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Search for heavy neutrinos and W_R bosons with right-handed couplings in a left-right symmetric model in pp collisions at $\sqrt{s} = 7\,\text{TeV}$

The CMS Collaboration*

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Abstract

Results are presented from a search for heavy, right-handed muon neutrinos, N_μ, and right-handed W_R bosons, which arise in the left-right symmetric extensions of the standard model. The analysis is based on a $5.0\,\text{fb}^{-1}$ sample of proton-proton collisions at a center-of-mass energy of 7 TeV, collected by the CMS detector at the Large Hadron Collider. No evidence is observed for an excess of events over the standard model expectation. For models with exact left-right symmetry, heavy right-handed neutrinos are excluded at 95% confidence level for a range of neutrino masses below the W_R mass, dependent on the value of M_{W_R}. The excluded region in the two-dimensional (M_{W_R}, M_{N_μ}) mass plane extends to $M_{W_R} = 2.5\,\text{TeV}$.

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*See Appendix A for the list of collaboration members

The maximal violation of parity conservation is a prominent feature of neutrino interactions that is included in the standard model (SM) in terms of purely left-handed couplings to the W boson. In addition, the observation of neutrino oscillations (see e.g. [1]), together with direct limits on neutrino masses [2], has demonstrated that neutrinos have tiny but non-vanishing masses, suggesting a distinct origin from the masses of the quarks and leptons.

The left-right (LR) symmetric extension of the standard model [3–6] provides a possible explanation for neutrino mass through the see-saw mechanism [7]. The LR symmetry is spontaneously broken at a multi-TeV mass scale, leading to parity violation in weak interactions as described by the SM. By introducing a right-handed SU(2) symmetry group, the LR model incorporates heavy right-handed Majorana neutrinos (N_ℓ, $\ell = \mathrm{e}, \mu, \tau$) as well as additional charged ($\mathrm{W}_\mathrm{R}^\pm$) and neutral ($\mathrm{Z}_\mathrm{R}$) gauge bosons.

We search for the production of W_R bosons from proton-proton collisions at the Large Hadron Collider (LHC). The W_R boson is assumed to decay to a muon and to a right-handed neutrino N_μ, which subsequently decays to produce a second muon together with a virtual W_R^*. If the N_μ is a Majorana particle as predicted in the LR model, the two final state muons may have the same sign. The virtual W_R^* decays to a pair of quarks which hadronize into jets (j), resulting in a final state with two muons and two jets:

$$\mathrm{W}_\mathrm{R} \to \mu_1 \mathrm{N}_\mu \to \mu_1 \mu_2 \mathrm{W}_\mathrm{R}^* \to \mu_1 \mu_2 \mathrm{q}\mathrm{q}' \to \mu_1 \mu_2 j_1 j_2.$$

The search presented in this Letter is characterized by the W_R and N_μ masses, $M_{\mathrm{W}_\mathrm{R}}$ and M_{N_μ}, which are allowed to vary independently. Although $M_{\mathrm{N}_\mu} > M_{\mathrm{W}_\mathrm{R}}$ is allowed, it is not considered in this analysis. The branching fraction for $\mathrm{W}_\mathrm{R} \to \mu \mathrm{N}_\mu$ depends on the number of heavy neutrino flavors that are accessible at LHC energies. To simplify the interpretation of the results, N_μ is assumed to be the only heavy neutrino flavor light enough to contribute significantly to the W_R decay width. CMS recently performed a search for heavy Majorana neutrinos in the final state containing two jets and two same-sign electrons or muons and set limits on the coupling between such a neutrino and the left-handed W of the SM as a function of M_{N_μ} [8], while this analysis considers on-shell production of a right-handed W_R boson. No charge requirements are imposed on the final state muons in this analysis.

For given W_R and N_μ masses, the signal cross section can be predicted from the assumed value of the coupling constant g_R, which denotes the strength of the gauge interactions of $\mathrm{W}_\mathrm{R}^\pm$ bosons. Strict left-right symmetry implies that g_R is equal to the (left-handed) weak interaction coupling strength g_L at $M_{\mathrm{W}_\mathrm{R}}$, which will be assumed throughout this Letter. Consequently, the W_R production cross section can be calculated by the FEWZ program [9] using the left-handed W' model [10, 11]. As an additional simplification, the left-right boson and lepton mixing angles are assumed to be small.

