (1986) 377, doi:10.1016/0370-2693(86)90771-9.

[4] S. Dimopoulos and K. Susskind, “Mass Without Scalars”, Nucl. Phys. B 155 (1979) 237, doi:10.1016/0550-3213(81)90304-7.

[5] S. Dimopoulos, “Technicolored Signatures”, Nucl. Phys. B 168 (1980) 69, doi:10.1016/0550-3213(80)90277-1.

[6] E. Eichten and K. Lane, “Dynamical Breaking of the Weak Interaction Symmetries”, Phys. Lett. B 90 (1980) 85, doi:10.1016/0370-2693(80)90065-9.

[7] V. D. Angelopoulos et al., “Search for New Quarks Suggested by the Superstring”, Nucl. Phys. B 292 (1987) 59, doi:10.1016/0550-3213(87)90637-7.

[8] O. Shanker, “πl2, Kl3, and K0- ¯K0 Constraints on Leptoquarks and Supersymmetric Particles”, Nucl. Phys. B 204 (1982) 375, doi:10.1016/0550-3213(82)90196-1.

[9] M. Krämer et al., “Pair Production of Scalar Leptoquarks at the CERN LHC”, Phys. Rev. D 71 (2005) 057503, doi:10.1103/PhysRevD.71.057503, arXiv:hep-ph/0411038.

[10] D0 Collaboration, “Search for Pair Production of Second Generation Scalar Leptoquarks in p ¯p Collisions at √s = 1.96 TeV”, Phys. Lett. B 671 (2009) 224, doi:10.1016/j.physletb.2008.12.017, arXiv:0808.4023.

[11] CMS Collaboration, “Search for Pair Production of Second-Generation Scalar Leptoquarks in pp Collisions at √s = 7 TeV”, Phys. Rev. Lett. 106 (2011) 201803, doi:10.1103/PhysRevLett.106.201803, arXiv:1012.4033.

[12] CMS Collaboration, “Search for Pair Production of First-Generation Scalar Leptoquarks in pp Collisions at √s = 7 TeV”, Phys. Rev. Lett. 106 (2011) 201802, doi:10.1103/PhysRevLett.106.201802, arXiv:1012.4031.

[13] CMS Collaboration, “Search for Pair Production of First Generation Scalar Leptoquarks in the eνjj Channel in pp Collisions at √s = 7 TeV”, Phys. Lett. B 703 (2011) 246, doi:10.1016/j.physletb.2011.07.089, arXiv:1105.5237.

[14] ATLAS Collaboration, “Search for Second Generation Scalar Leptoquarks in pp Collisions at √s = 7 TeV with the ATLAS Detector”, (2012), arXiv:1203.3172 Submitted to Eur. Phys. J. C.

[15] ATLAS Collaboration, “Search for First Generation Scalar Leptoquarks in pp Collisions at √s = 7 TeV with the ATLAS Detector”, Phys. Lett. B 709 (2012) 158, doi:10.1016/j.physletb.2012.02.004, arXiv:1112.4828.
[16] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* 3 (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

[17] T. Junk, “Confidence Level Computation for Combining Searches with Small Statistics”, *Nucl. Instrum. Meth. A* 434 (1999) 435, doi:10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.

[18] A. L. Read, “Modified frequentist analysis of search results (the $C_L$ method)”, CERN-OPEN 2000-205, (2000). 1st Workshop on Confidence Limits, CERN, Jan. 2000.

[19] CMS Collaboration, “Electron Reconstruction and Identification at $\sqrt{s} = 7$ TeV”, CMS Physics Analysis Summary CMS-PAS-EGM-10-004, (2010).

[20] CMS Collaboration, “Performance of muon identification in pp collisions at $\sqrt{s} = 7$ TeV”, CMS Physics Analysis Summary CMS-PAS-MUO-10-002, (2010).

[21] CMS Collaboration, “Commissioning of the Particle-Flow Reconstruction in Minimum-Bias and Jet Events from pp Collisions at 7 TeV”, CMS Physics Analysis Summary CMS-PAS-PFT-10-002, (2010).

[22] M. Cacciari, G. P. Salam, and G. Soyez, “The anti-$k_t$ jet clustering algorithm”, *JHEP* 04 (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.

[23] CMS collaboration, “Determination of jet energy calibration and transverse momentum resolution in CMS”, *JINST* 6 (2011) 11002, doi:10.1088/1748-0221/6/11/P11002, arXiv:1107.4277.

[24] T. Sjöstrand et al., “High Energy Physics Event Generation with PYTHIA 6.1”, *Comput. Phys. Commun.* 135 (2001) 238, doi:10.1016/S0010-4655(00)00236-8, arXiv:hep-ph/0010017.

[25] F. Maltoni and T. Stelzer, “Madevent: Automatic Event Generation with MadGraph”, *JHEP* 02 (2003) 027, doi:10.1088/1126-6708/2003/02/027, arXiv:hep-ph/0208156.

[26] J. Alwall et al., “MadGraph/MadEvent v4: The New Web Generation”, *JHEP* 09 (2007) 028, doi:10.1088/1126-6708/2007/09/028, arXiv:0706.2334.

[27] T. Gleisberg et al., “Event Generation with SHERPA 1.1”, *JHEP* 02 (2009) 007, doi:10.1088/1126-6708/2009/02/007, arXiv:0811.4622.

[28] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* 506 (2003) 250, doi:10.1016/S0168-9002(03)01368-8.

