Search for $W' \to tb$ decays in the lepton + jets final state in pp collisions at $\sqrt{s} = 8$TeV

S. Chatrchyan  
Yerevan Physics Institute

Ekaterina Avdeeva  
University of Nebraska-Lincoln, tsukanovaeg@gmail.com

Kenneth A. Bloom  
University of Nebraska - Lincoln, kbloom2@unl.edu

S. Bose  
University of Nebraska-Lincoln, sbose2@unl.edu

Daniel R. Claes  
University of Nebraska-Lincoln, dclaes@unl.edu

See next page for additional authors

Follow this and additional works at: http://digitalcommons.unl.edu/physicssnow

Chatrchyan, S.; Avdeeva, Ekaterina; Bloom, Kenneth A.; Bose, S.; Claes, Daniel R.; Dominguez, Aaron; Gonzalez Suarez, Rebeca; Keller, J.; Knowlton, D.; Kravchenko, Ilya; Lazo-Flores, J.; Malik, S.; Meier, F.; Snow, Gregory R.; and CMS collaboration, "Search for $W' \to tb$ decays in the lepton + jets final state in pp collisions at $\sqrt{s} = 8$TeV" (2014). Gregory Snow Publications. 92.  
http://digitalcommons.unl.edu/physicssnow/92

This Article is brought to you for free and open access by the Research Papers in Physics and Astronomy at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Gregory Snow Publications by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.
Authors
S. Chatrchyan, Ekaterina Avdeeva, Kenneth A. Bloom, S. Bose, Daniel R. Claes, Aaron Domínguez, Rebeca Gonzalez Suarez, J. Keller, D. Knowlton, Ilya Kravchenko, J. Lazo-Flores, S. Malik, F. Meier, Gregory R. Snow, and CMS collaboration
Search for $W' \rightarrow tb$ decays in the lepton + jets final state in pp collisions at $\sqrt{s} = 8$ TeV

The CMS collaboration

E-mail: cms-publication-committee-chair@cern.ch

ABSTRACT: Results are presented from a search for the production of a heavy gauge boson $W'$ decaying into a top and a bottom quark, using a data set collected by the CMS experiment at $\sqrt{s} = 8$ TeV and corresponding to an integrated luminosity of $19.5 \text{fb}^{-1}$. Various models of $W'$-boson production are studied by allowing for an arbitrary combination of left- and right-handed couplings. The analysis is based on the detection of events with a lepton (e, $\mu$), jets, and missing transverse energy in the final state. No evidence for $W'$-boson production is found and 95% confidence level upper limits on the production cross section times branching fraction are obtained. For $W'$ bosons with purely right-handed couplings, and for those with left-handed couplings assuming no interference effects, the observed 95% confidence level limit is $M(W') > 2.05$ TeV. For $W'$ bosons with purely left-handed couplings, including interference effects, the observed 95% confidence level limit is $M(W') > 1.84$ TeV. The results presented in this paper are the most stringent limits published to date.

KEYWORDS: Exotics, Hadron-Hadron Scattering

ArXiv ePrint: 1402.2176

doi:10.1007/JHEP05(2014)108
Massive charged gauge bosons, generically referred to as $W'$, are predicted by various extensions of the standard model (SM) \cite{1–5}. Searches for $W'$ bosons at the Large Hadron Collider (LHC) have been conducted in the lepton-neutrino, diboson, and light-quark final states \cite{6–15}. While the most stringent limits come from the searches in the leptonic final states ($W' \rightarrow \ell \nu$ where $\ell$ is a charged lepton), these constraints do not apply to $W'$ bosons with purely right-handed couplings if the mass of the hypothetical right-handed neutrino is larger than a few GeV \cite{16}. Dedicated searches for $W'$ bosons with purely right-handed couplings have been performed by the CMS and ATLAS Collaborations assuming the mass of the right-handed neutrino is less than the mass of the $W'$ boson \cite{17, 18}. Searches for right-handed $W'$ bosons that decay to a quark final state such as $W'^+ \rightarrow t\bar{b}$ (or charge conjugate) make no assumptions regarding the mass of the right-handed neutrino and are thus complementary to searches in the leptonic channels. Furthermore, the decay chain $W' \rightarrow t\bar{b}$, $t \rightarrow bW \rightarrow b\ell\nu$ is in principle fully reconstructable, thereby leading to observable resonant mass peaks even in the case of broad $W'$ resonances. In addition,
because of the presence of leptons in the final state, it is easier to suppress the continuum multijet background for this decay chain than for a generic $W' \rightarrow qq'$ decay. Finally, in some models the $W'$ boson may couple more strongly to fermions of the third generation than to fermions of the first and second generations $[19, 20]$. Thus the $W' \rightarrow tb$ decay is an important channel in the search for $W'$ bosons.

Experimental searches for $W' \rightarrow tb$ decays have been performed at the Tevatron $[21–23]$ and at the LHC $[24, 25]$. The CMS search at $\sqrt{s} = 7$ TeV $[24]$ set the best present mass limit in this channel of 1.85 TeV for $W'$ bosons with purely right-handed couplings. If the $W'$ boson has left-handed couplings, interference between $W' \rightarrow tb$ and SM single-top-quark production via $W \rightarrow tb$ can contribute as much as 5–20% of the total $W'$ rate, depending on the $W'$ mass and couplings $[26]$. This interference effect was taken into account in the CMS search. The CMS analysis also set constraints on an arbitrary set of left- and right-handed couplings of the $W'$ boson.

This Letter describes the first $W' \rightarrow tb$ search in pp collisions at $\sqrt{s} = 8$ TeV and uses data collected by the CMS experiment corresponding to an integrated luminosity of 19.5 fb$^{-1}$. For a $W'$ boson with a mass of 2 TeV, the production cross section at $\sqrt{s} = 8$ TeV is larger by approximately a factor of two compared to $\sqrt{s} = 7$ TeV $[27]$. The data set used in this analysis corresponds to an integrated luminosity that is approximately a factor of four larger than that in the $\sqrt{s} = 7$ TeV analysis. Following the approach of the earlier publication $[24]$, we analyse events with an electron ($e$) or muon ($\mu$), jets, and missing transverse energy ($E_T^{\text{miss}}$) for an arbitrary combination of left- and right-handed couplings.

2 CMS detector

The central feature of the CMS detector is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Located within the superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL). Muons are identified and measured in gas-ionisation detectors embedded in the outer steel magnetic flux-return yoke of the solenoid. The detector is subdivided into a cylindrical barrel and endcap disks on each side of the interaction point. Forward calorimeters complement the coverage provided by the barrel and endcap detectors. A more detailed description of the CMS detector can be found elsewhere $[28]$.

The CMS experiment uses a right-handed coordinate system, with the origin at the nominal interaction point, the $x$ axis pointing to the centre of the LHC ring, the $y$ axis pointing up (perpendicular to the plane of the LHC ring), and the $z$ axis along the anticlockwise-beam direction. The polar angle $\theta$ is measured from the positive $z$ axis and the azimuthal angle $\phi$ is measured in radians in the $x$-$y$ plane. The pseudorapidity $\eta$ is defined as $\eta = -\ln[\tan(\theta/2)]$.

The ECAL energy resolution for electrons with transverse energy $E_T \approx 45$ GeV from $Z \rightarrow ee$ decays is better than 2% in the central region of the ECAL barrel ($|\eta| < 0.8$), and is between 2% and 5% elsewhere. The inner tracker measures charged particles within the pseudorapidity range $|\eta| < 2.5$. It provides an impact parameter resolution of $\sim 15 \mu$m and
a transverse momentum ($p_T$) resolution of about 1.5% for 100 GeV particles. Matching muons to tracks measured in the silicon tracker results in a relative transverse momentum resolution for muons with $20 < p_T < 100$ GeV of 1.3-2.0% in the barrel and better than 6% in the endcaps. The $p_T$ resolution in the barrel is better than 10% for muons with $p_T$ up to 1 TeV [29].

A particle-flow (PF) algorithm [30, 31] combines the information from all CMS subdetectors to identify and reconstruct the individual particles emerging from all vertices: charged hadrons, neutral hadrons, photons, muons, and electrons. These particles are then used to reconstruct the $E_T^{\text{miss}}$ (defined as the modulus of the negative transverse momentum vector sum of all measured particles), jets, and to quantify lepton isolation. The PF jet energy resolution is typically 15% at 10 GeV, 8% at 100 GeV, and 4% at 1 TeV, to be compared to about 40%, 12%, and 5% obtained when the calorimeters alone are used for jet clustering.