Estimates based on $\mathrm{K}_\mathrm{L} - \mathrm{K}_\mathrm{S}$ mixing results imply a theoretical lower limit of $M_{\mathrm{W}_\mathrm{R}} \gtrsim 2.5\,\mathrm{TeV}$ [12, 13]. Searches for $\mathrm{W}_\mathrm{R} \to \mathrm{tb}$ decays at the Tevatron [14–16] and at the LHC [17, 18] exclude W_R masses below 1.85 TeV. An ATLAS search for $\mathrm{W}_\mathrm{R} \to \ell \mathrm{N}_\ell$ using similar model assumptions as those in this Letter, but allowing W_R decays to both N_e and N_μ, excluded a region in the two-dimensional parameter $(M_{\mathrm{W}_\mathrm{R}}, M_{\mathrm{N}_\ell})$ space extending to nearly $M_{\mathrm{W}_\mathrm{R}} = 2.5\,\mathrm{TeV}$ [19].

The analysis is based on a $5.0\,\mathrm{fb}^{-1}$ sample of proton-proton collision data at a center-of-mass energy of 7 TeV, collected by the Compact Muon Solenoid (CMS) detector [20] at the LHC. The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a field of 3.8 T. Within the field volume are the silicon pixel and strip trackers, the

lead-tungstate crystal electromagnetic calorimeter, and the brass/scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel return yoke, with detection planes made of three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. The CMS trigger system, composed of custom hardware processors at the first level followed by a processor farm at the next level, selects $\mathcal{O}(100\,\text{Hz})$ of the most interesting events. The events used in this analysis were collected with single-muon triggers whose p_T thresholds ranged from 24 GeV to 40 GeV, depending on the instantaneous luminosity.

The $\text{W}_\text{R} \to \mu\text{N}_\mu$ signal samples are generated using PYTHIA 6.4.24 [21], which includes the LR symmetric model with the standard assumptions mentioned previously, with CTEQ6L1 parton distribution functions [22]. We also study SM background processes using simulated samples: $\text{t}\bar{\text{t}}$ and single-top (both generated using POWHEG [23]), W and Drell–Yan production in association with jets (SHERPA [24]), and diboson production (PYTHIA). Generated events pass through the full CMS detector simulation based on GEANT4 [25].

The muon identification strategy is based on both the muon detectors and the inner tracker, described in Ref. [26]. At least one of the two muons used to define the W_R candidate is required to be matched to a muon candidate found by the trigger, and both muons are required to satisfy the tight identification criteria discussed in Ref. [27]. The muon identification requirements ensure good consistency between the measurements of the muon detector and the inner tracker, and suppress muons from decay-in-flight of hadrons as well as from shower punch-through. Non-isolated muon backgrounds are controlled by computing the sum of the transverse momentum of tracks within a cone about the muon direction of $\Delta R < 0.3$, with $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, given the azimuthal angle ϕ and $\eta = -\ln[\tan(\theta/2)]$, where θ is the polar angle with respect to the beam direction. The final p_T sum must be less than 10% of the muon transverse momentum.

Jets are reconstructed by forming clusters of charged and neutral hadrons, photons, and leptons that are first reconstructed based on the CMS particle-flow technique [28], using the anti-k_T clustering algorithm [29] with a radius parameter $R = 0.5$. Energy deposits in the calorimeter with characteristics that match those of noise or beam halo tracks are identified, and events are rejected if either of the two highest-p_T jet candidates was produced by such energy deposits. To suppress backgrounds from heavy-flavor-quark decays, any muon is rejected if found near a jet, with $\Delta R(\mu, j) < 0.5$.