[29] CMS Collaboration, “Absolute Calibration of the Luminosity Measurement at CMS: Winter 2012 Update”, CMS Physics Analysis Summary CMS-PAS-SMP-12-008, (2012).

[30] M. Botje et al., “The PDF4LHC Working Group Interim Recommendations”, (2011), arXiv:1101.0538.

[31] CMS Collaboration, “Search for Narrow Resonances in Dilepton Mass Spectra in $pp$ Collisions at $\sqrt{s} = 7$ TeV”, *Phys. Lett. B* (2012) doi:10.1016/j.physletb.2012.06.051, arXiv:1206.1849. In press. Corrected proofs available.
University of Sofia, Sofia, Bulgaria
A. Dimitrov, R. Hadjiiska, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China
J.G. Bian, C.M. Chen, H.S. Chen, C.H. Jiang, D. Liang, S. Liang, X. Meng, J. Tao, J. Wang, X. Wang, Z. Wang, H. Xiao, M. Xu, J. Zang, Z. Zhang

State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China
C. Asawatangtrakuldee, Y. Ban, Y. Guo, W. Li, S. Liu, Y. Mao, S.J. Qian, H. Teng, D. Wang, L. Zhang, W. Zou

Universidad de Los Andes, Bogota, Colombia
C. Avila, J.P. Gomez, B. Gomez Moreno, A.F. Osorio Oliveros, J.C. Sanabria

Technical University of Split, Split, Croatia
N. Godinovic, D. Lesal, R. Plestina, D. Polic, I. Puljak

University of Split, Split, Croatia
Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, S. Duric, K. Kadija, J. Luetic, S. Morovic

University of Cyprus, Nicosia, Cyprus
A. Attikis, M. Galanti, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis

Charles University, Prague, Czech Republic
M. Finger, M. Finger Jr.

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran, S. Elgammal, A. Ellich Kamel, S. Khalil, M.A. Mahmoud, A. Radi

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
M. Kadastik, M. Muntel, M. Raidal, L. Rebane, A. Tiko

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, G. Fedi, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
J. Harkonen, A. Heikkinen, V. Karimaki, R. Kinnunen, M.J. Kortelainen, T. Lampen, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, D. Ungaro, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland
K. Banzuzi, A. Karjalainen, A. Korpela, T. Tuuva

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
M. Besancon, S. Choudhury, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, L. Millischer, A. Nayak, J. Rander, A. Rosowsky, I. Shreyber, M. Titov

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj, C. Broutin, P. Busson, C. Charlot, N. Daci, T. Dahms, L. Dobrozynski, R. Granier de Cassagnac, M. Haguenaier, P. Miné, C. Mironov, I.N. Naranjo, M. Nguyen, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Siros, C. Veelken, A. Zabi
Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
J.-L. Agram, J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte, F. Drouhin, C. Ferro, J.-C. Fontaine, D. Gelé, U. Goerlach, P. Juillot, A.-C. Le Bihan, P. Van Hove

Centre de Calcul de l’Institut National de Physique Nucleaire et de Physique des Particules (IN2P3), Villeurbanne, France
F. Fassi, D. Mercier

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
S. Beauceron, N. Beaupere, O. Bondu, G. Boudoul, J. Chasserat, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, L. Sgandurra, V. Sordini, Y. Tschudi, P. Verdier, S. Viret

Centre de Calcul de l’Institut National de Physique Nucleaire et de Physique des Particules (IN2P3), Villeurbanne, France
F. Fassi, D. Mercier

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
S. Beauceron, N. Beaupere, O. Bondu, G. Boudoul, J. Chasserat, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, L. Sgandurra, V. Sordini, Y. Tschudi, P. Verdier, S. Viret

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
G. Anagnostou, C. Autermann, S. Beranek, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, B. Wittmer, V. Zhukov

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
M. Ata, J. Caudron, E. Dietz-Laursson, D. Duchardt, M. Erdmann, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, P. Kreuzer, M. Merschmeyer, A. Meyer, M. Olschewski, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier, M. Weber

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
M. Bontenackels, V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, J. Lingemann, A. Nowack, L. Perchalla, O. Pooth, P. Sauerland, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, J. Behr, W. Behrenhoff, U. Behrens, M. Bergholz, A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, E. Castro, F. Costanza, D. Dammann, C. Diez Pardos, G. Eckerlin, D. Eckstein, G. Flucke, A. Geiser, I. Glushkov, P. Gunnellini, S. Habib, J. Hauk, G. Hellwig, H. Jung, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann, B. Lutz, R. Mankel, I. Marfin, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, O. Novgorodova, J. Olzem, H. Perrey, A. Petrukhin, D. Pitzl, A. Raspereza, P.M. Ribeiro Cipriano, C. Riedl, E. Ron, M. Rosin, J. Salfeld-Nebgen, R. Schmidt, T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany
V. Blobel, J. Draeger, H. Enderle, J. Erfle, U. Gebbert, M. Görner, T. Hermanns, R.S. Höing, K. Kaschube, G. Kaussen, H. Kirschenmann, R. Klanner, J. Lange, B. Mura, F. Nowak, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, J. Thomsen, L. Vanelderen
Institut für Experimentelle Kernphysik, Karlsruhe, Germany
C. Barth, J. Berger, C. Böser, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, M. Guthoff, C. Hackstein, F. Hartmann, T. Hauth, M. Heinrich, H. Held, K.H. Hoffmann, U. Husemann, I. Katkov, J.R. Komaragiri, P. Lobelle Pardo, D. Martschei, S. Mueller, Th. Müller, M. Niegel, A. Nürnberg, O. Oberst, A. Oehler, J. Ott, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, S. Röcker, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, M. Zeise

