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Search for a W$^{'}$ boson decaying to a bottom quark and a top quark in pp collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration*

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Abstract

Results are presented from a search for a W$^{'}$ boson using a dataset corresponding to 5.0 fb^{-1} of integrated luminosity collected during 2011 by the CMS experiment at the LHC in pp collisions at $\sqrt{s} = 7$ TeV. The W$^{'}$ boson is modeled as a heavy W boson, but different scenarios for the couplings to fermions are considered, involving both left-handed and right-handed chiral projections of the fermions, as well as an arbitrary mixture of the two. The search is performed in the decay channel W$^{'}$ $\rightarrow$ tb, leading to a final state signature with a single lepton (e, μ), missing transverse energy, and jets, at least one of which is tagged as a b-jet. A W$^{'}$ boson that couples to fermions with the same coupling constant as the W but to the right-handed rather than left-handed chiral projections, is excluded for masses below 1.85 TeV at the 95% confidence level. For the first time using LHC data, constraints on the W$^{'}$ gauge coupling for a set of left- and right-handed coupling combinations have been placed. These results represent a significant improvement over previously published limits.

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*See Appendix A for the list of collaboration members

1 Introduction

New charged massive gauge bosons, usually called W', are predicted by various extensions of the standard model (SM), for example [1–4]. In contrast to the W boson, which couples only to left-handed fermions, the couplings of the W' boson may be purely left-handed, purely right-handed, or a mixture of the two, depending on the model. Direct searches for W' bosons have been conducted in leptonic final states and have resulted in lower limits for the W' mass of 2.15 TeV [5] and 2.5 TeV [6], obtained at the Large Hadron Collider (LHC) by the ATLAS and CMS experiments respectively. CMS has also searched for the process $\mathrm{W}' \to \mathrm{WZ}$ using the fully leptonic final state and has excluded W' bosons with masses below 1.14 TeV [7]. For W' bosons that couple only to right-handed fermions, the decay to leptons will be suppressed if the mass of the right-handed neutrino is larger than the mass of the W' boson. In that scenario, the limits from the leptonic searches do not apply. Thus it is important to search for W' bosons also in quark final states. Searches for dijet resonances by CMS [8] have led to the limit $M(\mathrm{W}') >$ 1.5 TeV.

In this Letter, we present the results of a search for W' via the $\mathrm{W}' \to \mathrm{tb}$ ($\mathrm{t\bar{b}}$ + $\mathrm{\bar{t}b}$) decay channel. This channel is especially important because in many models the W' boson is expected to be coupled more strongly to the third generation of quarks than to the first and second generations. In addition, it is easier to suppress the multijet background for the decay $\mathrm{W}' \to \mathrm{tb}$ than for the light quark decay $\mathrm{W}' \to \mathrm{q}'\bar{\mathrm{q}}$. In contrast to the leptonic searches, the tb final state is, up to a quadratic ambiguity, fully reconstructible, which means that one can search for W' resonant mass peaks even in the case of wider W' resonances.

Searches in the $\mathrm{W}' \to \mathrm{tb}$ channel at the Tevatron [9–11] and at the LHC by the ATLAS experiment [12] have led to the limit $M(\mathrm{W}') > 1.13$ TeV. The SM W boson and a W' boson with non-zero left-handed coupling strength couple to the same fermion multiplets and hence would interfere with each other in single-top production [13]. The interference term may contribute as much as 5-20% of the total rate, depending on the W' mass and its couplings [14]. The most recent D0 analysis [11], in which both left- and right-handed couplings are allowed and interference effects are included, observes an upper limit on the production cross section of between 0.10-1.3 pb, for W' bosons with masses between 0.6 and 1 TeV. The lower limit on the W' mass is 0.89 TeV, assuming right-handed couplings. A limit on the W' mass for any combination of left- and right-handed couplings is also included.

We present an analysis of events with the final state signature of an isolated lepton (e, μ), an undetected neutrino causing an imbalance in transverse momentum, and jets, at least one of which is tagged as a b-jet from the decay chain $\mathrm{W}' \to \mathrm{tb}$, $\mathrm{t} \to \mathrm{bW} \to \mathrm{b}\ell\nu$. The reconstructed tb invariant mass is used to search for W' bosons with arbitrary combinations of left- and right-handed couplings. A multivariate analysis optimized for W' bosons with purely right-handed couplings is also used. The primary sources of background are $\mathrm{t\bar{t}}$, W+jets, single-top (tW, s- and t-channel production), Z/γ^*+jets, diboson production (WW, WZ), and QCD multijet events with one jet misidentified as an isolated lepton. The contributions of these backgrounds is estimated from simulated event samples after applying correction factors derived from data in control regions well separated from the signal region.

2 The CMS detector

The Compact Muon Solenoid (CMS) detector comprises a superconducting solenoid providing a uniform magnetic field of 3.8 T. The inner tracking system comprises a silicon pixel and strip detector covering $|\eta| < 2.4$, where the pseudorapidity η is defined as $\eta = -\ln[\tan(\theta/2)]$. The polar angle θ is measured with respect to the counterclockwise-beam direction (positive z-axis) and the azimuthal angle ϕ in the transverse x-y plane. Surrounding the tracking volume, a lead tungstate crystal electromagnetic calorimeter (ECAL) with fine transverse $(\Delta\eta, \Delta\phi)$ granularity covers the region $|\eta| < 3$, and a brass/scintillator hadronic calorimeter covers $|\eta| < 5$. The steel return yoke outside the solenoid is instrumented with gas detectors, which are used to identify muons in the range $|\eta| < 2.4$. The central region is covered by drift tube chambers and the forward region by cathode strip chambers, each complemented by resistive plate chambers. In addition, the CMS detector has an extensive forward calorimetry. A two-level trigger system selects the most interesting pp collision events for physics analysis. A detailed description of the CMS detector can be found elsewhere [15].

3 Signal and background modeling

3.1 Signal modeling

The most general model-independent lowest-order effective Lagrangian for the interaction of the W' boson with SM fermions [16] can be written as

$$\mathcal{L} = \frac{V_{f_i f_j}}{2\sqrt{2}} g_w \bar{f}_i \gamma_\mu \left[a^R_{f_i f_j}(1+\gamma^5) + a^L_{f_i f_j}(1-\gamma^5) \right] \mathrm{W'}^\mu f_j + \text{h.c.}, \tag{1}$$

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, $g_w = e/(\sin\theta_\mathrm{W})$ is the SM weak coupling constant, and θ_W is the Weinberg angle. If the fermion (f) is a quark, $V_{f_i f_j}$ is the Cabibbo-Kobayashi-Maskawa (CKM) matrix element, and if it is a lepton, $V_{f_i f_j} = \delta_{ij}$ where δ_{ij} is the Kronecker delta and i and j are the generation numbers. The notation is defined such that for a W' boson with SM couplings $a^L_{f_i f_j} = 1$ and $a^R_{f_i f_j} = 0$.

This effective Lagrangian has been incorporated into the SINGLETOP Monte Carlo (MC) generator [17], which simulates electroweak top-quark production processes based on the complete set of tree-level Feynman diagrams calculated by the COMPHEP [18] package. This generator is used to simulate the s-channel W' signal including interference with the standard model W boson. The complete chain of W', top quark, and SM W boson decays are simulated taking into account finite widths and all spin correlations between resonance state production and subsequent decay. The top-quark mass, M_t, is chosen to be 172.5 GeV. The CTEQ6M parton distribution functions (PDF) are used and the factorization scale is set to $M(\mathrm{W}')$. Next-to-leading-order (NLO) corrections are included in the SINGLETOP generator and normalization and matching between various partonic subprocesses are performed, such that both NLO rates and shapes of distributions are reproduced [14, 16, 19–21].