3 Signal and background modelling

The $W' \rightarrow tb \rightarrow \ell \nu b b$ decay is characterized by the presence of a high-$p_T$ isolated lepton, significant $E_T^{\text{miss}}$ associated with the neutrino, and at least two high-$p_T$ b-jets (jets resulting from the fragmentation and hadronization of b quarks). Monte Carlo (MC) techniques are used to model the $W'$ signal and SM backgrounds capable of producing this final state.

3.1 Signal modelling

The signal modelling is identical to that in ref. [24] and uses the following lowest order effective Lagrangian to describe the interaction of the $W'$ boson with SM fermions:

$$\mathcal{L} = \frac{V_{f_i f_j}}{2 \sqrt{2}} g_w f_i f_j (\gamma \mu) \left( a_R^{f_i f_j} (1 + \gamma^5) + a_L^{f_i f_j} (1 - \gamma^5) \right) W'^{\mu} f_j + \text{h.c.,}$$

(3.1)

where $a_R^{f_i f_j}, a_L^{f_i f_j}$ are the right- and left-handed couplings of the $W'$ boson to fermions $f_i$ and $f_j$; $g_w = e / (\sin \theta_W)$ is the SM weak coupling constant and $\theta_W$ is the weak mixing angle; $V_{f_i f_j}$ is the Cabibbo-Kobayashi-Maskawa matrix element if the fermion $f$ is a quark, and $V_{f_i f_j} = \delta_{ij}$ if it is a lepton, where $\delta_{ij}$ is the Kronecker delta and $i, j$ are the generation numbers. For our search we consider models where $0 \leq a_L^{f_i f_j} \leq 1$. For a SM-like $W'$ boson, $a_L^{f_i f_j} = 1$ and $a_R^{f_i f_j} = 0$.

We simulate $W'$ bosons with mass values ranging from 0.8 to 3.0 TeV. The SINGLETOP MC generator [27] is used, which simulates electroweak top-quark production processes based on the complete set of tree-level Feynman diagrams calculated by the COMPHEP package [32]. Finite decay widths and spin correlations between resonance state production and subsequent decay are taken into account. The factorisation scale is set to the $W'$-boson mass for the generation of the samples and the computation of the leading-order (LO) cross section. The LO cross section is scaled to next-to-leading order (NLO) using a $K$ factor of 1.2 based on refs. [33, 34]. In order to ensure that the NLO rates and shapes of relevant distributions are reproduced, the SINGLETOP generator includes NLO corrections, and normalisation and matching between various partonic subprocesses are
performed. The top-quark mass is chosen to be 172.5 GeV and the CTEQ6M [35] parton distribution functions (PDF) are used. The uncertainty in the cross section is about 8.5% and includes contributions from the uncertainties in the renormalisation and factorisation scales (3.3%), PDFs (7.6%), $\alpha_s$ (1.3%), and the top-quark mass (<1%).

We produce the following sets of signal samples:

- $W'_L$ with $a^L_{ud} = a^L_{cs} = a^L_{tb} = 1$ and $a^R_{ud} = a^R_{cs} = a^R_{tb} = 0$
- $W'_R$ with $a^L_{ud} = a^L_{cs} = a^L_{tb} = 0$ and $a^R_{ud} = a^R_{cs} = a^R_{tb} = 1$
- $W'_{LR}$ with $a^L_{ud} = a^L_{cs} = a^L_{tb} = 1$ and $a^R_{ud} = a^R_{cs} = a^R_{tb} = 1$

The $W'_L$ bosons couple to the same fermion multiplets as the SM W boson. As a consequence, there will be interference between $s$-channel $tb$ production via a W boson and via a $W'_L$ boson. These two processes therefore cannot be generated separately. Thus the $W'_L$ and $W'_{LR}$ samples include SM $s$-channel $tb$ production including its interference with the $W'_L$ signal. Production of a $tb$ final state via a $W'_R$ boson does not interfere with $tb$ production via a W boson and therefore the $W'_R$ sample only includes $W'$ production.

The $W'_R$ boson can only decay leptonically if there is a right-handed neutrino $\nu_R$ of sufficiently small mass, $M(\nu_R)$, so that $M(\nu_R) + M(\ell) < M(W')$. If the mass of the right-handed neutrino is too large, $W'_R$ bosons can only decay to $q\bar{q}'$ final states, leading to different branching fractions for the $W'_R \rightarrow tb$ decay than for the $W'_L \rightarrow tb$ decay. In the absence of interference between the SM W boson and the $W'$ boson, and if there is a light right-handed neutrino, there is no practical difference for our search between $W'_L$ and $W'_R$ bosons.

### 3.2 Background modelling

The $t\bar{t}$, $W+$jets, single-top-quark ($s$-channel, $t$-channel, and $tW$ associated production), $Z/\gamma^*+jets$, and diboson (WW) background contributions are estimated from simulation, with corrections to the shape and normalisation derived from data.

The $t\bar{t}$, $W+$jets, and $Z/\gamma^*+jets$ background processes are generated with MadGraph 5.1 [36]. The $t\bar{t}$ background is normalized to the next-to-NLO (NNLO) cross section [37]. The SM single-top-quark backgrounds are estimated using samples generated with POWHEG [38], normalized to an approximate NNLO cross section [39]. For the $W'_R$ search, $s$-channel, $t$-channel, and $tW$ single-top-quark events are considered as backgrounds. Because of interference between $W'$ and $s$-channel single-top-quark production, in the analysis for $W'_L$ and $W'_{LR}$ bosons only the $t$-channel and the $tW$ processes contribute to the background. The diboson (WW) background is generated with PYTHIA 6.424 [40]. Instrumental background due to a jet misidentified as an isolated lepton was studied using a sample of QCD multijet events simulated with PYTHIA and was found to be negligible after the final selection.

### 3.3 Simulation

For all simulated samples, PYTHIA tune Z2* [41] is used for parton showering, hadronisation, and simulation of the underlying event. The PYTHIA and MadGraph backgrounds
use the CTEQ6L1 PDFs, and the POWHEG backgrounds use the CTEQ6M PDFs [35]. The resulting events are processed with the full GEANT4 [42] simulation of the CMS detector. The additional proton-proton interactions in each beam crossing (pileup) are modelled by superimposing extra minimum-bias interactions onto simulated events, with the distribution of the number of pileup interactions matching that in data.

4 Object and event preselection

The analysis relies on the reconstruction of electrons, muons, jets, and $E_{T}^{miss}$. Candidate events are required to pass an isolated electron (muon) trigger with a $p_T$ threshold of 27 (24) GeV and to have at least one reconstructed pp interaction vertex. In the offline selection, exactly one electron (muon) is required to be within the region of $|\eta| < 2.5$ (2.1). Additionally, the barrel/endcap transition region, $1.44 < |\eta| < 1.56$, is excluded for electrons. Electrons and muons are required to satisfy $p_T > 50$ GeV and a series of identification and isolation criteria. Electron candidates are selected using shower shape information, the quality of the track, the matching between the track and the electromagnetic cluster, the fraction of total cluster energy in the HCAL, and the amount of activity in the surrounding regions of the tracker and calorimeters. Events are removed whenever the electron is found to originate from a converted photon. The track associated with a muon candidate is required to have at least one pixel hit, hits in at least six layers of the inner tracker, at least one hit in the muon detector, and a good quality fit with $\chi^2/\text{d.o.f.} < 10$. Both electrons and muons are separated from jets by requiring $\Delta R(\text{jet}, \ell) = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} > 0.3$. Additionally, the cosmic ray background is effectively eliminated by requiring the transverse impact parameter of the muon with respect to the beam spot to be less than 2 mm. Electrons (muons) are required to have PF based relative isolation, $I_{\text{rel}}$, less than 0.10 (0.12). The quantity $I_{\text{rel}}$ is defined as the sum of the transverse momenta of all additional reconstructed particle candidates inside a cone around the electron (muon) in $(\eta, \phi)$ of $\Delta R < 0.3$ (0.4), divided by the $p_T$ of the electron (muon). An event-by-event correction is applied to the computation of the lepton isolation in order to account for the effect of pileup. Events containing a second lepton with looser identification and isolation requirements are also rejected. Scale factors, derived from comparing the efficiencies measured in data and simulation using $Z \rightarrow \ell\ell$ events, are obtained for lepton identification and isolation as a function of lepton $p_T$ and $\eta$. These are applied as corrections to the simulated events.