Institute of Nuclear Physics “Demokritos”, Aghia Paraskevi, Greece
G. Daskalakis, T. Geralis, S. Kesisoglou, A. Kyriakis, D. Loukas, I. Manolakos, A. Markou, C. Markou, C. Mavrommatis, E. Ntomari

University of Athens, Athens, Greece
L. Gouskos, T.J. Mertzimekis, A. Panagiotou, N. Saoulidou

University of Ioánnina, Ioánnina, Greece
I. Evangelou, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
G. Bencze, C. Hajdu, P. Hidas, D. Horváth, F. Sikler, V. Veszpremi, G. Vesztergombi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Molnar, J. Palinkas, Z. Szillasi

University of Debrecen, Debrecen, Hungary
J. Karancsi, P. Raics, Z.L. Trocsanyi, B. Ujvari

Panjab University, Chandigarh, India
S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Kaur, M.Z. Mehta, N. Nishu, L.K. Saini, A. Sharma, J.B. Singh

University of Delhi, Delhi, India
Ashok Kumar, Arun Kumar, S. Ahuja, A. Bhardwaj, B.C. Choudhary, S. Malhotra, M. Naimuddin, K. Ranjan, V. Sharma, R.K. Shivpuri

Saha Institute of Nuclear Physics, Kolkata, India
S. Banerjee, S. Bhattacharya, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, S. Sarkar, M. Sharan

Bhabha Atomic Research Centre, Mumbai, India
A. Abdulsalam, R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, P. Mehta, A.K. Mohanty, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research - EHEP, Mumbai, India
T. Aziz, S. Ganguly, M. Ghahiat, M. Maity, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research - HECR, Mumbai, India
S. Banerjee, S. Dugad

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
H. Arfaei, H. Bakhshiansohi, S.M. Etesami, A. Fahim, M. Hashemi, H. Hesari, A. Jafari, M. Khakzad, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh, M. Zeinali

INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy
M. Abbrescia, L. Barbone, C. Calabria, S. Chhibra, A. Colaleo, D. Creanza.
N. De Filippis\textsuperscript{a,c,5}, M. De Palma\textsuperscript{a,b}, L. Fiore\textsuperscript{a}, G. Iaselli\textsuperscript{a,c}, L. Lusito\textsuperscript{a,b}, G. Maggi\textsuperscript{a,c}, M. Maggi\textsuperscript{a}, B. Marangelli\textsuperscript{b}, S. My\textsuperscript{a,c}, S. Nuzzo\textsuperscript{a,b}, N. Pacifico\textsuperscript{a,b}, A. Pompili\textsuperscript{a,b}, G. Pugliese\textsuperscript{a,c}, G. Selvaggia\textsuperscript{a,b}, L. Silvestris\textsuperscript{a}, G. Singh\textsuperscript{b}, R. Venditti\textsuperscript{a,b}, G. Zito\textsuperscript{a}

INFN Sezione di Bologna \textsuperscript{a}, Università di Bologna \textsuperscript{b}, Bologna, Italy
G. Abbiendi\textsuperscript{a}, A.C. Benvenuti\textsuperscript{a}, D. Bonacorsi\textsuperscript{a,b}, S. Braibant-Giacomelli\textsuperscript{a,b}, L. Brigliadori\textsuperscript{a,b}, P. Capiluppi\textsuperscript{a,b}, A. Castro\textsuperscript{a,b}, F.R. Cavallo\textsuperscript{a}, M. Cuffiani\textsuperscript{a,b}, G.M. Dallavalle\textsuperscript{a}, F. Fabbri\textsuperscript{a}, A. Fanfani\textsuperscript{a,b}, D. Fasanella\textsuperscript{a,b,5}, P. Giacomelli\textsuperscript{a}, C. Grandi\textsuperscript{b}, L. Guiducci\textsuperscript{b}, S. Marcellini\textsuperscript{a}, G. Masetti\textsuperscript{a}, M. Menneghelli\textsuperscript{a,b,5}, A. Montanari\textsuperscript{a}, F.L. Navarria\textsuperscript{a,b}, F. Odorici\textsuperscript{a}, A. Perrotta\textsuperscript{a}, F. Primavera\textsuperscript{a,b}, A.M. Rossi\textsuperscript{a,b}, T. Roivelli\textsuperscript{a,b}, G. Siroli\textsuperscript{a,b}, R. Travaglini\textsuperscript{a,b}

INFN Sezione di Catania \textsuperscript{a}, Università di Catania \textsuperscript{a}, Catania, Italy
S. Albergo\textsuperscript{a,b}, G. Cappello\textsuperscript{a,b}, M. Chiorboli\textsuperscript{a,b}, S. Costa\textsuperscript{a,b}, R. Potenza\textsuperscript{a,b}, A. Tricomi\textsuperscript{a,b}, C. Tuve\textsuperscript{a,b}