In approximately 95% of simulated signal event samples, the W_R final state decay products are the highest p_T muons and jets in the event. $\text{W}_\text{R} \to \mu\text{N}_\mu$ candidates are thus formed from the two highest-p_T muons and the two highest-p_T jets in the event. As the initial two-body decay $\text{W}_\text{R} \to \mu\text{N}_\mu$ tends to produce a high-momentum muon, events are selected in which the leading muon has $p_\text{T} > 60\,\text{GeV}$ and the subleading muon has $p_\text{T} > 30\,\text{GeV}$. A minimum transverse momentum requirement of 40 GeV is imposed on the jet candidates after correcting for the effects of the extra pp collisions in the event and the jet energy response of the detector. Backgrounds are suppressed by requiring the invariant mass of the dimuon system $M_{\mu\mu} > 200\,\text{GeV}$ and the four-object mass $M_{\mu\mu jj} > 600\,\text{GeV}$.

The signal acceptance is found to be typically near 80% at $M_{\text{N}_\mu} \sim M_{\text{W}_\text{R}}/2$ and decreases rapidly for $M_{\text{N}_\mu} \lesssim 0.10 M_{\text{W}_\text{R}}$. At low neutrino mass, the $\text{N}_\mu \to \mu jj$ decay products tend to overlap due to the boost from W_R decay, and the two jets may not be distinguishable or the muon from N_μ decay may be too close to a jet. For W_R signal events which meet the kinematic acceptance requirements, the efficiency to reconstruct the four high-p_T objects using the CMS detector ranges between 75% and 80% as a function of W_R and N_μ mass.

Table 1: The total number of events reconstructed in data, and the expected contributions from signal and background (bkgd) samples, after different stages of the selection requirements are applied. The first selection given below requires two muons with $p_T > 30\,\text{GeV}$ and two jets with $p_T > 40\,\text{GeV}$ meeting all requirements described in the text. The "Signal" column indicates the expected contribution for $M_{W_R} = 1800\,\text{GeV}$, with $M_{N_\mu} = 1000\,\text{GeV}$. The uncertainties for the background expectation are derived for the final stage of selection and more details are given in the text. The yields from earlier stages of the selection have greater relative uncertainty than that for the full selection.

Selection stage	Data	Signal	Total bkgd	$t\bar{t}$	Z+jets	Other
Two muons, two jets	21769	50	21061	1603	19136	322
$\mu_1\ p_T > 60\,\text{GeV}$	13328	50	12862	1106	11531	225
$M_{\mu\mu} > 200\,\text{GeV}$	365	48	341	211	116	14
$M_{\mu\mu jj} > 600\,\text{GeV}$	164	48 ± 13	152 ± 22	81 ± 18	65 ± 9	6 ± 3

After the muon requirements are applied, the SM backgrounds for $W_R \to \mu N_\mu$ consist primarily of events from processes with two isolated high-p_T muons, namely $t\bar{t} \to bW^+\bar{b}W^-$ and Z+jets processes. The impact of the selection criteria on background processes is shown in Table 1.

The $t\bar{t}$ background contribution is estimated using a control sample of $e\mu jj$ events reconstructed in data and simulation. This sample is dominated by $t\bar{t}$ events, with small contributions from other SM processes estimated using simulation. The simulated $t\bar{t}$ background contribution is scaled to data using events satisfying $M_{e\mu} > 200\,\text{GeV}$, which is equivalent to the third selection stage in Table 1. The scale factor for the simulated $t\bar{t}$ sample, relative to the $t\bar{t}$ cross section measured by CMS [30], is 0.97 ± 0.06. The uncertainty on this scale factor reflects the number of events in data with $M_{e\mu} > 200\,\text{GeV}$. Applying this scale factor to the $t\bar{t}$ simulation, the $M_{e\mu jj}$ distributions in data and simulation are found to be in agreement. This scale factor is applied to the simulated $t\bar{t}$ event sample at all stages of selection in order to estimate the expected number of $pp \to t\bar{t} + X$ events that survive successive selection criteria.

The Z+jets background contribution is estimated from $Z \to \mu\mu$ decays reconstructed in simulation and data. The simulated Z+jets background contribution is normalized to data using events in the dimuon mass region $60\,\text{GeV} < M_{\mu\mu} < 120\,\text{GeV}$ after requiring $\mu_1\ p_T > 60\,\text{GeV}$ as indicated in Table 1. Accounting for other SM background processes, the simulated Z+jets scale factor is 1.43 ± 0.01 relative to inclusive next-to-next-to-leading order calculations. The uncertainty on this value reflects the number of events from data with $60\,\text{GeV} < M_{\mu\mu} < 120\,\text{GeV}$. After rescaling the Z+jets simulation, the shape of the $M_{\mu\mu}$ distribution for data is in agreement with simulation for $M_{\mu\mu} > 60\,\text{GeV}$.