Jets are clustered using the anti-$k_T$ algorithm [43] with a distance parameter of $R = 0.5$ and are required to satisfy $p_T > 30$ GeV and $|\eta| < 2.4$. At least two jets are required in the event with the highest-$p_T$ (leading) jet $p_T > 120$ GeV and the second leading jet $p_T > 40$ GeV. The jet $p_T$ in the simulated samples is smeared to account for the better jet energy resolution observed in the simulation compared to data [44]. Jet energy corrections are applied to correct for residual non-uniformity and non-linearity of the detector response. Jet energies are also corrected by subtracting the average contribution from pileup interactions [45, 46].

The final state of the $W' \rightarrow tb$ decay includes two b quarks; therefore at least one of the two leading jets is required to be tagged as a b-jet. We use the combined secondary
vertex tagger with the medium operating point [47]. Data-to-simulation scale factors for
the b-tagging efficiency and the light-quark or gluon (udsg) jet mistag rate are applied on
a jet-by-jet basis to all b-jets, c-jets, and udsg jets in the simulated events. Scale factors
are also applied to W+jets events in which a b, c, or udsg jet is produced in association
with the W boson, in order to bring the data and simulation yields into agreement.
The procedure used is identical to the one described in ref. [24]. Based on lepton + jets
samples with various jet multiplicities, W+b and W+c corrections are derived [48]. To ac-
count for differences between the lepton + jets topology and the topology considered here,
additional W+udsg and W+b/c corrections are derived from two background-dominated
event samples, one without any b-tagged jets and one without any b-tagging requirement.
These corrections are then applied to the simulated W+jets events. We find that the
W+b, W+c, and W+udsg contributions need to be corrected by an overall factor of 1.21,
1.66, and 0.83, respectively. These corrections agree within their uncertainties with the
corresponding corrections derived in ref. [24].

Finally, the $E_T^{\text{miss}}$ is required to exceed 20 GeV in both the electron and muon samples
in order to reduce the QCD multijet background.

5 Data analysis

The distinguishing feature of a W′ signal is a narrow resonance structure in the tb invariant-
mass spectrum. The tb invariant mass is reconstructed from the combination of the charged
lepton, the neutrino, the jet which gives the best top-quark mass reconstruction, and
the highest-$p_T$ jet in the event that is not associated with the top quark. The $x$ and $y$
components of the neutrino momentum are obtained from the missing transverse energy.
The $z$ component is calculated by constraining the invariant mass of the lepton-neutrino
pair to the W-boson mass (80.4 GeV). This constraint leads to a quadratic equation in
$p_T^{\nu}$. In the case of two real solutions, both of the solutions are used to reconstruct the W-
boson candidates. In the case of complex solutions, the real part is assigned to $p_T^{\nu}$ and the
imaginary part is forced to zero by relaxing the W-boson mass constraint and recomputing
$p_T^{\nu}$. The $p_T^{\nu}$ solution that gives the invariant mass of the lepton-neutrino pair closest to
80.4 GeV is chosen, resulting in a single W-boson candidate. Top-quark candidates are then
reconstructed using the W-boson candidate(s) and all of the selected jets in the event, and
the top-quark candidate with mass closest to 172.5 GeV is chosen. The W′-boson candidate
is obtained by combining the best top-quark candidate with the highest-$p_T$ jet, excluding
the one used for the best top-quark candidate. For a 2.0 TeV W′ boson, this procedure
assigns the correct jets from the W′ decay 83% of the time.

Since the W+jets process is one of the major backgrounds for the W′ signal process
(see table 1), a study is performed to check that the shape of the W+jets mass distribution
is well-modelled by the simulation. This cross-check utilizes the fact that events that
have no b-tagged jets, but satisfy all other selection criteria, are expected to originate
predominantly from W+jets events. The purity of W+jets events for this control sample
is greater than 85%. The shape of the W+jets background is obtained by subtracting the
backgrounds from sources other than W+jets from the distributions in data. The resulting
invariant-mass distribution is compared to the distribution from the W+jets MC sample with zero b-tagged jets. The difference between the distributions is included as a systematic uncertainty in the shape of the W+jets background. Using simulated events, the W+jets background was verified to be independent of the number of b-tagged jets by comparing the mass distribution with zero b-tagged jets with that obtained by requiring one or more b-tagged jets.

Measurements of the top-quark differential cross sections have shown that the top-quark $p_T$ distribution is not properly modelled in simulated events [49]. We therefore reweight the $t\bar{t}$ sample using an empirical function of the generated top quark and anti-top quark $p_T$ determined from studies of the $t\bar{t}$ differential cross section. Residual differences with respect to the unweighted distribution are taken into account as a systematic uncertainty in the $t\bar{t}$ background prediction. We check the applicability of these weights to our kinematic region by defining a control region in data that is dominated by $t\bar{t}$ events.

The control region is defined by the following requirements, which are designed to ensure small ($\lesssim 2\%$) potential signal contamination: $N_{\text{jets}} \geq 4$, the total number of b-tagged jets (including jets with $p_T$ values less than those of the two leading jets) $N_{b\text{-tags}} \geq 2$, and $400 < M(tb) < 750 \text{ GeV}$. We perform a fit to the ratio of data to expected background events for the top-quark $p_T$ distribution using a Landau function and reweight the events in the simulated $t\bar{t}$ sample using the result of the fit. This method gives results that are consistent with the generator-level reweighting procedure.

Figure 1 shows the reconstructed $tb$ invariant-mass distribution obtained from data and from simulated $W'$ signal samples with four different mass values ($M(W') = 1.8$, 2.0, 2.5, and 3.0 TeV). Also shown are the dominant background contributions. The distributions are shown after the preselection described in section 4, as well as three final selection criteria which are imposed to improve the signal-to-background discrimination: the $p_T$ of the selected top-quark candidate $p_T^t > 85 \text{ GeV}$, the $p_T$ of the vector sum of the two leading jets $p_T^{\text{jet1,jet2}} > 140 \text{ GeV}$, and the mass of the selected top-quark candidate with $130 \text{ GeV} < M(t) < 210 \text{ GeV}$. The distributions are shown separately for the electron and muon samples, for events which have one or both of the two leading jets tagged as b-jets. The number of events remaining with one and two b-tagged jets after the preselection and final selection are listed in table 1. The yields measured in data and those predicted from simulation agree within the statistical and systematic uncertainties, which are described in the following section.

### 6 Systematic uncertainties

The systematic uncertainties that are relevant for this analysis fall into two categories: (i) uncertainties in the total event yield and (ii) uncertainties that impact both the shape and the total event yield of the distributions. The first category includes uncertainties in the total integrated luminosity of the data sample (2.6\%) [50], lepton reconstruction and identification efficiencies (1\%), trigger modelling (1–2\%), and the theoretical $t\bar{t}$ cross section (8\%).
Table 1. Number of selected data, signal, and background events. For the background samples, the number of expected events is computed corresponding to an integrated luminosity of 19.5 fb$^{-1}$. The final two columns for each sample include the following selections: $p_T > 85$ GeV, $p_{T\text{jet}1,\text{jet}2} > 140$ GeV, $130 < M(t) < 210$ GeV. The combined statistical and systematic uncertainty on the total background prediction is also shown. The standard model $s$-channel $tb$ process contributes to the background only in the search for $W_R'$ bosons owing to its interference with the $W_L'\rightarrow tb$ process. The number of events for the $W_L'$ signal takes into account the interference with the SM $s$-channel $tb$ process.

The second category includes the uncertainty from the jet energy scale and resolution, and from the b-tagging and the mis-tagging efficiency scale factors. For the W+jets samples, uncertainties relating to the extraction of the light- (13%) and heavy-flavour (15%) scale factors from data are also included [47]. As discussed in the previous section, additional uncertainties are assigned relating to the W+jets background shape and to the top quark $p_T$ spectrum. The variation of the renormalisation and factorisation scale $Q^2$ used in the strong coupling constant $\alpha_s(Q^2)$, and the jet-parton matching scale uncertainties in the MLM scheme [51] are evaluated for the $t\bar{t}$ background sample. These uncertainties are evaluated by raising and lowering the corresponding parameters by one standard deviation (or in the case of the renormalisation and factorisation scale $Q$ and the jet parton matching scale by a factor 2 and 0.5), and repeating the analysis.
Figure 1. The reconstructed invariant-mass distribution of the $W'$-boson candidates after the final selection. Events with electrons (muons) are shown on the left (right) panel for data, background and four different $W'_R$ signal mass hypotheses (1.8, 2.0, 2.5, and 3.0 TeV). All events are required to have one or both of the two leading jets tagged as b-jets. The hatched bands represent the total normalisation uncertainty in the predicted backgrounds. The pull is defined as the difference between the observed data yield and the predicted background, divided by the uncertainty. For these plots it is assumed that $M(\nu_R) \ll M(W'_R)$ and for the purpose of illustration the expected yields for the $W'_R$ signal samples are scaled by a factor of 20.
7 Results

The $W'$-boson mass distribution observed in the data and the prediction for the total expected background agree within statistical and systematic uncertainties (see table 1 and figure 1). We set upper limits on the $W'$-boson production cross section for different $W'$-boson masses.