We generate the following simulated samples: W'_L bosons that couple only to left-handed fermions ($a^L_{ud} = a^L_{cs} = a^L_{tb} = 1$, $a^R_{ud} = a^R_{cs} = a^R_{tb} = 0$), W'_R bosons that couple only to right-handed fermions ($a^L_{ud} = a^L_{cs} = a^L_{tb} = 0$, $a^R_{ud} = a^R_{cs} = a^R_{tb} = 1$), and $\mathrm{W}'_\mathrm{mixed}$ bosons that couple equally to both ($a^L_{ud} = a^L_{cs} = a^L_{tb} = 1$, $a^R_{ud} = a^R_{cs} = a^R_{tb} = 1$).

Since W'_L bosons couple to the same fermion multiplets as the SM W boson, there is interference between the two tb production diagrams; the W'_R bosons couple to different final-state quantum numbers and therefore do not interfere with the SM W boson. The leptonic decays of W'_R involve a right-handed neutrino ν_R of unknown mass. If $M_{\mathrm{W}'} < M_{\nu_R}$, W'_R bosons can only decay to $\mathrm{q}'\bar{\mathrm{q}}$ final states. If $M_{\nu_R} \ll M_{\mathrm{W}'}$, they can also decay to the $\ell\nu$ final state leading to different branching fractions for $\mathrm{W}' \to \mathrm{tb}$. For this analysis, we make the conservative assumption that $M_{\nu_R} \ll M_{\mathrm{W}'}$.

Figure 1 shows the invariant mass distributions for W'_{R}, W'_{L}, and $\mathrm{W}'_{\mathrm{mixed}}$ bosons. These distributions are obtained after applying the selection criteria described in Section 4 and matching the reconstructed jets, lepton, and an imbalance in transverse momentum of a W' boson with mass 1.2 TeV to the generator level objects. These distributions show a resonant structure around the generated W' mass. However, the invariant mass distributions for W'_{L} and $\mathrm{W}'_{\mathrm{mixed}}$ bosons also include the contribution from s-channel single top quark production and show a minimum corresponding to the destructive interference between the amplitudes for production of left-handed fermions via the W and W' bosons. The width of the W' boson with a mass of 0.8 (2) TeV is about 25 (80) GeV, which is smaller than the detector resolution and hence does not have an appreciable effect on our search.

The COMPHEP simulation samples of W' bosons are generated at mass values ranging from 0.8 to 2.1 TeV. The leading-order (LO) cross section computed by COMPHEP is then scaled to the NLO using a k-factor of 1.2 [16]. The uncertainty in the cross section is about 8.5% and includes contributions from the NLO scale (3.3%), PDFs (7.6%), α_s (1.3%), and the top-quark mass ($< 1\%$).

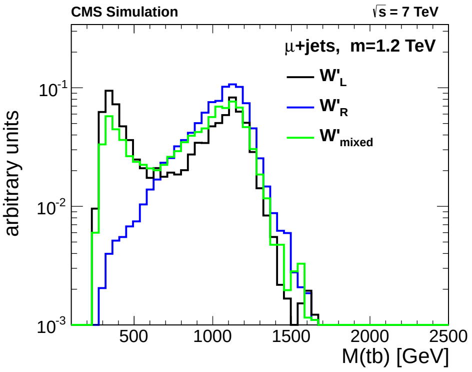

Figure 1: Simulated invariant mass distributions for production of W'_{R}, W'_{L}, and $\mathrm{W}'_{\mathrm{mixed}}$ with a mass 1.2 TeV. For the cases of W'_{L} and $\mathrm{W}'_{\mathrm{mixed}}$, the invariant mass distributions also include the contribution from s-channel single top quark production and show a minimum corresponding to the destructive interference between the amplitudes for production of left-handed fermions via the W and W'_{L} bosons. These distributions are after applying the selection criteria described in Sec. 4.

3.2 Background modeling

Contributions from the background processes are estimated using samples of simulated events. The W+jets and Drell–Yan backgrounds are estimated using samples of events generated with the MADGRAPH [22] generator. The $\mathrm{t\bar{t}}$ samples are generated using MADGRAPH and normalized to the approximate next-to-next-to-leading-order (NNLO) cross section [23]. Electroweak diboson (WW,WZ) backgrounds are generated with PYTHIA v6.4 [24] and scaled to the NLO cross section calculated using MCFM [25]. The three single top production channels (tW, s-, and t-channel) are estimated using simulated samples generated with POWHEG [26], normalized to the NLO cross section calculation [27–29]. For the W'_{R} search, the three single-top production channels are considered as backgrounds. In the analysis for W'_{L} and $\mathrm{W}'_{\mathrm{mixed}}$ bosons, because of interference between s-channel single-top production and W', only tW and t-channel contribute to the backgrounds. Instrumental background due to a jet misidentified as an isolated lepton is estimated using a sample of QCD multijet background events generated using PYTHIA. The instrumental background contributions were also verified using a control sample of multijet events from data. Both the signal and background parton-level samples are processed with PYTHIA for parton fragmentation and hadronization. The simulation of the CMS detector is performed using GEANT4 [30].

4 Event selection

The $W^{'} \rightarrow tb$ decay with $t \rightarrow Wb$ and $W \rightarrow \ell\nu$ is characterized by the presence of at least two b jets with high transverse momentum (p_T), a significant length of the vectorial sum of the negative transvers momenta of all objects in the event (E_T^{miss}) associated with an escaping neutrino,and a high-p_T isolated lepton. The isolation requirement is based on the ratio of the total transverse energy observed from all hadrons and photons in a cone of size $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$ around the lepton direction to the transverse momentum of the lepton itself (relative isolation).

Candidate events are recorded if they pass an online trigger requiring an isolated muon trigger or an electron + jets + E_T^{miss} trigger and are required to have at least one reconstructed primary vertex. Leptons, jets, and E_T^{miss} are reconstructed using the particle-flow (PF) algorithm [31]. At least one lepton is required to be within the detector acceptance ($|\eta| < 2.5$ for electrons excluding the barrel/endcap transition region, $1.44 < |\eta| < 1.56$, and $|\eta| < 2.1$ for muons). The selected data samples corresponds to a total integrated luminosity of $5.0 \pm 0.1\,\mathrm{fb}^{-1}$.

Leptons are required to be separated from jets by $\Delta R(\mathrm{jet}, \ell) > 0.3$. Muons are required to have relative isolation less than 0.15 and transverse momentum $p_T > 32\,\mathrm{GeV}$. The track associated with a muon candidate is required to have at least ten hits in the silicon tracker, at least one pixel hit and a good quality global fit with χ^2 per degree of freedom <10 including at least one hit in the muon detector. Electron candidates are selected using shower-shape information, the quality of the track and the match between the track and electromagnetic cluster, the fraction of total cluster energy in the hadronic calorimeter, and the amount of activity in the surrounding regions of the tracker and calorimeters [32]. Electrons are required to have isolation less than 0.125, $p_T > 35\,\mathrm{GeV}$, and are initially identified by matching a track to a cluster of energy in the ECAL. Events are removed whenever the electron is determined to originate from a converted photon. Events containing a second lepton with isolation requirement less than 0.2 and a minimum p_T requirement for muons (electrons) of $10\,\mathrm{GeV}$ ($15\,\mathrm{GeV}$) are also rejected. Additionally, the cosmic-ray background is reduced by requiring the transverse impact parameter of the lepton with respect to the beam spot to be less than 0.2 mm.