INFN Sezione di Firenze \textsuperscript{a}, Università di Firenze \textsuperscript{b}, Firenze, Italy
G. Barbagli\textsuperscript{a}, V. Ciulli\textsuperscript{a,b}, C. Cividini\textsuperscript{a}, R. D’Alessandro\textsuperscript{a,b}, E. Focardi\textsuperscript{a,b}, S. Frosali\textsuperscript{a,b}, E. Gallo\textsuperscript{a}, S. Gonzi\textsuperscript{b}, M. Meschini\textsuperscript{a}, S. Paoletti\textsuperscript{a}, G. Sguazzoni\textsuperscript{a}, A. Tropiano\textsuperscript{a}

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, S. Colafranceschi\textsuperscript{24}, F. Fabbri, D. Piccolo

INFN Sezione di Genova, Genova, Italy
P. Fabbricatore, R. Muserich, S. Tosi

INFN Sezione di Milano-Bicocca \textsuperscript{a}, Università di Milano-Bicocca \textsuperscript{b}, Milano, Italy
A. Benaglia\textsuperscript{a,b}, F. De Guio\textsuperscript{a,b}, L. Di Matteo\textsuperscript{a,b,5}, S. Fioretti\textsuperscript{a,b}, S. Gennai\textsuperscript{a,b,5}, A. Ghezzi\textsuperscript{a,b}, S. Malvezzi\textsuperscript{a}, R.A. Manzioni\textsuperscript{a,b}, A. Martelli\textsuperscript{a,b}, A. Massironi\textsuperscript{a,b,5}, D. Menasce\textsuperscript{a}, L. Moroni\textsuperscript{a}, M. Paganoni\textsuperscript{a,b}, D. Pedrini\textsuperscript{a}, S. Ragazzi\textsuperscript{a,b}, N. Redaelli\textsuperscript{a}, S. Sala\textsuperscript{a}, T. Tabarelli de Fatis\textsuperscript{a,b}

INFN Sezione di Napoli "Napoli \textsuperscript{a}, Università di Napoli \textsuperscript{b}, Napoli, Italy
S. Buontempo\textsuperscript{a}, C.A. Carrillo Montoya\textsuperscript{a}, N. Cavallo\textsuperscript{a,26}, A. De Cosa\textsuperscript{a,b,5}, O. Dogangun\textsuperscript{a,b}, F. Fabozzi\textsuperscript{a,26}, A.O.M. Iorio\textsuperscript{a}, L. Lista\textsuperscript{a}, S. Meola\textsuperscript{a,27}, M. Merola\textsuperscript{a,b}, P. Paolucci\textsuperscript{a,5}

INFN Sezione di Padova \textsuperscript{a}, Università di Padova \textsuperscript{b}, Università di Trento \textsuperscript{b}, Padova, Italy
P. Azzi\textsuperscript{a}, N. Bacchetta\textsuperscript{a,5}, P. Bellan\textsuperscript{a,b}, D. Bisello\textsuperscript{a,b}, A. Branca\textsuperscript{a,b,5}, R. Carlin\textsuperscript{a,b}, P. Checchia\textsuperscript{a}, T. Dorigo\textsuperscript{a}, U. Dosselli\textsuperscript{a}, F. Gasparini\textsuperscript{a,b}, U. Garas\textsuperscript{a,b}, A. Gozzelino\textsuperscript{a}, K. Kanishchev\textsuperscript{a,c}, S. Lacaprara\textsuperscript{a}, I. Lazzizzera\textsuperscript{a,c}, M. Margoni\textsuperscript{a,b}, A.T. Meneguzzo\textsuperscript{a,b}, M. Nespolo\textsuperscript{a,b,5}, J. Pazzini\textsuperscript{a,b}, P. Ronchese\textsuperscript{a,b}, F. Simonetto\textsuperscript{a,b}, E. Torassa\textsuperscript{a,b}, S. Vanini\textsuperscript{a,b}, P. Zotto\textsuperscript{a,b}, G. Zumerle\textsuperscript{a}

INFN Sezione di Pavia \textsuperscript{a}, Università di Pavia \textsuperscript{a,b}, Pavia, Italy
M. Gabusi\textsuperscript{a,b}, S.P. Ratti\textsuperscript{a,b}, C. Riccardi\textsuperscript{a,b}, P. Torre\textsuperscript{a,b}, P. Vitulo\textsuperscript{a,b}

INFN Sezione di Perugia \textsuperscript{a}, Università di Perugia \textsuperscript{b}, Perugia, Italy
M. Biasini\textsuperscript{a,b}, G.M. Bilei\textsuperscript{a}, L. Fan\textsuperscript{a}, P. Lariccia\textsuperscript{a,b}, G. Mantovani\textsuperscript{a,b}, M. Menichelli\textsuperscript{a}, A. Nappi\textsuperscript{a,b}, F. Romeo\textsuperscript{a,b}, A. Saha\textsuperscript{a}, A. Santocchia\textsuperscript{a,b}, A. Spiezia\textsuperscript{a,b}, S. Taroni\textsuperscript{a,b}