7.1 Cross section limits

The limits are computed using a Bayesian approach with a flat prior on the signal cross section with the \textsc{theta} package \cite{theta}. In order to reduce the bin-by-bin statistical uncertainty in the predicted event yields obtained from the simulated samples, we bin the invariant-mass distribution using one bin from 100 to 300 GeV, 17 bins of 100 GeV width from 300 to 2000 GeV, and two additional bins from 2000 to 2200 GeV and from 2200 to 4000 GeV. Four categories are defined according to the lepton flavor (electron or muon) and b-tag multiplicity (one or two b-tagged jets) to improve the sensitivity of the analysis. The resulting distributions serve as the inputs to the limit setting procedure, and the limit is based on the posterior probability defined by using all categories simultaneously. A binned likelihood is used to calculate upper limits on the signal production cross section times total leptonic branching fraction: \( \sigma(pp \rightarrow W') \times B(W' \rightarrow tb \rightarrow \ell \nu bb) \), where \( \ell = e/\mu/\tau \). The search is sensitive to the $W' \rightarrow tb \rightarrow \tau \nu bb$ decay mode if the tau subsequently decays to an electron or muon. Therefore $\tau \rightarrow e/\mu$ events are included in the signal and background estimations of the electron and muon samples, respectively. The limit computation accounts for the effects of systematic uncertainties (discussed in section 6) in the normalisation and shape of the invariant-mass distributions, as well as for statistical fluctuations in the background templates. Expected limits on the production cross section for each $W'_{R}\text{-boson mass are also computed as a measure of the sensitivity of the analysis.}

In figure 2, the solid black line denotes the observed limit and the red lines represent the predicted theoretical cross section times leptonic branching fractions. The lower mass limit is defined by the mass value corresponding to the intersection of the observed upper limit on the production cross section times leptonic branching fraction with the theoretical prediction. For $W'$ bosons with right-handed couplings to fermions the observed (expected) limit is 2.05 (2.02) TeV at 95% confidence level (CL). These limits also apply to a left-handed $W'$ boson when no interference with the SM is taken into account. Assuming heavy right-handed neutrinos ($M(\nu_{R}) > M(W')$), the observed (expected) limit is 2.13 (2.12) TeV at 95% CL.

7.2 Limits on coupling strengths

The effective Lagrangian given by eq. (1) can be analysed for arbitrary combinations of left-handed or right-handed coupling strengths \cite{24}. The cross section for single-top-quark production in the presence of a $W'$ boson for any set of coupling values can be written in terms of the cross sections of our signal MC samples, $\sigma_{L}$ for purely left-handed couplings $(a^{L}, a^{R}) = (1, 0)$, $\sigma_{R}$ for purely right-handed couplings $(a^{L}, a^{R}) = (0, 1)$, $\sigma_{LR}$ for mixed
Figure 2. The expected (dashed black line) and observed (solid black line) 95% CL upper limits on the production cross section of right-handed $W'$ bosons obtained for the electron sample (top left), muon sample (top right), and their combination (bottom) along with the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty in the expected exclusion limit. The theoretical cross section times branching fraction for right-handed $W'$-boson production $\sigma(pp \to W'_R) \times B(W'_R \to t\bar{b} \to \ell\nu_{bb})$, where $\ell = e/\mu/\tau$, is shown as a solid (dot-dashed) red line, when assuming light (heavy) right-handed neutrinos.

Note that for pure $W'_R$ production this reduces to the sum of SM $s$-channel $t\bar{b}$ and $W'_R$ production. For pure $W'_L$ or $W'_{LR}$ production this reduces to the cross section of the $W'_L$ or the $W'_{LR}$ sample which already includes SM $s$-channel $t\bar{b}$ production and its interference with $W'$ production.

Theoretical cross sections are computed using the set of parameter values $\alpha = (1, 1)$, and $\sigma_{SM}$ for SM couplings $(a^L, a^R) = (0, 0)$. It is given by:

$$\sigma = \sigma_{SM} + a^L_{ud}a^L_{tb}(\sigma_L - \sigma_R - \sigma_{SM}) + \left( (a^L_{ud}a^L_{tb})^2 + (a^R_{ud}a^R_{tb})^2 \right) \sigma_R + \frac{1}{2} \left( (a^L_{ud}a^R_{tb})^2 + (a^R_{ud}a^L_{tb})^2 \right) (\sigma_{LR} - \sigma_L - \sigma_R).$$

(7.1)
We assume that the couplings to first-generation quarks, $a_{ud}$, that are important for the production of the $W'$ boson, and the couplings to third-generation quarks, $a_{tb}$, that are important for the decay of the $W'$ boson, are equal. The event samples are combined according to eq. (7.1) to give the predicted invariant-mass distributions for each value of $a^L$ and $a^R$.

We vary both $a^L$ and $a^R$ in the range (0,1) with a step size of 0.1, for each $M(W')$. For each of these combinations of $a^L$, $a^R$, and $M(W')$, we determine the expected and observed 95% CL upper limits on the cross section and compare them to the corresponding theoretical prediction. If the limit is below the theoretical prediction, this point in ($a^L, a^R, M(W')$) space is excluded. Figure 3 shows the excluded $W'$-boson mass for each point in the ($a^L, a^R$) plane. The observed (expected) mass limit for a $W'$ boson with only left-handed couplings, including interference with the SM, is 1.84 (1.84) TeV.

8 Summary

We have performed a search for a $W'$ boson in the $tb$ decay channel using a data set corresponding to an integrated luminosity of 19.5 fb$^{-1}$ of pp collisions collected by the CMS detector at $\sqrt{s} = 8$ TeV. No evidence for the presence of a $W'$ boson is found, and 95% confidence level upper limits on $\sigma(pp \to W') \times B(W' \to tb \to \ell\nu bb)$ are set. We compare our measurement to the theoretical prediction for the cross section to determine the lower limit on the mass of the $W'$ boson. For $W'$ bosons with right-handed couplings to fermions (and for left-handed couplings to fermions, when assuming no interference effects) the observed (expected) limit is 2.05 (2.02) TeV at 95% confidence level. In the case with heavy right-
handed neutrinos ($M(\nu_R) > M(W'_R)$), the observed (expected) limit is 2.13 (2.12) TeV at 95% confidence level. For a $W'$ boson with only left-handed couplings, including interference effects, the observed (expected) limit is 1.84 (1.84) TeV at 95% confidence level. We also set constraints on the $W'$ gauge coupling independent of their chiral structure. The results presented in this paper are the most stringent limits obtained to date.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: 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 and CSF (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 NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS and RFBR (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); ThEPCenter, IPST, STAR and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (U.S.A.).

Individuals have received support from the Marie-Curie programme and the European Research Council and EPLANET (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; 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 Ministry of Education, Youth and Sports (MEYS) of Czech Republic; the Council of Science and Industrial Research, India; the Compagnia di San Paolo (Torino); the HOMING PLUS programme of Foundation for Polish Science, cofinanced by EU, Regional Development Fund; and the Thalis and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF.

Open Access. This article is distributed under the terms of the Creative Commons Attribution License (CC-BY 4.0), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited.
References

[1] M. Schmaltz, Little Higgs review, Ann. Rev. Nucl. Part. Sci. 55 (2005) 229 [hep-ph/0502182] [inSPIRE].

[2] T. Appelquist, H.-C. Cheng and B.A. Dobrescu, Bounds on universal extra dimensions, Phys. Rev. D 64 (2001) 035002 [hep-ph/0012100] [inSPIRE].

[3] H.-C. Cheng, C.T. Hill, S. Pokorski and J. Wang, The Standard model in the latticized bulk, Phys. Rev. D 64 (2001) 065007 [hep-th/0104179] [inSPIRE].

[4] R.S. Chivukula, E.H. Simmons and J. Terning, Limits on noncommuting extended technicolor, Phys. Rev. D 53 (1996) 5258 [hep-ph/9506427] [inSPIRE].

[5] R.N. Mohapatra and J.C. Pati, Left-Right Gauge Symmetry and an Isoconjugate Model of CP-violation, Phys. Rev. D 11 (1975) 566 [inSPIRE].

[6] CMS collaboration, Search for new physics in final states with a lepton and missing transverse energy in pp collisions at the LHC, Phys. Rev. D 87 (2013) 072005 [arXiv:1302.2812] [inSPIRE].