Jets are clustered using the anti-k_T algorithm with a size parameter $\Delta R = 0.5$ [33] and are required to have $p_T > 30\,\mathrm{GeV}$ and $|\eta| < 2.4$. Corrections are applied to account for the dependence of the jet response as a function of p_T and η [34] and the effects of multiple primary collisions at high instantaneous luminosity. At least two jets are required in the event with the leading jet $p_T > 100\,\mathrm{GeV}$ and second leading jet $p_T > 40\,\mathrm{GeV}$. Given that there would be two b quarks in the final state, at least one of the two leading jets is required to be tagged as a b jet. The combined secondary vertex [35] tagger with the medium operating point is used for this analysis. The chosen operating point is found to provide best sensitivity based on signal acceptance and expected limits [36].

The QCD multijet background is reduced by requiring $E_T^{miss} > 20\,\mathrm{GeV}$ for the muon + jets channel. Since the multijet background from events in which a jet is misidentified as a lepton is larger for the electron + jets channel, and because of the presence of a E_T^{miss} requirement in the electron trigger, a tighter $E_T^{miss} > 35\,\mathrm{GeV}$ requirement is imposed for this channel.

To estimate the W' signal and background yields, data-to-MC scale factors (f) measured using Drell–Yan data are applied in order to account for the differences in the lepton trigger and in the identification and isolation efficiencies. Scale factors related to the b-tagging efficiency and the light-quark tag rate (mistag rate), with a jet p_{T} and η dependency, are applied on a jet-by-jet basis to all b-, c-, and light quark jets in the various MC samples [36].

Additional scale factors are applied to W+jets events in which a b quark, a charm quark, or a light quark are produced in association with the W boson. The overall W+jets yield is normalized to the NNLO cross section [37] before requiring a b-tagged jet. The fraction of heavy flavor ($\mathrm{Wb\overline{b}}$, $\mathrm{Wc\overline{c}}$) events is scaled by an additional empirical correction derived using lepton+jets samples with various jet multiplicities [38]. Since this correction was obtained for events with a different topology than those selected in this analysis, an additional correction factor is derived using two data samples: events containing zero b-quark jets (0-b-tagged sample) and the inclusive sample after all the selection criteria, excluding any b-tagging requirement (preselection sample). Both samples are background dominated with negligible signal contribution. By comparing the W+jets background prediction with observed data in these two samples, through an iterative process, we extract W+light jets (f_{Wlf}) and heavy-flavor jets (f_{Whf}) scale factors. The value of the heavy-flavor jets scale factor determined via this method is within the uncertainties of the heavy flavor jet corrections derived in Ref. [38]. Both f_{Wlf} and f_{Whf} scale factors are applied to obtain the expected number of W+jets events.

The observed number of events and the expected background yields after applying the above selection criteria and scale factors are listed in Table 1. These numbers are in agreement between the observed data and the expected background yields. The signal efficiency ranges from 87% to 67% for W'_{R} masses from 0.8 to 1.9 TeV respectively.

Table 1: Number of selected observed data events, and number of predicted signal and background events. For the background samples, the expectation is computed corresponding to an integrated luminosity of 5.0 fb^{-1}. The total background yields include the normalization uncertainty on the predicted backgrounds. "Additional selection" correspond to requirements of the W' invariant mass analysis (described in Sec. 5.1) and are: $p_{\mathrm{T}}(\mathrm{top}) > 75\,\mathrm{GeV}$, $p_{\mathrm{T}}(\mathrm{jet1,jet2}) > 100\,\mathrm{GeV}$, $130 < M(\mathrm{top}) < 210\,\mathrm{GeV}$.

	Number of events					
Process	e+jets			μ+jets		
	b-tagged jets		Additional	b-tagged jets		Additional
Signal	=1	≥ 1	selection	= 1	≥ 1	selection
W'_{R} (0.8 TeV)	405	631	463	539	838	605
W'_{R} (1.2 TeV)	63	90	68	76	109	81
W'_{R} (1.6 TeV)	11	14	11	11	15	11
W'_{R} (1.9 TeV)	3	4	3	3	4	3
						Background
$\mathrm{t\overline{t}}$	8496	10659	4795	13392	16957	6692
t-channel	587	686	300	1047	1223	442
s-channel	46	73	32	81	134	51
tW-channel	549	628	270	886	1007	395
$\mathrm{W}(\rightarrow)\ell\nu$+jets	4588	4760	1404	8673	9023	2350
$\mathrm{Z}\gamma^{*}(\rightarrow \ell\ell)$+jets	164	173	68	388	414	135
Diboson	51	52	17	77	79	27
Multijet QCD	104	225	0	121	121	0
Total background	14585±3199	17256±3780	6886±1371	24665±4917	28958±5765	10092±1807
Data	14337	16758	6638	23979	28392	9821

5 Data analysis

In this section, we describe two analyses to search for W' bosons. The reconstructed tb invariant mass analysis is used to search for W' bosons with arbitrary combinations of left- and right-handed couplings while a multivariate analysis is optimized for the search of W' bosons with purely right-handed couplings.

5.1 The tb invariant mass analysis

The distinguishing feature of a W' signal is a resonance structure in the tb invariant mass. However, we cannot directly measure the tb invariant mass. Instead we reconstruct the invariant mass from the combination of the charged lepton, the neutrino, and the jet that gives the best top-quark mass reconstruction, and the highest p_{T} jet that is not associated with the top-quark. The missing transverse energy is used to obtain the xy-components of the neutrino momentum. The z-component is calculated by constraining the $E_{\mathrm{T}}^{\mathrm{miss}}$ and lepton momentum to the W-boson mass (80.4 GeV). This constraint leads to a quadratic equation in $|p_z^\nu|$. When the W reconstruction yields two real solutions, both solutions are used to reconstruct the top candidates. When the solution is complex, the $E_{\mathrm{T}}^{\mathrm{miss}}$ is minimally modified to give one real solution. In order to reconstruct the top quark momentum vector, the neutrino solutions are used to compute the possible W momentum vectors. The top-quark candidates are then reconstructed using the possible W solutions and all of the selected jets in the event. The candidate with mass closest to 172.5 GeV is chosen as the best representation of the top quark ($M(\mathrm{W}, \text{best jet})$). The W' invariant mass ($M(\text{best jet}, \text{jet2}, \mathrm{W})$) is obtained by combining the “best” top-quark candidate with the highest p_{T} jet (jet2) remaining after the top-quark reconstruction.

Figure 2 shows the reconstructed tb invariant mass distribution for the data and simulated W' signal samples generated at four different mass values (0.8, 1.2, 1.6, and 1.9 TeV). Also included in the plots are the main background contributions. The data and background distributions are shown for sub-samples with one or more b tags, separately for the electron and muon channels. Three additional criteria are imposed for improving the signal-to-background discrimination: the p_{T} of the best top candidate must be greater than 75 GeV, the p_{T} of the system comprising of the two leading jets $p_{\mathrm{T}}(\text{jet1,jet2})$ must be greater than 100 GeV, and the best top candidate must have a mass $M(W, \text{best jet})$ greater than 130 GeV and less than 210 GeV.