INFN Sezione di Pisa \textsuperscript{a}, Università di Pisa \textsuperscript{b}, Scuola Normale Superiore di Pisa \textsuperscript{a}, Pisa, Italy
P. Azzurri\textsuperscript{a,c}, G. Bagliesi\textsuperscript{a}, T. Boccali\textsuperscript{a}, G. Broccolo\textsuperscript{a,c}, R. Castaldi\textsuperscript{a}, R.T. D’Agnolo\textsuperscript{a,b,c,5}, R. Dell’Orso\textsuperscript{a}, F. Fioriti\textsuperscript{a,b,5}, L. Foa\textsuperscript{a,c}, A. Giassi\textsuperscript{a}, A. Kraan\textsuperscript{a}, F. Ligabue\textsuperscript{a,c}, T. Lomtadze\textsuperscript{a}, L. Martini\textsuperscript{a,28}, A. Messineo\textsuperscript{a,b}, F. Palla\textsuperscript{a}, A. Rizzi\textsuperscript{a,b}, A.T. Serban\textsuperscript{a,29}, P. Spagnolo\textsuperscript{a}, P. Squillacioti\textsuperscript{a,5}, R. Tenchini\textsuperscript{a}, G. Tonelli\textsuperscript{a,b}, A. Venturi\textsuperscript{a}, P.G. Verdini\textsuperscript{a}

INFN Sezione di Roma \textsuperscript{a}, Università di Roma "La Sapienza" \textsuperscript{b}, Roma, Italy
L. Barone\textsuperscript{a,b}, F. Cavallari\textsuperscript{a}, D. Del Re\textsuperscript{a,b}, M. Diemoz\textsuperscript{a}, C. Fanelli, M. Grassi\textsuperscript{a,b,5}, E. Longo\textsuperscript{a,b},
P. Meridiani\textsuperscript{a,}\textsuperscript{5}, F. Micheli\textsuperscript{a,}\textsuperscript{b}, S. Nourbakhsh\textsuperscript{a,}\textsuperscript{b}, G. Organtini\textsuperscript{a,}\textsuperscript{b}, R. Paramatti\textsuperscript{a}, S. Rahatlou\textsuperscript{a,}\textsuperscript{b}, M. Sigamani\textsuperscript{a}, L. Soffi\textsuperscript{a,}\textsuperscript{b}

INFN Sezione di Torino \textsuperscript{a}, Università di Torino \textsuperscript{b}, Università del Piemonte Orientale (Novara) \textsuperscript{c}, Torino, Italy

N. Amapane\textsuperscript{a,}\textsuperscript{b}, R. Arcidiacono\textsuperscript{a,}\textsuperscript{c}, S. Argiro\textsuperscript{a,}\textsuperscript{b}, M. Arneodo\textsuperscript{a,}\textsuperscript{c}, C. Biino\textsuperscript{a}, N. Cartiglia\textsuperscript{a}, M. Costa\textsuperscript{a,}\textsuperscript{b}, N. Demaria\textsuperscript{a}, C. Mariotti\textsuperscript{a,}\textsuperscript{5}, S. Maselli\textsuperscript{a}, E. Migliore\textsuperscript{a,}\textsuperscript{b}, V. Monaco\textsuperscript{a,}\textsuperscript{b}, M. Musich\textsuperscript{a,}\textsuperscript{5}, M.M. Obertino\textsuperscript{a,}\textsuperscript{c}, N. Pastrone\textsuperscript{a}, M. Pelliccioni\textsuperscript{a}, A. Potenza\textsuperscript{a,}\textsuperscript{b}, A. Romero\textsuperscript{a,}\textsuperscript{b}, M. Ruspa\textsuperscript{a,}\textsuperscript{c}, R. Sacchi\textsuperscript{a,}\textsuperscript{b}, A. Solano\textsuperscript{a,}\textsuperscript{b}, A. Staiano\textsuperscript{a}, A. Vilela Pereira\textsuperscript{a}

INFN Sezione di Trieste \textsuperscript{a}, Università di Trieste \textsuperscript{b}, Trieste, Italy

S. Belforte\textsuperscript{a}, V. Candelise\textsuperscript{a,}\textsuperscript{b}, M. Casarsa\textsuperscript{a}, F. Cossutti\textsuperscript{a}, G. Della Ricca\textsuperscript{a,}\textsuperscript{b}, B. Gobbo\textsuperscript{a}, M. Marone\textsuperscript{a,}\textsuperscript{b,}\textsuperscript{5}, D. Montanino\textsuperscript{a,}\textsuperscript{b,}\textsuperscript{5}, A. Penzo\textsuperscript{a}, A. Schizzi\textsuperscript{a,}\textsuperscript{b}

Kangwon National University, Chunchon, Korea
S.G. Heo, T.Y. Kim, S.K. Nam

Kyungpook National University, Daegu, Korea
S. Chang, D.H. Kim, G.N. Kim, D.J. Kong, H. Park, S.R. Ro, D.C. Son, T. Son

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
J.Y. Kim, Zero J. Kim, S. Song

Korea University, Seoul, Korea
S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park

University of Seoul, Seoul, Korea
M. Choi, J.H. Kim, C. Park, I.C. Park, S. Park, G. Ryu

Sungkyunkwan University, Suwon, Korea
Y. Cho, Y. Choi, Y.K. Choi, J. Goh, M.S. Kim, E. Kwon, B. Lee, J. Lee, S. Lee, H. Seo, I. Yu

Vilnius University, Vilnius, Lithuania
M.J. Bilinskas, I. Grigelionis, M. Janulis, A. Juodagalvis

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, R. Lopez-Fernandez, R. Magaña Villalba, J. Martínez-Ortega, A. Sánchez-Hernández, L.M. Villasenor-Cendejas

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
H.A. Salazar Ibarguen

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
A.J. Bell, P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood
National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
M. Ahmad, M.H. Ansari, M.I. Asghar, H.R. Hoorani, S. Khalid, W.A. Khan, T. Khurshid, S. Qazi, M.A. Shah, M. Shoaib