[7] CMS collaboration, Search for leptonic decays of $W'$ bosons in pp collisions at $\sqrt{s}=7$ TeV, JHEP 08 (2012) 023 [arXiv:1204.4764] [inSPIRE].

[8] ATLAS collaboration, ATLAS search for a heavy gauge boson decaying to a charged lepton and a neutrino in pp collisions at $\sqrt{s}=7$ TeV, Eur. Phys. J. C 72 (2012) 2241 [arXiv:1209.4446] [inSPIRE].

[9] CMS collaboration, Search for heavy resonances in the W/Z-tagged dijet mass spectrum in pp collisions at 7 TeV, Phys. Lett. B 723 (2013) 280 [arXiv:1212.1910] [inSPIRE].

[10] CMS collaboration, Search for exotic resonances decaying into $WZ/ZZ$ in pp collisions at $\sqrt{s}=7$ TeV, Phys. Rev. D 85 (2012) 112012 [arXiv:1204.1648] [inSPIRE].

[11] CMS collaboration, Search for a $W'$ or Techni-$\rho$ Decaying into $WZ$ in pp Collisions at $\sqrt{s}=7$ TeV, Phys. Rev. Lett. 109 (2012) 141801 [arXiv:1206.0433] [inSPIRE].

[12] ATLAS collaboration, Search for resonant diboson production in the WW/WZ→μνjj decay channels with the ATLAS detector at $\sqrt{s}=7$ TeV, Phys. Rev. D 87 (2013) 112006 [arXiv:1305.0125] [inSPIRE].

[13] ATLAS collaboration, Search for resonant WZ production in the WZ → $\ell\nu\ell'\nu'$ channel in $\sqrt{s}=7$ TeV pp collisions with the ATLAS detector, Phys. Rev. D 85 (2012) 112012 [arXiv:1204.1648] [inSPIRE].

[14] CMS collaboration, Search for narrow resonances using the dijet mass spectrum in pp collisions at $\sqrt{s}=8$ TeV, Phys. Rev. D 87 (2013) 114015 [arXiv:1302.4794] [inSPIRE].

[15] ATLAS collaboration, ATLAS search for new phenomena in dijet mass and angular distributions using pp collisions at $\sqrt{s}=7$ TeV, JHEP 01 (2013) 029 [arXiv:1210.1718] [inSPIRE].

[16] M. Nemevˇ sek, F. Nesti, G. Senjanovi´ c and Y. Zhang, First Limits on Left-Right Symmetry Scale from LHC Data, Phys. Rev. D 83 (2011) 115014 [arXiv:1103.1627] [inSPIRE].

[17] CMS collaboration, Search for heavy neutrinos and $W[R]$ bosons with right-handed couplings in a left-right symmetric model in pp collisions at $\sqrt{s} = 7$ TeV, Phys. Rev. Lett. 109 (2012) 261802 [arXiv:1210.2402] [inSPIRE].
ATLAS collaboration, *Search for heavy neutrinos and right-handed W bosons in events with two leptons and jets in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, *Eur. Phys. J.* C 72 (2012) 2056 [arXiv:1203.5420] [SPIRE].

D.J. Muller and S. Nandi, *Top flavor: A Separate SU(2) for the third family*, *Phys. Lett.* B 383 (1996) 345 [hep-ph/9602390] [SPIRE].

E. Mallawi, T.M.P. Tait and C.P. Yuan, *A Model of strong flavor dynamics for the top quark*, *Phys. Lett.* B 385 (1996) 345 [hep-ph/9603390] [SPIRE].

D.J. Muller and S. Nandi, *Top flavor: A Separate SU(2) for the third family*, *Phys. Lett.* B 383 (1996) 345 [hep-ph/9603390] [SPIRE].

E. Malkawi, T.M.P. Tait and C.P. Yuan, *A Model of strong flavor dynamics for the top quark*, *Phys. Lett.* B 385 (1996) 304 [hep-ph/9603349] [SPIRE].

CDF collaboration, T. Aaltonen et al., *Search for the Production of Narrow $t\bar{b}$ Resonances in 1.9 fb$^{-1}$ of pp Collisions at $\sqrt{s} = 1.96$ TeV*, *Phys. Rev. Lett.* 103 (2009) 041801 [arXiv:0902.3276] [SPIRE].

D0 collaboration, V.M. Abazov et al., *Search for $W'$ Boson Resonances Decaying to a Top Quark and a Bottom Quark*, *Phys. Rev. Lett.* 100 (2008) 211803 [arXiv:0803.3256] [SPIRE].

D0 collaboration, V.M. Abazov et al., *Search for $W' \rightarrow t\bar{b}$ resonances with left- and right-handed couplings to fermions*, *Phys. Lett.* B 699 (2011) 145 [arXiv:1101.0806] [SPIRE].

CMS collaboration, *Search for a $W'$ boson decaying to a bottom quark and a top quark in pp collisions at $\sqrt{s} = 7$ TeV*, *Phys. Lett.* B 718 (2013) 1229 [arXiv:1208.0956] [SPIRE].

ATLAS collaboration, *Search for tb resonances in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, *Phys. Rev. Lett.* 109 (2012) 081801 [arXiv:1205.1016] [SPIRE].

E. Boos, V.I. Savrin and A.V. Sherstnev, *Method for simulating electroweak top-quark production events in the NLO approximation: SingleTop event generator*, *Phys. Atom. Nucl.* 69 (2006) 1317 [SPIRE].

E.E. Boos, V.E. Bunichev, L.V. Dudko, V.I. Savrin and A.V. Sherstnev, *Method for simulating electroweak top-quark production events in the NLO approximation: SingleTop event generator*, *Phys. Atom. Nucl.* 69 (2006) 1317 [SPIRE].

E. Boos, V. Bunichev, L. Dudko and M. Perfilov, *Interference between $W'$ and $W$ in single-top quark production processes*, *Phys. Lett.* B 655 (2007) 245 [hep-ph/0610080] [SPIRE].

E. Boos, V.E. Bunichev, L.V. Dudko, V.I. Savrin and A.V. Sherstnev, *Method for simulating electroweak top-quark production events in the NLO approximation: SingleTop event generator*, *Phys. Atom. Nucl.* 69 (2006) 1317 [SPIRE].

CMS collaboration, *The CMS experiment at the CERN LHC*, 2008 *JINST* 3 S08004 [SPIRE].

CMS collaboration, *Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV*, 2012 *JINST* 7 P10002 [arXiv:1206.4071] [SPIRE].

CMS collaboration, *Particle-Flow Event Reconstruction in CMS and Performance for Jets, Taus and MET*, CMS-PAS-PFT-09-001.

CMS collaboration, *Commissioning of the Particle-flow Event Reconstruction with the first LHC collisions recorded in the CMS detector*, CMS-PAS-PFT-10-001.

CompHEP collaboration, E. Boos et al., *CompHEP 4.4: Automatic computations from Lagrangians to events*, *Nucl. Instrum. Meth.* A 534 (2004) 250 [hep-ph/0403113] [SPIRE].

Z. Sullivan, *Fully differential $W'$ production and decay at next-to-leading order in QCD*, *Phys. Rev.* D 66 (2002) 075011 [hep-ph/0207290] [SPIRE].

D. Duffy and Z. Sullivan, *Model independent reach for W-prime bosons at the LHC*, *Phys. Rev.* D 86 (2012) 075018 [arXiv:1208.4858] [SPIRE].

J. Pumplin, D.R. Stump, J. Huston, H.L. Lai, P.M. Nadolsky et al., *New generation of parton distributions with uncertainties from global QCD analysis*, *JHEP* 07 (2002) 012 [hep-ph/0201195] [SPIRE].
[36] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer and T. Stelzer, MadGraph 4: going beyond, JHEP 06 (2011) 128 [arXiv:1106.0522] [inSPIRE].

[37] M. Czakon, P. Fiedler and A. Mitov, Total Top-Quark Pair-Production Cross Section at Hadron Colliders Through O($\alpha_S^4$), Phys. Rev. Lett. 110 (2013) 252004 [arXiv:1303.6254] [inSPIRE].

[38] S. Frixione, P. Nason and C. Oleari, Matching NLO QCD computations with Parton Shower simulations: the POWHEG method, JHEP 11 (2007) 070 [arXiv:0709.2092] [inSPIRE].

[39] N. Kidonakis, NNLL threshold resummation for top-pair and single-top production, arXiv:1210.7813 [inSPIRE].

[40] T. Sjostrand, S. Mrenna and P.Z. Skands, PYTHIA 6.4 physics and manual, JHEP 05 (2006) 026 [hep-ph/0603175] [inSPIRE].