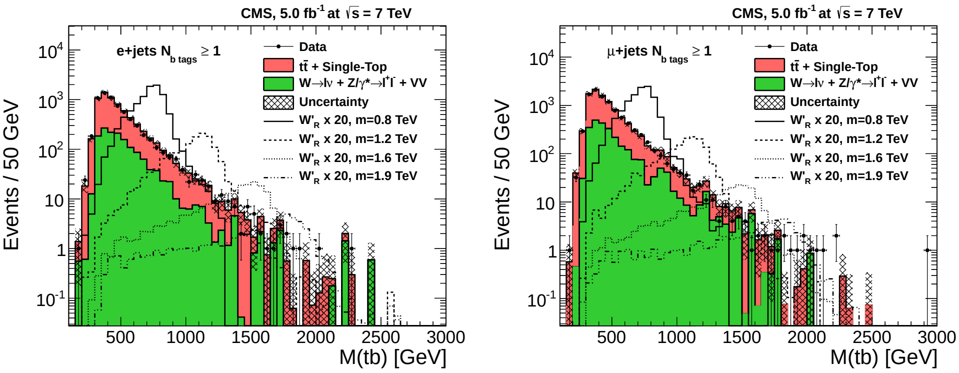

Figure 2: Reconstructed W' invariant mass distributions after the full selection. Events with electrons (muons) are shown in the left panel (right panel) for data, background, and four different W'_{R} signal mass points (0.8, 1.2, 1.6, and 1.9 TeV). The hatched bands represent the total normalization uncertainty in the predicted backgrounds. For the purpose of illustration, the expected yields for W' signal samples are scaled by a factor of 20.

Since the W+jets process is one of the major backgrounds to the W' signal (see Table 1), a study is performed to verify that the W+jets shape is modeled realistically in the simulation. Events with zero b-tagged jets in data that satisfy all other selection criteria are expected to originate predominantly from the W+jets background. These events are used to verify the shape of the W+jets background invariant mass distribution in data. The shape is obtained by subtracting the backgrounds other than W+jets from the data. The invariant mass distribution with zero b-tagged jets derived from data using this method is compared with that from the W+jets MC sample. They was found to be in agreement, validating the simulation. Any small residual difference is taken into account as a systematic uncertainty. The difference between the distributions is included as a systematic uncertainty on the shape of the W+jets background. Using MC samples, it is also checked that the shape of W+jets background does not depend on the number of b-tagged jets by comparing the tb invariant mass distribution with without b-tagged jets with the distribution produced by requiring one or more b-tagged jets.

5.2 The boosted decision tree analysis

The boosted decision tree (BDT) multivariate analysis technique [39–41] is also used to distinguish between the W' signal and the background. For the BDT analysis we apply all the selection criteria described in Sec. 4, except the additional selection given in Table 1. This method, based on judicious selection of discriminating variables, provides a considerable increase in sensitivity for the W' search compared to the W' invariant mass analysis, described in Section 5.1.

The discriminating variables used for the BDT analysis fall into the following categories: object kinematics, individual transverse momentum (p_{T}) or pseudorapidity (η) variables; event kinematics, e.g. total transverse energy or invariant mass variables; angular correlations, either ΔR, angles $\Delta\phi$ between jets and leptons, or top-quark spin correlation variables; and top-quark reconstruction variables identifying which jets to use for the top quark reconstruction. The final set of variables chosen for this analysis is shown in Table 2. The "$\mathrm{jet}_{1,2,3,4}$" corresponds to first, second, third and fourth highest p_{T} jet; "$\mathrm{btag}_{1,2}$" corresponds to first, second highest p_{T} b-tagged jet; "$\mathrm{notbest}_{1,2}$" corresponds to highest and second highest p_{T} jet not used in the reconstruction of best top candidate. Class "alljets" includes all the jets in the event in the global variable. The sum of the transverse energies is H_T. The invariant mass of the objects is M. The transverse mass of the objects is M_T. The sum of z-components of the momenta of all jets is p_z. The angle between x and y, is $\cos(\mathrm{x,y})_r$ where the subscript indicates the reference frame.

The input variables selected for the BDT are checked for accurate modeling. We consider an initial set of about 50 variables as inputs to the BDT. The selection of the final list of input variables uses important components from the BDT training procedure, namely the ranking of variables in the order of their importance and correlations among these variables. In order to maximize the information and keep the training optimal, the variables with smallest correlations are selected. The final list of variables is determined through an iterative process of training and selection (based on ranking and correlations), and the degree of agreement between the data and MC in two background-dominated regions (W+jets and $\mathrm{t\bar{t}}$). While the relative importance of the various variables used by the BDT depends on the W' mass, for a 2 TeV W'_{R}, the four most important variables are $\cos(\mathrm{best,lepton})_{\mathrm{besttop}}$, $M(\mathrm{alljets})$, $\Delta\phi(\mathrm{lepton,jet1})$, and $p_{\mathrm{T}}(\mathrm{jet1})$. The W+jets dominated sample is defined by requiring exactly two jets, at least one b-tagged jet, and the scalar sum of the transverse energies of all kinematic objects in the event to be less than 300 GeV. The $\mathrm{t\bar{t}}$ dominated sample is defined by requiring more than four jets, and at least one b-tagged jet.

Table 2: Variables used for the multivariate analysis in four different categories. For the angular variables, the subscript indicates the reference frame.

Object kinematics	**Event kinematics**
η(jet1)	Aplanarity(alljets)
p_{T}(jet1)	Sphericity(alljets)
η(jet2)	Centrality(alljets)
p_{T}(jet2)	M(btag1,btag2,W)
η(jet3)	M(jet1,jet2,W)
p_{T}(jet3)	M(alljets)
η(jet4)	M(alljets,W)
η(lepton)	M(W)
p_{T}(lightjet)	M(alljets,lepton,$E_{\mathrm{T}}^{\mathrm{miss}}$)
p_{T}(lepton)	M(jet1,jet2)
η(notbest1)	M_T(W)
p_{T}(notbest1)	p_{T}(jet1,jet2)
p_{T}(notbest2)	p_{T}(jet1,jet2,W)
$E_{\mathrm{T}}^{\mathrm{miss}}$	p_z/H_T(alljets)
Top quark reconstruction	**Angular correlations**
$M(W,\mathrm{btag1})$ ("btag1" top mass)	$\Delta\phi$(lepton,jet1)
$M(W,\mathrm{best1})$ ("best" top mass)	$\Delta\phi$(lepton,jet2)
$M(W,\mathrm{btag2})$ ("btag2" top mass)	$\Delta\phi$(jet1,jet2)
$p_{\mathrm{T}}(W,\mathrm{btag1})$ ("btag1" top p_{T})	cos(best,lepton)$_{\mathrm{besttop}}$
$p_{\mathrm{T}}(W,\mathrm{btag2})$ ("btag2" top p_{T})	cos(light,lepton)$_{\mathrm{besttop}}$
	ΔR(jet1,jet2)

The BDTs are trained at each W' mass. We use the Adaptive Boost Algorithm (AdaBoost) with value 0.2 and 400 trees for training. We use the Gini index [42] as the criterion for node splitting. The training to distinguish between signal and the total expected background is performed separately for the electron and muon event samples, after requiring the presence of one or more b-tagged jets. In order to avoid training bias, the background and signal samples are split into two statistically independent samples. The first sample is used for training of the BDT and the second sample is used to obtain the final results for the W' signal expectations. Cross checks are performed by comparing the data and MC for various BDT input variables and the output discriminants in two control regions, one dominated by W+jets background events and the other by $\mathrm{t\bar{t}}$ background events. Figure 3 shows data and background comparison for a W'_{R} with mass of 1 TeV, for both e+jets and μ+jets events.