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
G. Brona, K. Bunkowski, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolkowski

Soltan Institute for Nuclear Studies, Warsaw, Poland
H. Bialkowska, B. Boimska, T. Frueboes, R. Gokieli, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, G. Wrochna, P. Zalewski

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
N. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, J. Seixas, J. Varela, P. Vischia

Joint Institute for Nuclear Research, Dubna, Russia
I. Belotelov, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, G. Kozlov, A. Lanev, A. Malakhov, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, V. Smirnov, A. Volodko, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St Petersburg), Russia
S. Evstvyukhin, V. Golovtsov, Y. Ivanov, P. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, V. Matveev, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, M. Erofeeva, V. Gavrilo, M. Kossol, N. Lyakhovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, M. Dubinin, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, S. Petrushanko, A. Popov, L. Sarycheva, V. Savrin, A. Snigirev

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, G. Mesyats, S.V. Rusakov, A. Vinogradov

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bittoukov, V. Grishin, V. Kachanov, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic, M. Djordjevic, M. Ekmedzic, D. Kricsic, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Aguilar-Benitez, J. Alcaraz Maestre, P. Arce, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, C. Fernandez
Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, G. Codispoti, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain
H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J. Piedra Gomez

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Félcini, M. Fernandez, G. Fernandez, J. Gonzalez Sanchez, A. Graziano, C. Jorda, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, T. Rodrigo, A.Y. Rodriguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, E. Auffray, G. Auzinger, M. Bachts, P. Baillon, A.H. Ball, D. Barney, J.F. Benitez, C. Bernet, G. Bianchi, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, D. D’Enterria, A. Dabrowski, A. De Roeck, S. Di Guida, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, B. Frisch, W. Funk, G. Georgiou, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Girone, M. Giunta, F. Glege, R. Gomez-Reino Garrido, P. Govoni, S. Gowdy, R. Guida, M. Hansen, P. Harris, C. Hartl, J. Harvey, B. Hegner, A. Hinzmann, V. Innocente, P. Janot, K. Kaadze, E. Karavatis, K. Kousouris, P. Lecoq, Y.-J. Lee, P. Lenzi, C. Lourenço, N. Magini, T. Mäki, M. Malberti, L. Malgeri, M. Mannelli, L. Maselli, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, P. Musella, E. Nesvold, T. Orimoto, L. Orsini, E. Palencia Cortezon, E. Perez, L. Perrozzi, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, G. Polese, L. Quertenmont, A. Racz, W. Reece, J. Rodrigues Antunes, G. Rolandi, C. Rovelli, M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwik, I. Segoni, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas, D. Spiga, A. Tsiropoulos, G.I. Veres, J.R. Vlimant, H.K. Wöhri, S.D. Wurm, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kottlinski, U. Langenegger, F. Meier, D. Renker, T. Rohe, J. Sibille

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
L. Bäni, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, J. Eugster, K. Freudenreich, C. Grab, D. Hits, P. Lecomte, W. Lüstermann, A.C. Marini, P. Martinez Ruiz del Arbol, N. Mohr, F. Moortgat, C. Nügler, P. Nef, F. Nessi-Tedaldi, F. Pandolfi, L. Pape, F. Pauss, M. Peruzzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, A. Starodumov, B. Stieger, M. Takahashi, L. Tauscher, A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H.A. Weber, L. Wehrli

Universität Zürich, Zurich, Switzerland
C. Amsler, V. Chiocchia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, P. Otiougova, P. Robmann, H. Snoek, S. Tupper, M. Verzetti

National Central University, Chung-Li, Taiwan
Y.H. Chang, K.H. Chen, C.M. Kuo, S.W. Li, W. Lin, Z.K. Liu, Y.J. Lu, D. Mekterovic, A.P. Singh, R. Volpe, S.S. Yu
National Taiwan University (NTU), Taipei, Taiwan
P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, C. Dietz, U. Grundler, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, R.-S. Lu, D. Majumder, E. Petrakou, X. Shi, J.G. Shiu, Y.M. Tzeng, X. Wan, M. Wang

Chulalongkorn University, Bangkok, Thailand
B. Asavapibhop, N. Srimanobhas

Cukurova University, Adana, Turkey
A. Adiguzel, M.N. Bakirci, S. Cerci, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, T. Karaman, G. Karapinar, A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk, A. Polatoz, K. Sogut, D. Sunar Cerci, B. Tali, H. Topakli, L.N. Vergili, M. Vergili

Middle East Technical University, Physics Department, Ankara, Turkey
I.V. Akin, T. Aliev, B. Bilin, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, M. Yalvac, E. Yildirim, M. Zeyrek

Bogazici University, Istanbul, Turkey
E. Gülmez, B. Isildak, M. Kaya, O. Kaya, S. Ozkorucuklu, N. Sonmez

Istanbul Technical University, Istanbul, Turkey
K. Cankocak

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom
F. Bostock, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, L. Kreczko, S. Metson, D.M. Newbold, K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom
L. Basso, K.W. Bell, A. Belyaev, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Jackson, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley

Imperial College, London, United Kingdom
R. Bainbridge, G. Ball, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Gneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, G. Karapostoli, L. Lyons, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko, A. Papageorgiou, J. Pela, M. Pesaresi, K. Petridis, M. Pioppi, D.M. Raymond, S. Rogerson, A. Rose, M.J. Ryan, C. Seez, P. Sharp, A. Sparrow, M. Stoye, A. Tapper, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, T. Whyntie