[41] CMS collaboration, Measurement of the underlying event activity at the LHC with $\sqrt{s} = 7$ TeV and comparison with $\sqrt{s} = 0.9$ TeV, JHEP 09 (2011) 109 [arXiv:1107.0330] [inSPIRE].

[42] GEANT4 collaboration, S. Agostinelli et al., GEANT4 — a simulation toolkit, Nucl. Instrum. Meth. A 506 (2003) 250 [inSPIRE].

[43] M. Cacciari, G.P. Salam and G. Soyez, The anti-$k_t$ jet clustering algorithm, JHEP 04 (2008) 063 [arXiv:0802.1189] [inSPIRE].

[44] CMS collaboration, Determination of jet energy calibration and transverse momentum resolution in CMS, 2011 JINST 6 P11002 [arXiv:1107.4277] [inSPIRE].

[45] M. Cacciari, G.P. Salam, Pileup subtraction using jet areas, Phys. Lett. B 659 (2008) 119 [arXiv:0707.1378] [inSPIRE].

[46] M. Cacciari, G.P. Salam and G. Soyez, The catchment area of jets, JHEP 04 (2008) 005 [arXiv:0802.1188] [inSPIRE].

[47] CMS collaboration, Identification of $b$-quark jets with the CMS experiment, 2013 JINST 8 P04013 [arXiv:1211.4462] [inSPIRE].

[48] CMS collaboration, Measurement of the $t\bar{t}$ production cross section in $pp$ collisions at 7 TeV in lepton + jets events using $b$-quark jet identification, Phys. Rev. D 84 (2011) 092004 [arXiv:1108.3773] [inSPIRE].

[49] CMS collaboration, Measurement of differential top-quark pair production cross sections in $pp$ collisions at $\sqrt{s} = 7$ TeV, Eur. Phys. J. C 73 (2013) 2339 [arXiv:1211.2220] [inSPIRE].

[50] CMS collaboration, CMS luminosity based on pixel cluster counting - summer 2013 update, CMS-PAS-LUM-13-001.

[51] J. Alwall, S. Hoche, F. Krauss, N. Lavesson, L. Lonnblad et al., Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions, Eur. Phys. J. C 53 (2008) 473 [arXiv:0706.2569] [inSPIRE].

[52] T. Muller, J. Ott and J. Wagner-Kuhr, theta — a framework for template-based modeling and inference, CMS Internal Note CMS-IN 2010/017.
The CMS collaboration

Yerevan Physics Institute, Yerevan, Armenia
S. Chatrchyan, V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria
W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan1, M. Friedl, R. Frühwirth1, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler1, W. Kiesenhofer, V. Knünz, M. Krammer1, I. Krätschmer, D. Liko, I. Mikulec, D. Rabady2, B. Rahbaran, H. Rohringer, R. Schöbelck, J. Strauss, A. Taurok, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz1

National Centre for Particle and High Energy Physics, Minsk, Belarus
V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium
S. Alderweireldt, M. Bansal, S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, S. Luycx, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Vrije Universiteit Brussel, Brussel, Belgium
F. Blekman, S. Blyweert, J. D’Hondt, N. Heracleous, A. Kalogeropoulos, J. Keaveney, T.J. Kim, S. Lowette, M. Maes, A. Olbrechts, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

Université Libre de Bruxelles, Bruxelles, Belgium
C. Caillol, B. Clerbaux, G. De Lentdecker, L. Favart, A.P.R. Gay, A. Léonard, P.E. Marage, A. Mohammadi, L. Perniè, T. Reis, T. Seva, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang

Ghent University, Gent, Belgium
V. Adler, K. Beernaert, L. Benucci, A. Cimmino, S. Costantini, S. Dildick, G. Garcia, B. Klein, J. Lellouch, J. McCartin, A.A. Ocampo Rios, D. Ryckbosch, S. Salva Diblen, M. Sigamani, N. Strobbe, F. Thyssen, M. Tytgat, S. Walsh, E. Yazgan, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Basegmez, C. Beluffi5, G. Bruno, R. Castello, A. Caudron, L. Cead, G.G. Da Silveira, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco4, J. Hollar, P. Jez, M. Komm, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, D. Pagano, A. Pin, K. Piotrzkowski, A. Popov5, L. Quertenmont, M. Selvaggi, M. Vidal Marono, J.M. Vizan Garcia

Université de Mons, Mons, Belgium
N. Beliy, T. Caebergs, E. Daubie, G.H. Hammad
Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, M. Correa Martins Junior, T. Martins, M.E. Pol, M.H.G. Souza

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, W. Carvalho, J. Chinellato, A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, M. Malek, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, J. Santaolalla, A. Santoro, A. Sznajder, E.J. Tonelli Manganote, A. Vilela Pereira

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil
C.A. Bernardes, F.A. Dias, T.R. Fernandez Perez Tomei, E.M. Gregores, C. Lagana, P.G. Mercadante, S.F. Novaes, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
V. Genchev, P. Iaydjiev, A. Marinov, S. Piperov, M. Rodozov, G. Sultanov, M. Vutova

University of Sofia, Sofia, Bulgaria
A. Dimitrov, I. Glushkov, R. Hadjiiska, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China
J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, R. Du, C.H. Jiang, D. Liang, S. Liang, X. Meng, R. Plestina, J. Tao, X. Wang, Z. Wang

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
C. Asawatangtrakuldee, Y. Ban, Y. Guo, Q. Li, W. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, L. Zhang, W. Zou

Universidad de Los Andes, Bogota, Colombia
C. Avila, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

Technical University of Split, Split, Croatia
N. Godinovic, D. Lelas, D. Polic, I. Puljak

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

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, K. Kadija, J. Luetic, D. Mekterovic, S. Morovic, L. Tikvica

University of Cyprus, Nicosia, Cyprus
A. Attikis, 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
A.A. Abdelalim9, Y. Assran10, S. Elgammal11, A. Ellithi Kamel12, M.A. Mahmoud13, A. Radi11,14

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
M. Kadastik, M. Müntel, M. Murumaa, 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. Härkönen, V. Karimäki, R. Kinnunen, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland
T. Tuuva

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, 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, A. Nayak, J. Rander, A. Rosowsky, M. Titov

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
S. Baffioni, F. Beaudette, P. Busson, C. Charlot, N. Daci, T. Dahms, M. Dalchenko, L. Dobrzynski, A. Florent, R. Granier de Cassagnac, P. Miné, C. Mironov, I.N. Naranjo, M. Nguyen, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Veelken, Y. Yilmaz, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
J.-L. Agram15, J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte15, F. Drouhin15, J.-C. Fontaine15, D. Gelé, U. Goerlach, C. Goetzmann, P. Juillot, A.-C. Le Bihan, P. Van Hove

Centre de Calcul de l’Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
S. Beauceron, N. Beaupere, G. Boudoul, S. Brochet, J. Chasserat, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, J.D. Ruiz Alvarez, L. Sgandurra, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret, H. Xiao
Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, S. Beranek, M. Bontenackels, B. Calpas, M. Edelhoff, L. Feld, O. Hindrichs, K. Klein, 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-Laursonn, D. Duchardt, M. Erdmann, R. Fischer, A. Göth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, S. Knutzen, P. Kreuzer, M. Messchmeyer, A. Meyer, M. Olschewski, K. Padeken, P. Papacz, H. Reithler, S.A. Schmitz, L. Sonnenschein, D. Teyssier, S. Thié, M. Weber

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

Deutsches Elektronen-Synchrotron, Hamburg, Germany
I. Asin, N. Bartosik, J. Behr, W. Behrenhoff, U. Behrens, A.J. Bell, M. Bergholz, A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, S. Choudhury, F. Costanza, C. Diez Pardos, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, T. Eichhorn, G. Flucke, A. Geiser, A. Grebenyuk, P. Gunnellini, S. Habib, J. Hauk, G. Hellwig, M. Hempel, D. Horton, H. Jung, M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, M. Krämer, D. Krücker, W. Lange, J. Leonard, K. Lipka, W. Lohmann, B. Lutz, R. Mankel, I. Marfin, I.-A. Melzer-Pellmann, A.B. Meyer, J. Münich, A. Mussgiller, S. Naumann-Emme, O. Novgorodova, F. Nowak, H. Perrey, A. Petrukhin, D. Pitzl, R. Placakyte, A. Raspereza, P.M. Ribeiro Cipriano, C. Riedl, E. Ron, M.Ö. Sahin, J. Salfeld-Nebgen, P. Saxena, R. Schmidt, T. Schoerner-Sadenius, M. Schröder, M. Stein, A.D.R. Vargas Trevino, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany
M. Aldaya Martin, V. Blobel, H. Enderle, J. Erfle, E. Garutti, K. Goebel, M. Görner, M. Gosselin, J. Haller, R.S. Höing, H. Kirschenmann, R. Klanner, R. Kogler, J. Lange, I. Marchesini, J. Ott, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Seidel, J. Sibille, V. Sola, H. Stadie, G. Steinbrück, D. Troendle, E. Usai, L. Vanelderen