6 Systematic uncertainties

The sources of systematic uncertainties fall into two categories: (i) uncertainties in the normalization, and (ii) uncertainties affecting both shape and normalization of the distributions. The first category includes uncertainties on the integrated luminosity (2.2%) [43], theoretical cross-sections and branching fractions (15%), object identification efficiencies (3%), and trigger modeling (3%). Also included in this group are uncertainties related to obtaining the heavy-flavor ratio from data [38]. In the limit estimation, these are defined through log-normal priors based on their mean values and their uncertainties. The shape-changing category includes the uncertainty from the jet energy scale, the b-tagging efficiency and mis-tag rate scale factors. For the W+jets samples, uncertainties on the light- and heavy-flavor scale factors are also included. This uncertainty has the largest impact in the limit estimation. The variation of the factorization scale Q^2 used in the strong coupling constant $\alpha_s(Q^2)$, and the jet-parton matching

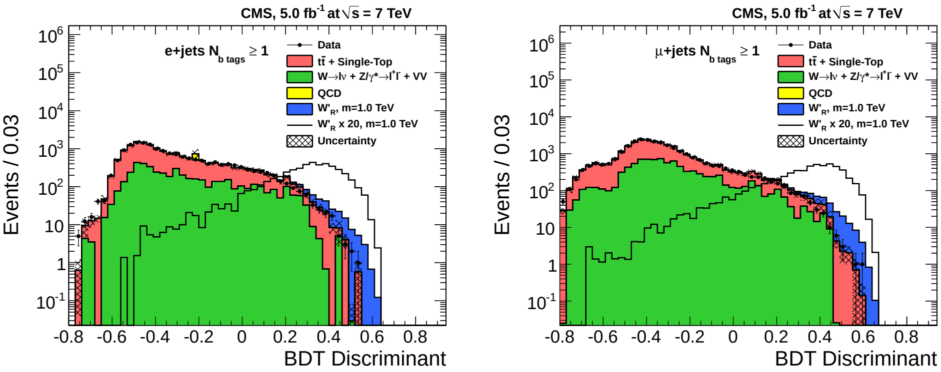

Figure 3: Distribution of the BDT output discriminant. Plots for the e+jets (left) and the μ+jets (right) samples are shown for data, expected backgrounds, and a W'_R signal with mass of 1 TeV. The hatched bands represent the total normalization uncertainty on the predicted backgrounds.

scale [44] uncertainties are evaluated for the $\mathrm{t\bar{t}}$ background sample. In the case of W+jets, there is an additional systematic uncertainty due to the shape difference between data and simulation as observed in the 0-b-tagged sample. These shape uncertainties are evaluated by raising and lowering the corresponding correction by one standard deviation and repeating the complete analysis. Then, a bin-wise interpolation using a cubic spline between histogram templates at the different variations is performed. A nuisance parameter is associated to the interpolation and included in the limit estimation. Systematic uncertainties from a mismodeling of the number of simultaneous primary interactions is found to be negligible in this analysis.

7 Results

The observed W' mass distribution (Fig. 2) and the BDT discriminant distributions (Fig. 3) in the data agree with the prediction for the total expected background within uncertainties. We proceed to set upper limits on the W' boson production cross section for different W' masses.

7.1 Cross section limits

The limits are computed using a variant of the $\mathrm{CL_s}$ statistic [45, 46]. A binned likelihood is used to calculate upper limits on the signal production cross section times branching fraction: $\sigma(\mathrm{pp} \rightarrow \mathrm{W}' \rightarrow \mathrm{tb})$. The procedure accounts for the effects on normalization and shape from systematic uncertainties, see Sec. 6, as well as for the limited number of events in the background templates. Expected cross section limits for each W'_R boson mass are also computed as a measure of the sensitivity of the analysis. To obtain the best sensitivity, we combine the muon and electron samples.

The BDT discriminant distributions, trained for every mass point, are also used to set upper limits on the production cross section of the W'_R. The expected and measured 95% CL upper limits on the production cross section times decay branching fraction for the W'_R bosons are shown in Figure 4. The sensitivity achieved using the BDT output discriminant is greater than that obtained using the shape of the distribution of the W' boson invariant mass.

In all the plots shown in Figure 4, the black solid line denotes the observed limit and the red solid line represents the theoretical cross section predictions. We define the lower limit on the W' mass by the point where the measured cross section limit crosses the theoretical cross section [14, 16].

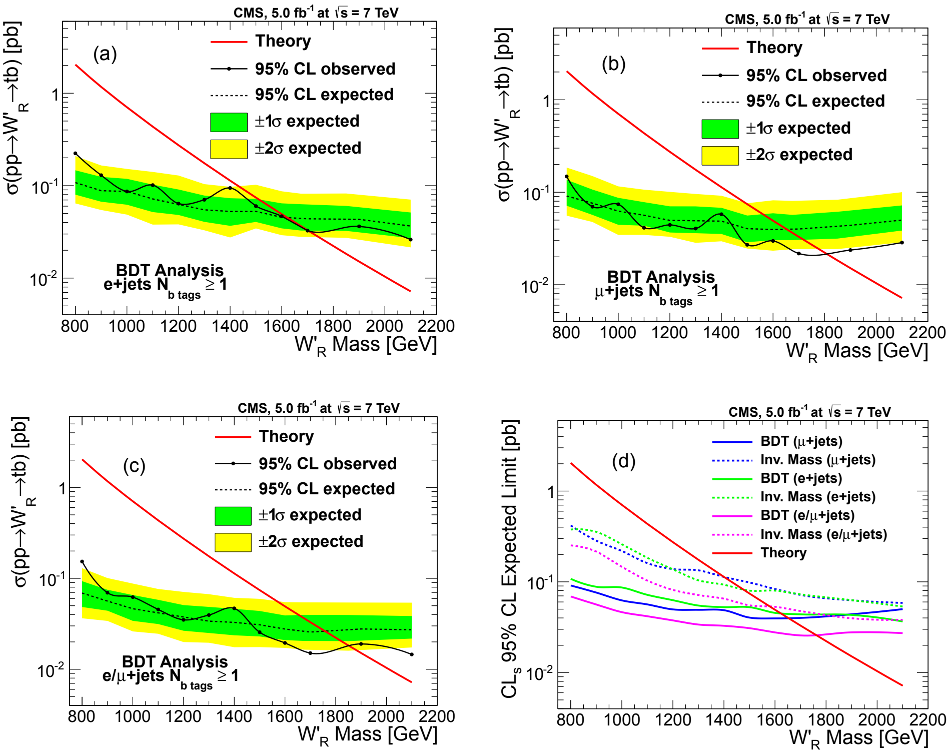

Figure 4: The expected and measured 95% CL upper limits on the production cross section times branching fraction of right handed W' bosons obtained using the BDT discriminant for ≥ 1 b-tagged electron+jets events (a), muon+jets events (b), and combined (c). Also shown (d) is a comparison of the expected 95% CL upper cross section limits obtained using invariant mass distribution and BDT output for right handed W' bosons for ≥ 1 b-tagged muon+jet events, electron+jet events, and combined. The solid red line represents the theoretical prediction.