Brunel University, Uxbridge, United Kingdom
M. Chadwick, J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leggat, D. Leslie, W. Martin, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, USA
K. Hatakeyama, H. Liu, T. Scarborough

The University of Alabama, Tuscaloosa, USA
O. Charaf, C. Henderson, P. Rumerio
Boston University, Boston, USA
A. Avetisyan, T. Bose, C. Fantasia, A. Heister, J. St. John, P. Lawson, D. Lazic, J. Rohlf, D. Sperka, L. Sulak

Brown University, Providence, USA
J. Alimena, S. Bhattacharya, D. Cutts, A. Ferapontov, U. Heintz, S. Jabeen, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, D. Nguyen, M. Segala, T. Sinthuprasith, T. Speer, K.V. Tsang

University of California, Davis, Davis, USA
R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, J. Dolen, R. Erbacher, M. Gardner, R. Houtz, W. Ko, A. Kopecky, R. Lander, O. Mall, T. Miceli, D. Pellett, F. Ricci-tam, B. Rutherford, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra

University of California, Los Angeles, Los Angeles, USA
V. Andreev, D. Cline, R. Cousins, J. Duris, S. Erhan, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, C. Jarvis, C. Plager, G. Rakness, P. Schlein, P. Traczyk, V. Valuev, M. Weber

University of California, Riverside, Riverside, USA
J. Babb, R. Clare, M.E. Dinardo, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng, H. Liu, O.R. Long, A. Luthra, H. Nguyen, S. Paramesvaran, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, San Diego, La Jolla, USA
W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, I. Macneill, B. Mangano, S. Padhi, C. Palmer, G. Petracci, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech, F. Würthwein, A. Yagil, J. Yoo

University of California, Santa Barbara, Santa Barbara, USA
D. Barge, R. Bellan, C. Campagnari, M. D’Alfonso, T. Danielson, K. Flowers, P. Geffert, J. Incandela, C. Justus, P. Kalavase, S.A. Koay, D. Kovalskyi, V. Krutelyov, S. Lowette, N. Mccoll, V. Pavlunin, F. Rebassoo, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, C. West

California Institute of Technology, Pasadena, USA
A. Apresyan, A. Bornheim, Y. Chen, E. Di Marco, J. Duarte, M. Gataullin, Y. Ma, A. Mott, H.B. Newman, C. Rogan, M. Spiropulu, V. Timciuc, J. Veverka, R. Wilkinson, S. Xie, Y. Yang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
B. Akgun, V. Azzolini, A. Calamba, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, Y.F. Liu, M. Paulini, H. Vogel, I. Vorobiev

University of Colorado at Boulder, Boulder, USA
J.P. Cumalat, B.R. Drell, W.T. Ford, A. Gaz, E. Luiggi Lopez, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, USA
J. Alexander, A. Chatterjee, N. Eggert, L.K. Gibbons, B. Heltsley, A. Khukhunaishvili, B. Kreis, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Ryd, E. Salvati, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Tucker, J. Vaughan, Y. Weng, L. Winstrom, P. Wittich

Fairfield University, Fairfield, USA
D. Winn
Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, J. Anderson, L.A.T. Bauer, A. Beret, J. Berryhill, P.C. Bhat, I. Bloch, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, V.D. Elvira, I. Fisk, J. Freeman, Y. Gao, D. Green, O. Gutsche, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, B. Kilminster, B. Klima, S. Kunori, S. Kwan, C. Leonidopoulos, J. Linacre, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko, C. Newman-Holmes, V. O’Dell, O. Prokofyev, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Updinger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, F. Yumiceva, J.C. Yun

University of Florida, Gainesville, USA
D. Acosta, P. Avery, D. Bourilkov, M. Chen, T. Cheng, S. Das, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, J. Hugon, B. Kim, J. Kingsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic, G. Mitselmakher, L. Muniz, M. Park, R. Remington, A. Rinkevicius, P. Sellers, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

Florida International University, Miami, USA
V. Gaultney, S. Hewamanage, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, USA
T. Adams, A. Askew, J. Bochenek, J. Chen, B. Diamond, S.V. Gleyzer, J. Haas, S. Hagopian, V. Hagopian, M. Jenkins, K.F. Johnson, H. Prosper, V. Veeraraghavan, M. Weinberg

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, B. Dorney, M. Hohlmann, H. Kalakhety, I. Vodopiyanov

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, I. Bucinskaite, J. Callner, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, F. Lacroix, M. Malek, C. O’Brien, C. Silkworth, D. Strom, P. Turner, N. Varelas

The University of Iowa, Iowa City, USA
U. Akgun, E.A. Albayrak, B. Bilki, W. Clarida, F. Duru, S. Griffiths, J.-P. Merlo, H. Mermerkaya, A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, Y. Onel, F. Ozok, S. Sen, P. Tan, E. Tiras, J. Wetzel, T. Yetkin, K. Yi

Johns Hopkins University, Baltimore, USA
B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, G. Giurgiu, A.V. Gritsan, Z.J. Guo, G. Hu, P. Maksimovic, S. Rappoccio, M. Swartz, A. Whitbeck

The University of Kansas, Lawrence, USA
P. Baringer, A. Bean, G. Benelli, R.P. Kenny II, M. Murray, D. Noonan, S. Sanders, R. Stringer, G. Tinti, J.S. Wood, V. Zhukova