Institut für Experimentelle Kernphysik, Karlsruhe, Germany
C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, M. Guthoff, F. Hartmann, T. Hauth, H. Held, K.H. Hoffmann, U. Husemann, I. Katkov, A. Kornmayer, E. Kuznetsova, P. Lobelle Pardo, D. Martschei, M.U. Mozer, Th. Müller, M. Niegel, A. Nürnberg, O. Oberst, G. Quast, K. Rabbertz,
F. Ratnikov, S. Röcker, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, R. Wolf, M. Zeise

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

G. Anagnostou, G. Daskalakis, T. Geralis, S. Kesisoglou, A. Kyriakis, D. Loukas, A. Markou, C. Markou, E. Ntomari, A. Psallidas, I. Topsis-giotis

University of Athens, Athens, Greece

L. Gouskos, A. Panagiotou, N. Saoulidou, E. Stiliaris

University of Ioánnina, Ioánnina, Greece

X. Aslanoglou, I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, E. Paradis

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, P. Hidas, D. Horvath, F. Sikler, V. Veszpremi, G. Vesztergombi, A.J. Zsigmond

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

National Institute of Science Education and Research, Bhubaneswar, India

S.K. Swain

Panjab University, Chandigarh, India

S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Kaur, M.Z. Mehta, M. Mittal, N. Nishu, A. Sharma, J.B. Singh

University of Delhi, Delhi, India

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

Saha Institute of Nuclear Physics, Kolkata, India

S. Banerjee, S. Bhattacharya, K. Chatterjee, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, A. Modak, S. Mukherjee, D. Roy, S. Sarkar, M. Sharan, A.P. Singh

Bhabha Atomic Research Centre, Mumbai, India

A. Abdulsalam, D. Dutta, S. Kailas, V. Kumar, A.K. Mohanty, L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research - EHEP, Mumbai, India

T. Aziz, R.M. Chatterjee, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu, G. Kole, S. Kumar, M. Maity, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage
Kangwon National University, Chunchon, Korea
S. Chang, T.Y. Kim, S.K. Nam

Kyungpook National University, Daegu, Korea
D.H. Kim, G.N. Kim, J.E. Kim, D.J. Kong, S. Lee, Y.D. Oh, H. Park, D.C. 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, Y. Kim, K.S. Lee, S.K. Park, Y. Roh

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

Sungkyunkwan University, Suwon, Korea
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
A. Juodagalvis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
J.R. Komaragiri

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, J. Martinez-Ortega, A. Sanchez-Hernandez, 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 Autonoma de San Luis Potosi, San Luis Potosi, Mexico
E. Casimiro Linares, A. Morelos Pineda

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
M. Ahmad, M.I. Asghar, J. Butt, H.R. Hoorani, W.A. Khan, T. Khurshid, S. Qazi, M.A. Shah, M. Shoaib

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluja, B. Boimska, T. Frueboes, M. Gorski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, G. Wrochna, P. Zalewski
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. Krolikowski, M. Misiura, W. Wolszczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
P. Bargassa, C. Beirão Da Cruz E Silva, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, F. Nguyen, J. Rodrigues Antunes, J. Seixas², J. Varela, P. Vischia

Joint Institute for Nuclear Research, Dubna, Russia
I. Golutvin, A. Kamenev, V. Karjavin, V. Konoplyanikov, V. Korenkov, G. Kozlov, A. Lanev, A. Malakhov, V. Matveev³⁴, P. Moisenz, V. Palchik, V. Perelygin, M. Savina, S. Shmatov, S. Shulha, V. Smirnov, E. Tikhonenko, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
V. Golovtsov, Y. Ivanov, V. Kim³⁵, 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, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, A. Spiridonov, V. Stolin, E. Vlasov, A. Zhokin

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

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, V. Bunichev, M. Dubinin⁷, L. Dudko, A. Ershov, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, M. Perfilov, S. Petrushanko, V. Savrin

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, A. Kalinin, 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. Adzic³⁶, M. Djordjevic, M. Ekmedzic, J. Milosevic
Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Aguilar-Benitez, J. Alcaraz Maestre, 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, E. Navarro De Martino, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, J.F. de Trocóniz, M. Missiroli

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

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. Fernandez, G. Gomez, J. Gonzalez Sanchez, A. Graziano, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez, 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. Bachtis, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, L. Benhabib, J.F. Benitez, C. Bernet, G. Bianchi, P. Bloch, A. Bocci, A. Bonato, O. Bondu, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, S. Colafranceschi, M. D’Alfonso, D. d’Enterra, A. Dabrowski, A. David, F. De Guio, A. De Roeck, S. De Visscher, S. Di Guida, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, J. Eugster, G. Franzoni, W. Funk, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Girone, M. Giunta, F. Glege, R. Gomez-Reino Garrido, S. Gowdy, R. Guida, J. Hammer, M. Hansen, P. Harris, V. Innocente, P. Janot, E. Karavakis, K. Kousouris, K. Krajezcar, P. Lecoq, C. Lourenço, N. Magini, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, P. Musella, L. Orsini, E. Palencia Cortezon, E. Perez, L. Perrozzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, M. Plagge, A. Racz, W. Reece, G. Rolandi, M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Spichas, D. Spiga, J. Steggemann, B. Stieger, M. Stoye, A. Tsirou, G.I. Veres, J.R. Vlimant, H.K. Wöhri, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, D. Renker, T. Rohe
Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
F. Bachmair, L. Bäni, L. Bianchini, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, P. Eller, C. Grab, D. Hits, W. Lustermann, B. Mangano, A.C. Marini, P. Martinez Ruiz del Arbol, D. Meister, N. Mohr, C. Nägeli, N. Pef, F. Nessi-Tedaldi, F. Pandolfi, L. Pape, F. Pauss, M. Peruzzi, M. Quittnat, F.J. Ronga, M. Rossini, A. Starodumov, M. Takahashi, L. Tauscher†, K. Theofilatos, D. Treille, R. Wallny, H.A. Weber

Universität Zürich, Zurich, Switzerland
C. Amsler, V. Chiocchia, A. De Cosa, C. Favaro, A. Hinzmann, T. Hreus, M. Ivoa Rikova, B. Kilminster, B. Millan Mejias, J. Ngadiuba, P. Robmann, H. Snoek, S. Taroni, M. Verzetti, Y. Yang

National Central University, Chung-Li, Taiwan
M. Cardaci, K.H. Chen, C. Ferro, C.M. Kuo, S.W. Li, W. Lin, Y.J. Lu, 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, P.H. Chen, C. Dietz, U. Grundler, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, Y.F. Liu, R.-S. Lu, D. Majumder, E. Petrakou, X. Shi, J.G. Shiu, Y.M. Tzeng, M. Wang, R. Wilken

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

Cukurova University, Adana, Turkey
A. Adiguzel, M.N. Bakirci, S. Cerci, C. Dozen, I. Dumanoglu, E. Eskut, S. Giris, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk, A. Polatoz, K. Sogut, D. Sunar Cerci, B. Tali, H. Topakli, 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, G. Karapinar, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, M. Yalvac, M. Zeyrek

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

Istanbul Technical University, Istanbul, Turkey
H. Bahtiyar, E. Barlas, K. Cankocak, Y.O. Günaydın, F.I. Vardarlı, M. Yücel

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

University of Bristol, Bristol, United Kingdom
J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, Z. Meng, D.M. Newbold, S. Parameswaran, A. Poll, S. Senkin, V.J. Smith, T. Williams
Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, A. Belyaev, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Ilic, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, W.J. Womersley, S.D. Worm

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

Brunel University, Uxbridge, United Kingdom
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, U.S.A.
J. Dittmann, K. Hatakeyama, A. Kasmi, H. Liu, T. Scarborough

The University of Alabama, Tuscaloosa, U.S.A.
O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio

Boston University, Boston, U.S.A.
A. Avetisyan, T. Bose, C. Fantasia, A. Heister, P. Lawson, D. Lazic, J. Rohlf, D. Sperka, J. St. John, L. Sulak