In the electron channel, we observe 2 events with a mass above 2 TeV with an expected background of 3.0 ± 1.5 events. In the muon channel, we observe 6 events with an expected background of 1.4 ± 0.9 events. This gives a total of 8 events with an expected background of 4.4 ± 1.7 events with a mass above 2 TeV. The significance of the excursion in the muon channel is 2.2 standard deviations. The dominant contributions to the expected background above 2 TeV come from W+jets and top-quark production.

7.2 Limits on coupling strengths

From the effective Lagrangian given in Eq. (1), it can be shown that the cross section for single-top quark production in the presence of a W' boson can be expressed, for arbitrary combinations of left-handed (a^L) or right-handed (a^R) coupling strengths, in terms of four cross sections, σ_L, σ_R, σ_{LR}, and σ_{SM}.

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

Where σ_L is the cross section for purely left-handed couplings $(a^L, a^R) = (1, 0)$, σ_R is the cross section for purely right-handed couplings $(a^L, a^R) = (0, 1)$, σ_{LR} is the cross section for mixed couplings $(a^L, a^R) = (1, 1)$, and σ_{SM} is the cross section for SM couplings $(a^L, a^R) = (0, 0)$.

We assume that the couplings to first-generation quarks, a_{ud}, which are important for the production of the W' boson, and the couplings to third-generation quarks, a_{tb}, which are important for the decay of the W' boson, are equal. For given values of a^L and a^R, the distributions are obtained by combining the four signal samples according to Eq. (2).

We vary both a^L and a^R between 0 and 1 in steps of 0.1, for a series of values of the mass of the W' boson. For each of these combinations of a^L, a^R, and $M(\mathrm{W}')$, we determine the expected and observed 95% CL upper limits on the cross section. We then assume values for a^L, and a^R, and interpolate the cross section limit in the mass value. Figure 5 shows the contours for the W' boson mass in the (a^L, a^R) plane for which the cross section limit equals the predicted cross section. For each contour of W' mass, combinations of the couplings a^R and a^L above and to the right of the curve are excluded The contours are obtained using the W' invariant mass distribution.

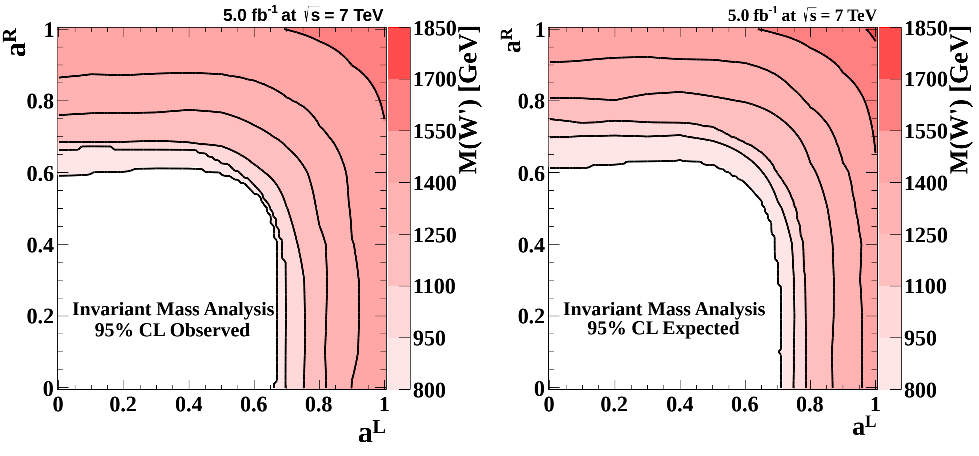

Figure 5: Contour plots of $M(\mathrm{W}')$ in the (a^L, a^R) plane at which the 95% CL upper cross section limit equals the predicted cross section for the combined e, μ+jets sample. The left (right) panel is for observed (expected) limits. The color-scale axis shows the W' mass in GeV. The dark lines represent equispaced contours of W' mass at 150 GeV intervals.

8 Summary

A search for W' boson production in the tb decay channel has been performed in pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$ using data corresponding to an integrated luminosity of $5.0\,\mathrm{fb}^{-1}$ collected during 2011 by the CMS experiment at the LHC. Two analyses have searched for W' bosons, one uses the reconstructed tb invariant mass analysis to search for $W^{'}$ bosons with arbitrary combinations of left- and right-handed couplings while a multivariate analysis is optimized for the search of $W^{'}$ bosons with purely right-handed couplings. No evidence for $W^{'}$ boson production is found and 95% CL upper limits on the production cross section times branching ratio are set for arbitrary mixtures of couplings to left- and right-handed fermions. Our measurement is compared to the theoretical prediction for the nominal value of the cross section to determine the lower limits on the mass of the $W^{'}$. For $W^{'}$ bosons with right-handed couplings to fermions (and for left-handed couplings to fermions, when no interference with SM is included), a limit of 1.85 TeV is established. For the first time using the LHC data, constraints on the $W^{'}$ gauge coupling for a set of left- and right-handed coupling combinations have been placed. These results represent a significant improvement over previously published limits.

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A 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. Fabjan[1], M. Friedl, R. Frühwirth[1], V.M. Ghete, J. Hammer, N. Hörmann, J. Hrubec, M. Jeitler[1], W. Kiesenhofer, V. Knünz, M. Krammer[1], D. Liko, I. Mikulec, M. Pernicka[†], B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, P. Wagner, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz[1]

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

Universiteit Antwerpen, Antwerpen, Belgium
S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, S. Luyckx, T. Maes, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, M. Selvaggi, Z. Staykova, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Vrije Universiteit Brussel, Brussel, Belgium
F. Blekman, S. Blyweert, J. D'Hondt, R. Gonzalez Suarez, A. Kalogeropoulos, M. Maes, A. Olbrechts, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

Université Libre de Bruxelles, Bruxelles, Belgium
B. Clerbaux, G. De Lentdecker, V. Dero, A.P.R. Gay, T. Hreus, A. Léonard, P.E. Marage, T. Reis, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang

Ghent University, Ghent, Belgium
V. Adler, K. Beernaert, A. Cimmino, S. Costantini, G. Garcia, M. Grunewald, B. Klein, J. Lellouch, A. Marinov, J. Mccartin, A.A. Ocampo Rios, D. Ryckbosch, N. Strobbe, F. Thyssen, M. Tytgat, P. Verwilligen, S. Walsh, E. Yazgan, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Basegmez, G. Bruno, R. Castello, A. Caudron, L. Ceard, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco[2], J. Hollar, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, D. Pagano, L. Perrini, A. Pin, K. Piotrzkowski, N. Schul, 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, D. De Jesus Damiao, 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, A. Custódio, E.M. Da Costa, C. De Oliveira Martins, S. Fonseca De Souza, D. Matos Figueiredo, L. Mundim, H. Nogima, V. Oguri, W.L. Prado Da Silva, A. Santoro, L. Soares Jorge, A. Sznajder

Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil
C.A. Bernardes[3], F.A. Dias[4], T.R. Fernandez Perez Tomei, E. M. Gregores[3], C. Lagana, F. Marinho, P.G. Mercadante[3], S.F. Novaes, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
V. Genchev[5], P. Iaydjiev[5], S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, M. Vutova

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, G.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, S. Guo, Y. Guo, W. Li, S. Liu, Y. Mao, S.J. Qian, H. Teng, S. Wang, B. Zhu, 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. Lelas, R. Plestina[6], D. Polic, I. Puljak[5]