Kansas State University, Manhattan, USA
A.F. Barfuss, T. Bolton, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze

Lawrence Livermore National Laboratory, Livermore, USA
J. Gronberg, D. Lange, D. Wright

University of Maryland, College Park, USA
A. Baden, M. Boutemeur, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, R.G. Kellogg, M. Kirn,
Purdue University Calumet, Hammond, USA
S. Guragain, N. Parashar

Rice University, Houston, USA
A. Adair, C. Boulahouache, K.M. Ecklund, F.J.M. Geurts, W. Li, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

University of Rochester, Rochester, USA
B. Betchart, A. Bodek, Y.S. Chung, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, D.C. Miner, D. Vishnevskiy, M. Zielinski

The Rockefeller University, New York, USA
A. Bhatti, R. Ciesielski, L. Demortier, K. Goulianos, G. Lungu, S. Malik, C. Mesropian

Rutgers, the State University of New Jersey, Piscataway, USA
S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, A. Lath, S. Panwalkar, M. Park, R. Patel, V. Rekovic, J. Robles, K. Rose, S. Salur, S. Schnetzer, C. Seitz, S. Somalwar, R. Stone, S. Thomas

University of Tennessee, Knoxville, USA
G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

Texas A&M University, College Station, USA
R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon59, V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, S. Sengupta, I. Suarez, A. Tatarinov, D. Toback

Texas Tech University, Lubbock, USA
N. Akchurin, J. Damgov, C. Dragoiu, P.R. Dudero, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, Y. Roh, I. Volobouev

Vanderbilt University, Nashville, USA
E. Appelt, A.G. Delannoy, C. Florez, S. Greene, A. Gurrola, W. Johns, C. Johnston, P. Kurt, C. Maguire, A. Melo, M. Sharma, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

University of Virginia, Charlottesville, USA
M.W. Arenton, M. Balazs, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, J. Wood, R. Yohay

Wayne State University, Detroit, USA
S. Gollapinini, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, A. Sakharov

University of Wisconsin, Madison, USA
M. Anderson, D. Belknap, L. Borrello, D. Carlsmith, M. Cepeda, S. Dasu, L. Gray, K.S. Grogg, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, J. Leonard, R. Loveless, A. Mohapatra, I. Ojalvo, F. Palmonari, G.A. Pierro, I. Ross, A. Savin, W.H. Smith, J. Swanson

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
3: Also at Universidade Federal do ABC, Santo Andre, Brazil
4: Also at California Institute of Technology, Pasadena, USA
5: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
6: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
7: Also at Suez Canal University, Suez, Egypt
8: Also at Zewail City of Science and Technology, Zewail, Egypt
9: Also at Cairo University, Cairo, Egypt
10: Also at Fayoum University, El-Fayoum, Egypt
11: Also at British University, Cairo, Egypt
12: Now at Ain Shams University, Cairo, Egypt
13: Also at Soltan Institute for Nuclear Studies, Warsaw, Poland
14: Also at Université de Haute-Alsace, Mulhouse, France
15: Now at Joint Institute for Nuclear Research, Dubna, Russia
16: Also at Moscow State University, Moscow, Russia
17: Also at Brandenburg University of Technology, Cottbus, Germany
18: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
19: Also at Eötvös Loránd University, Budapest, Hungary
20: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
21: Also at University of Visva-Bharati, Santiniketan, India
22: Also at Sharif University of Technology, Tehran, Iran
23: Also at Isfahan University of Technology, Isfahan, Iran
24: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Teheran, Iran
25: Also at Facoltà Ingegneria Università di Roma, Roma, Italy
26: Also at Università della Basilicata, Potenza, Italy
27: Also at Università degli Studi Guglielmo Marconi, Roma, Italy
28: Also at Università degli studi di Siena, Siena, Italy
29: Also at University of Bucharest, Faculty of Physics, Bucuresti-Magurele, Romania
30: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
31: Also at University of Florida, Gainesville, USA
32: Also at University of California, Los Angeles, Los Angeles, USA
33: Also at Scuola Normale e Sezione dell’ INFN, Pisa, Italy
34: Also at INFN Sezione di Roma; Università di Roma “La Sapienza”, Roma, Italy
35: Also at University of Athens, Athens, Greece
36: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
37: Also at The University of Kansas, Lawrence, USA
38: Also at Paul Scherrer Institut, Villigen, Switzerland
39: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
40: Also at Gaziosmanpasa University, Tokat, Turkey
41: Also at Adiyaman University, Adiyaman, Turkey
42: Also at Izmir Institute of Technology, Izmir, Turkey
43: Also at The University of Iowa, Iowa City, USA
44: Also at Mersin University, Mersin, Turkey
45: Also at Ozyegin University, Istanbul, Turkey
46: Also at Kafkas University, Kars, Turkey
47: Also at Suleyman Demirel University, Isparta, Turkey
48: Also at Ege University, Izmir, Turkey
49: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
50: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
51: Also at University of Sydney, Sydney, Australia
52: Also at Utah Valley University, Orem, USA
53: Also at Institute for Nuclear Research, Moscow, Russia
54: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
55: Also at Argonne National Laboratory, Argonne, USA
56: Also at Erzincan University, Erzincan, Turkey
57: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
58: Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
59: Also at Kyungpook National University, Daegu, Korea