Brown University, Providence, U.S.A.
J. Alimena, S. Bhattacharya, G. Christopher, D. Cutts, Z. Demiragli, A. Ferapontov, A. Garabedian, U. Heintz, S. Jabeen, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, M. Segala, T. Sinthuprasith, T. Speer, J. Swanson

University of California, Davis, Davis, U.S.A.
R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, M. Gardner, W. Ko, A. Kopecky, R. Lander, T. Miceli, D. Pellett, J. Pilot, F. Ricci-Tam, B. Rutherford, M. Searle, S. Shalhout, J. Smith, M. Squires, M. Tripathi, S. Wilbur, R. Yohay

University of California, Los Angeles, U.S.A.
V. Andreev, D. Cline, R. Cousins, S. Erhan, P. Everaerts, C. Farrell, M. Felcini, J. Hauser, M. Ignatenko, C. Jarvis, G. Rakness, P. Schlein†, E. Takasugi, V. Valuev, M. Weber

University of California, Riverside, Riverside, U.S.A.
J. Babb, R. Clare, J. Ellison, J.W. Gary, G. Hanson, J. Heilman, P. Jandir, F. Lacroix, H. Liu, O.R. Long, A. Luthra, M. Malberti, H. Nguyen, A. Shrinivas, J. Sturdy, S. Sumowidagdo, S. Wimpenny
University of Minnesota, Minneapolis, U.S.A.
B. Dahmes, A. De Benedetti, A. Gude, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans,
N. Pastika, R. Rusack, A. Singovsky, N. Tambe, J. Turkewitz

University of Mississippi, Oxford, U.S.A.
J.G. Acosta, L.M. Cremaldi, R. Kroeger, S. Oliveros, L. Perera, R. Rahmat, D.A. Sanders,
D. Summers

University of Nebraska-Lincoln, Lincoln, U.S.A.
E. Avdeeva, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, R. Gonzalez Suarez, J. Keller,
D. Knowlton, I. Kravchenko, J. Lazo-Flores, S. Malik, F. Meier, G.R. Snow

State University of New York at Buffalo, Buffalo, U.S.A.
J. Dolen, A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S. Rappoccio, Z. Wan

Northeastern University, Boston, U.S.A.
G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, J. Haley, A. Massironi, D. Nash,
T. Orimoto, D. Trocino, D. Wood, J. Zhang

Northwestern University, Evanston, U.S.A.
A. Anastassov, K.A. Hahn, A. Kubik, L. Lusito, N. Mucia, N. Odell, B. Pollack, A. Pozd-

nyakov, M. Schmitt, S. Stoynev, K. Sung, M. Velasco, S. Won

University of Notre Dame, Notre Dame, U.S.A.
D. Berry, A. Brinkerhoff, K.M. Chan, A. Drozdetskiy, M. Hildreth, C. Jessop, D.J. Kar-
mgard, N. Kellams, J. Kolb, K. Lannon, W. Luo, S. Lynch, N. Marzilli, D.M. Morse,
T. Pearson, M. Planer, R. Ruchti, J. Slaunwhite, N. Valls, M. Wayne, M. Wolf, A. Woodard

The Ohio State University, Columbus, U.S.A.
L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, C. Hill, R. Hughes, K. Kotov, T.Y. Ling,
D. Puigh, M. Rodenburg, G. Smith, C. Vuosalo, B.L. Winer, H. Wolfe, H.W. Wulsin

Princeton University, Princeton, U.S.A.
E. Berry, P. Elmer, V. Halyo, P. Hebda, J. Hegeman, A. Hunt, P. Jindal, S.A. Koay,
P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, A. Raval,
H. Saka, D. Stickland, C. Tully, J.S. Werner, S.C. Zenz, A. Zuranski

University of Puerto Rico, Mayaguez, U.S.A.
E. Brownson, A. Lopez, H. Mendez, J.E. Ramirez Vargas

Purdue University, West Lafayette, U.S.A.
E. Alagoz, D. Benedetti, G. Bolla, D. Bortoletto, M. De Mattia, A. Everett, Z. Hu,
M. Jones, K. Jung, M. Kress, N. Leonardo, D. Lopes Pegna, V. Marousson, P. Merkel,
D.H. Miller, N. Neumeister, B.C. Radburn-Smith, I. Shipsey, D. Silvers, A. Svyatkovskiy,
F. Wang, W. Xie, L. Xu, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University Calumet, Hammond, U.S.A.
N. Parashar, J. Stupak
Rice University, Houston, U.S.A.
A. Adair, B. Akgun, K.M. Ecklund, F.J.M. Geurts, W. Li, B. Michlin, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

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

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

Rutgers, The State University of New Jersey, Piscataway, U.S.A.
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, S. Salur, S. Schnetzer, C. Seitz, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, U.S.A.
K. Rose, S. Spanier, Z.C. Yang, A. York

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

Texas Tech University, Lubbock, U.S.A.
N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Dudero, K. Kovitanggoon, S. Kunori, S.W. Lee, T. Libeiro, I. Volobouev

Vanderbilt University, Nashville, U.S.A.
E. Appelt, A.G. Delannoy, S. Greene, A. Gurrola, W. Johns, C. Maguire, Y. Mao, A. Melo, M. Sharma, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

University of Virginia, Charlottesville, U.S.A.
M.W. Arenton, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hriosky, A. Ledovskoy, C. Lin, C. Neu, J. Wood

Wayne State University, Detroit, U.S.A.
S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachichi Kankanamge Don, P. Lamichhane

University of Wisconsin, Madison, U.S.A.
D.A. Belknap, L. Borrello, D. Carlsmith, M. Cepeda, S. Dasu, S. Duric, E. Friis, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, J. Klukas, A. Lanaro, A. Levine, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, I. Ross, A. Sakharov, T. Sarangi, A. Savin, W.H. Smith

†: Deceased
1 Also at Vienna University of Technology, Vienna, Austria
2 Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
3 Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
4 Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
5 Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
6 Also at Universidade Estadual de Campinas, Campinas, Brazil
7 Also at California Institute of Technology, Pasadena, U.S.A.
8 Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
9 Also at Zewail City of Science and Technology, Zewail, Egypt
10 Also at Suez Canal University, Suez, Egypt
11 Also at British University in Egypt, Cairo, Egypt
12 Also at Cairo University, Cairo, Egypt
13 Also at Fayoum University, El-Fayoum, Egypt
14 Also at Ain Shams University, Cairo, Egypt
15 Also at Université de Haute Alsace, Mulhouse, France
16 Also at Joint Institute for Nuclear Research, Dubna, Russia
17 Also at Brandenburg University of Technology, Cottbus, Germany
18 Also at The University of Kansas, Lawrence, U.S.A.
19 Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
20 Also at Eötvös Loránd University, Budapest, Hungary
21 Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
22 Also at King Abdulaziz University, Jeddah, Saudi Arabia
23 Also at University of Visva-Bharati, Santiniketan, India
24 Also at University of Ruhuna, Matara, Sri Lanka
25 Also at Isfahan University of Technology, Isfahan, Iran
26 Also at Sharif University of Technology, Tehran, Iran
27 Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
28 Also at Laboratori Nazionali di Legnaro dell’INFN, Legnaro, Italy
29 Also at Università degli Studi di Siena, Siena, Italy
30 Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France
31 Also at Purdue University, West Lafayette, U.S.A.
32 Also at Universidad Michoacana de San Nicolas de Hidalgo, Morelia, Mexico
33 Also at National Centre for Nuclear Research, Swierk, Poland
34 Also at Institute for Nuclear Research, Moscow, Russia
35 Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
36 Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
37 Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
38 Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy
39 Also at University of Athens, Athens, Greece
40 Also at Paul Scherrer Institut, Villigen, Switzerland
41 Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
42 Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
43 Also at Gaziosmanpasa University, Tokat, Turkey
44 Also at Adiyaman University, Adiyaman, Turkey
45 Also at Cag University, Mersin, Turkey
46 Also at Mersin University, Mersin, Turkey
47 Also at Izmir Institute of Technology, Izmir, Turkey
48 Also at Ozyegin University, Istanbul, Turkey
49 Also at Kafkas University, Kars, Turkey
50 Also at Istanbul University, Faculty of Science, Istanbul, Turkey
51 Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
52 Also at Kahramanmaras Sütçü İmam University, Kahramanmaras, Turkey
53 Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
54 Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
55 Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
56 Also at Utah Valley University, Orem, U.S.A.
57 Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
58 Also at Argonne National Laboratory, Argonne, U.S.A.
59 Also at Erzincan University, Erzince, Turkey
60 Also at Yildiz Technical University, Istanbul, Turkey
61 Also at Texas A&M University at Qatar, Doha, Qatar
62 Also at Kyungpook National University, Daegu, Korea