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[7], S. Elgammal[8], A. Ellithi Kamel[9], S. Khalil[8], M.A. Mahmoud[10], A. Radi[11,12]

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

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

Helsinki Institute of Physics, Helsinki, Finland
J. Härkönen, A. Heikkinen, 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, 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[13], C. Broutin, P. Busson, C. Charlot, N. Daci, T. Dahms, L. Dobrzynski, R. Granier de Cassagnac, M. Haguenauer, P. Miné, C. Mironov, M. Nguyen, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Veelken, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
J.-L. Agram[14], J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte[14], F. Drouhin[14], C. Ferro, J.-C. Fontaine[14], 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, CNRS/IN2P3, Villeurbanne, France, 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[5], D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, S. Tosi, Y. Tschudi, P. Verdier, S. Viret

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze[15]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
G. Anagnostou, 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[16]

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
M. Ata, J. Caudron, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, P. Kreuzer, J. Lingemann, C. Magass, 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, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Nowack, L. Perchalla, O. Pooth, J. Rennefeld, P. Sauerland, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, J. Behr, W. Behrenhoff, U. Behrens, M. Bergholz[17], 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[17], B. Lutz, R. Mankel, I. Marfin, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, 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[17], T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany
C. Autermann, 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[5], C. Hackstein, F. Hartmann, T. Hauth[5], M. Heinrich, H. Held, K.H. Hoffmann, S. Honc, I. Katkov[16], 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, A. Scheurer, 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[5], P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
G. Bencze, C. Hajdu[5], P. Hidas, D. Horvath[18], F. Sikler, V. Veszpremi, G. Vesztergombi[19]

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. Jindal, M. Kaur, M.Z. Mehta, N. Nishu, L.K. Saini, A. Sharma, J. 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[5], L.M. Pant, P. Shukla

Tata Institute of Fundamental Research - EHEP, Mumbai, India
T. Aziz, S. Ganguly, M. Guchait[20], M. Maity[21], 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[22], S.M. Etesami[23], A. Fahim[22], M. Hashemi, H. Hesari, A. Jafari[22], M. Khakzad, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh[24], M. Zeinali[23]

INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy
M. Abbrescia[a,b], L. Barbone[a,b], C. Calabria[a,b,5], S.S. Chhibra[a,b], A. Colaleo[a], D. Creanza[a,c],

N. De Filippis[a,c,5], M. De Palma[a,b], L. Fiore[a], G. Iaselli[a,c], L. Lusito[a,b], G. Maggi[a,c], M. Maggi[a], B. Marangelli[a,b], S. My[a,c], S. Nuzzo[a,b], N. Pacifico[a,b], A. Pompili[a,b], G. Pugliese[a,c], G. Selvaggi[a,b], L. Silvestris[a], G. Singh[a,b], R. Venditti[a,b], G. Zito[a]

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

INFN Sezione di Catania [a], Università di Catania [b], Catania, Italy
S. Albergo[a,b], G. Cappello[a,b], M. Chiorboli[a,b], S. Costa[a,b], R. Potenza[a,b], A. Tricomi[a,b], C. Tuve[a,b]

INFN Sezione di Firenze [a], Università di Firenze [b], Firenze, Italy
G. Barbagli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], S. Frosali[a,b], E. Gallo[a], S. Gonzi[a,b], M. Meschini[a], S. Paoletti[a], G. Sguazzoni[a], A. Tropiano[a,5]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, S. Colafranceschi[25], F. Fabbri, D. Piccolo

INFN Sezione di Genova, Genova, Italy
P. Fabbricatore, R. Musenich

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

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

INFN Sezione di Padova [a], Università di Padova [b], Università di Trento (Trento) [c], Padova, Italy
P. Azzi[a], N. Bacchetta[a,5], D. Bisello[a,b], A. Branca[a,b,5], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a], F. Gasparini[a,b], U. Gasparini[a,b], A. Gozzelino[a], K. Kanishchev[a,c], S. Lacaprara[a], I. Lazzizzera[a,c], M. Margoni[a,b], A.T. Meneguzzo[a,b], J. Pazzini[a,b], N. Pozzobon[a,b], P. Ronchese[a,b], F. Simonetto[a,b], E. Torassa[a], M. Tosi[a,b,5], A. Triossi[a], S. Vanini[a,b], P. Zotto[a,b], A. Zucchetta[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy
M. Gabusi[a,b], S.P. Ratti[a,b], C. Riccardi[a,b], P. Torre[a,b], P. Vitulo[a,b]

INFN Sezione di Perugia [a], Università di Perugia [b], Perugia, Italy
M. Biasini[a,b], G.M. Bilei[a], L. Fanò[a,b], P. Lariccia[a,b], A. Lucaroni[a,b,5], G. Mantovani[a,b], M. Menichelli[a], A. Nappi[a,b], F. Romeo[a,b], A. Saha[a], A. Santocchia[a,b], S. Taroni[a,b,5]

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

INFN Sezione di Roma [a], Università di Roma "La Sapienza" [b], Roma, Italy
L. Barone[a,b], F. Cavallari[a], D. Del Re[a,b,5], M. Diemoz[a], M. Grassi[a,b,5], E. Longo[a,b],

P. Meridiani[a,5], F. Micheli[a,b], S. Nourbakhsh[a,b], G. Organtini[a,b], R. Paramatti[a], S. Rahatlou[a,b], M. Sigamani[a], L. Soffi[a,b]

INFN Sezione di Torino [a], Università di Torino [b], Università del Piemonte Orientale (Novara) [c], Torino, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], C. Biino[a], N. Cartiglia[a], M. Costa[a,b], G. Dellacasa[a], N. Demaria[a], A. Graziano[a,b], C. Mariotti[a,5], S. Maselli[a], E. Migliore[a,b], V. Monaco[a,b], M. Musich[a,5], M.M. Obertino[a,c], N. Pastrone[a], M. Pelliccioni[a], A. Potenza[a,b], A. Romero[a,b], R. Sacchi[a,b], A. Solano[a,b], A. Staiano[a], A. Vilela Pereira[a]

INFN Sezione di Trieste [a], Università di Trieste [b], Trieste, Italy
S. Belforte[a], V. Candelise[a,b], F. Cossutti[a], G. Della Ricca[a,b], B. Gobbo[a], M. Marone[a,b,5], D. Montanino[a,b,5], A. Penzo[a], A. Schizzi[a,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.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. Krolikowski

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, M. Fernandes, 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, A. Kamenev, V. Karjavin, G. Kozlov, A. Lanev, A. Malakhov, P. Moisenz, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, V. Smirnov, A. Volodko, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St Petersburg), Russia
S. Evstyukhin, V. Golovtsov, Y. Ivanov, V. 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. Gavrilov, M. Kossov[5], N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, V. Bunichev, M. Dubinin[4], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, 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. Bitioukov, V. Grishin[5], V. Kachanov, D. Konstantinov, A. Korablev, 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[30], M. Djordjevic, M. Ekmedzic, D. Krpic[30], 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. Felcini[31], M. Fernandez, G. Gomez, J. Gonzalez Sanchez, C. Jorda, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, M. Sobron Sanudo, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, J.F. Benitez, C. Bernet[6], 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. 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. Karavakis, K. Kousouris, P. Lecoq, Y.-J. Lee, P. Lenzi, C. Lourenço, T. Mäki, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, 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[32], T. Rommerskirchen, C. Rovelli[33], M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas[34], D. Spiga, M. Spiropulu[4], A. Tsirou, G.I. Veres[19], J.R. Vlimant, H.K. Wöhri, S.D. Worm[35], 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. Kotlinski, U. Langenegger, F. Meier, D. Renker, T. Rohe, J. Sibille[36]

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. Dünser, J. Eugster, K. Freudenreich, C. Grab, D. Hits, P. Lecomte, W. Lustermann, A.C. Marini, P. Martinez Ruiz del Arbol, N. Mohr, F. Moortgat, C. Nägeli[37], 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[38], 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
E. Aguilo, C. Amsler, V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, P. Otiougova, P. Robmann, H. Snoek, S. Tupputi, 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

Cukurova University, Adana, Turkey
A. Adiguzel, M.N. Bakirci[39], S. Cerci[40], C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, G. Karapinar[41], A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk[42], A. Polatoz, K. Sogut[43], D. Sunar Cerci[40], B. Tali[40], H. Topakli[39], 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[44], M. Kaya[45], O. Kaya[45], S. Ozkorucuklu[46], N. Sonmez[47]

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[35], K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom
L. Basso[48], K.W. Bell, A. Belyaev[48], 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. Guneratne 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[38], A. Papageorgiou, J. Pela[5], M. Pesaresi, K. Petridis, M. Pioppi[49], 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, T. Miceli, D. Pellett, 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[†], J. Tucker, 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[50], 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. Petrucciani, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech[51], 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, V. Timciuc, P. Traczyk, J. Veverka, R. Wilkinson, Y. Yang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
B. Akgun, 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, C.J. Edelmaier, W.T. Ford, A. Gaz, B. Heyburn, 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. 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. Bauerdick, A. Beretvas, 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, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko[52], C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, P. Tan, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, 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, 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. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic[53], G. Mitselmakher, L. Muniz, R. Remington, A. Rinkevicius, P. Sellers, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

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

Florida State University, Tallahassee, USA
J.R. Adams, 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, C. Dragoiu, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, F. Lacroix, M. Malek, C. O'Brien, C. Silkworth, D. Strom, N. Varelas

The University of Iowa, Iowa City, USA
U. Akgun, E.A. Albayrak, B. Bilki[54], W. Clarida, F. Duru, S. Griffiths, J.-P. Merlo, H. Mermerkaya[55], A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, Y. Onel, F. Ozok, S. Sen, 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, O. Grachov, R.P. Kenny Iii, 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,

T. Kolberg, Y. Lu, M. Marionneau, A.C. Mignerey, K. Pedro, A. Peterman, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, E. Twedt

Massachusetts Institute of Technology, Cambridge, USA
G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, G. Gomez Ceballos, M. Goncharov, K.A. Hahn, Y. Kim, M. Klute, K. Krajczar[56], W. Li, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephans, F. Stöckli, K. Sumorok, K. Sung, D. Velicanu, E.A. Wenger, R. Wolf, B. Wyslouch, S. Xie, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

University of Minnesota, Minneapolis, USA
S.I. Cooper, B. Dahmes, A. De Benedetti, G. Franzoni, A. Gude, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, N. Pastika, R. Rusack, M. Sasseville, A. Singovsky, N. Tambe, J. Turkewitz

University of Mississippi, University, USA
L.M. Cremaldi, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders

University of Nebraska-Lincoln, Lincoln, USA
E. Avdeeva, K. Bloom, S. Bose, J. Butt, D.R. Claes, A. Dominguez, M. Eads, J. Keller, I. Kravchenko, J. Lazo-Flores, H. Malbouisson, S. Malik, G.R. Snow

State University of New York at Buffalo, Buffalo, USA
U. Baur, A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S.P. Shipkowski, K. Smith

Northeastern University, Boston, USA
G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, J. Haley, D. Nash, D. Trocino, D. Wood, J. Zhang

Northwestern University, Evanston, USA
A. Anastassov, A. Kubik, N. Mucia, N. Odell, R.A. Ofierzynski, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, M. Velasco, S. Won

University of Notre Dame, Notre Dame, USA
L. Antonelli, D. Berry, A. Brinkerhoff, M. Hildreth, C. Jessop, D.J. Karmgard, J. Kolb, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, R. Ruchti, J. Slaunwhite, N. Valls, M. Wayne, M. Wolf

The Ohio State University, Columbus, USA
B. Bylsma, L.S. Durkin, A. Hart, C. Hill, R. Hughes, R. Hughes, K. Kotov, T.Y. Ling, D. Puigh, M. Rodenburg, C. Vuosalo, G. Williams, B.L. Winer

Princeton University, Princeton, USA
N. Adam, E. Berry, P. Elmer, D. Gerbaudo, V. Halyo, P. Hebda, J. Hegeman, A. Hunt, P. Jindal, D. Lopes Pegna, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, A. Raval, B. Safdi, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

University of Puerto Rico, Mayaguez, USA
J.G. Acosta, E. Brownson, X.T. Huang, A. Lopez, H. Mendez, S. Oliveros, J.E. Ramirez Vargas, A. Zatserklyaniy

Purdue University, West Lafayette, USA
E. Alagoz, V.E. Barnes, D. Benedetti, G. Bolla, D. Bortoletto, M. De Mattia, A. Everett, Z. Hu, M. Jones, O. Koybasi, M. Kress, A.T. Laasanen, N. Leonardo, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, I. Shipsey, D. Silvers, A. Svyatkovskiy, M. Vidal Marono, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University Calumet, Hammond, USA
S. Guragain, N. Parashar

Rice University, Houston, USA
A. Adair, C. Boulahouache, K.M. Ecklund, F.J.M. Geurts, 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, 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. Kamon[57], 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, P.R. Dudero, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, Y. Roh, I. Volobouev

Vanderbilt University, Nashville, USA
E. Appelt, C. Florez, S. Greene, A. Gurrola, W. Johns, C. Johnston, P. Kurt, C. Maguire, A. Melo, 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. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, A. Sakharov

University of Wisconsin, Madison, USA
M. Anderson, M. Bachtis, D. Belknap, L. Borrello, D. Carlsmith, M. Cepeda, S. Dasu, E. Friis, 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 California, Los Angeles, Los Angeles, USA
32: Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy
33: Also at INFN Sezione di Roma; Università di Roma "La Sapienza", Roma, Italy
34: Also at University of Athens, Athens, Greece
35: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
36: Also at The University of Kansas, Lawrence, USA
37: Also at Paul Scherrer Institut, Villigen, Switzerland
38: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
39: Also at Gaziosmanpasa University, Tokat, Turkey
40: Also at Adiyaman University, Adiyaman, Turkey
41: Also at Izmir Institute of Technology, Izmir, Turkey
42: Also at The University of Iowa, Iowa City, USA
43: Also at Mersin University, Mersin, Turkey
44: Also at Ozyegin University, Istanbul, Turkey
45: Also at Kafkas University, Kars, Turkey
46: Also at Suleyman Demirel University, Isparta, Turkey
47: Also at Ege University, Izmir, Turkey
48: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
49: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
50: Also at University of Sydney, Sydney, Australia
51: Also at Utah Valley University, Orem, USA

52: Also at Institute for Nuclear Research, Moscow, Russia
53: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
54: Also at Argonne National Laboratory, Argonne, USA
55: Also at Erzincan University, Erzincan, Turkey
56: Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
57: Also at Kyungpook National University, Daegu, Korea