After all selection criteria are applied, the $t\bar{t}$ and Z+jets processes dominate the total SM background contribution. Other SM processes, mostly diboson and single top, comprise less than 5% of the total background and their contributions are estimated from simulation. Background from W+jets processes, also estimated from simulation, is negligible. The background contribution from multijet processes is estimated using control samples from data and is roughly 0.1% of the total SM background after all selection requirements are applied.

The observed and expected number of events surviving the selections are summarized in Table 1. The yields reflect the number of background events surviving each selection stage, with normalization factors obtained from control sample studies ($t\bar{t}$, Z+jets, and multijet processes) or taken directly from simulation. The data are found to be in agreement with SM expectations.

The reconstructed four-object mass in data and simulation is used to estimate limits on W_R production. The $M_{\mu\mu jj}$ distribution for $W_R \to \mu\mu jj$ signal events, for each W_R mass assumption, is included together with the SM background distributions to search for evidence of W_R production.

The dominant uncertainty related to $W_R \to \mu N_\mu$ production arises from the variation in the predicted signal production cross section as a result of the uncertainties in the parton distribution functions (PDFs) of the proton. This uncertainty varies between 4% and 22%, depending on the W_R mass hypothesis, following the PDF4LHC prescriptions [31] for the CT10 [32] and MSTW2008 [33] PDF sets.

The uncertainties associated with muon reconstruction and identification are determined from $Z \to \mu^+\mu^-$ events reconstructed in both data and simulation. The size of this uncertainty is about 15% for signal and 5% for background processes.

The shape of each SM background $M_{\mu\mu jj}$ distribution is modeled by an exponential ($e^{a+bM_{\mu\mu jj}}$) lineshape, and the background contributions as a function of mass are determined from the result of fits applied to each background type: $t\bar{t}$, Z+jets, and other SM backgrounds. The background uncertainty is dominated by the uncertainty in the background modeling and is computed as a function of $\mu\mu jj$ mass.

The uncertainty in the exponential fit is taken as the uncertainty due to background modeling. Each background distribution is also fit with an alternative suite of exponential functions to allow for deviations from the assumed shape at high mass. For a given $M_{\mu\mu jj}$ range, we take the maximum of the deviation, relative to the nominal exponential fit, from any alternative fit result as the uncertainty due to background modeling if this deviation exceeds the nominal fit uncertainty.

Uncertainties in the jet energy scale and resolution impact the shape of the signal and background $M_{\mu\mu jj}$ distributions, contributing less than 10% to the signal and background uncertainties. The normalization of the various background samples contributes 5% to the total uncertainty. Muon resolution and trigger efficiency uncertainties, and additional factorization and scale theoretical uncertainties, contribute to the total uncertainty to a lesser extent. The uncertainties in the total number of background events are derived taking into account the relative contribution of all background events after the full event selection, and the correlation of each effect between all background processes.

The total uncertainty for signal and background is summarized in Table 1. The $M_{\mu\mu jj}$ distribution for events with $M_{\mu\mu} > 200\,\text{GeV}$ is presented in Fig. 1, which also summarizes the background uncertainty as a function of $M_{\mu\mu jj}$ and demonstrates the dominant background model uncertainty relative to the total background uncertainty.

As no evidence for $W_R \to \mu N_\mu$ decay is found, limits on W_R production are estimated using a multibin technique based on the RooStats package [34]. The bin width of 200 GeV, comparable to the mass resolution for a reconstructed W_R boson with mass below 2.5 TeV, is chosen for the $M_{\mu\mu jj}$ distributions used to compute the limits. The background inputs to the limit calculation use the results of the exponential fit, while the signal input is taken directly from the $M_{\mu\mu jj}$ distribution for each signal W_R mass assumption. Uncertainties are included as nuisance parameters in the limit calculations. A CL_S limit setting technique [35, 36] is used to estimate the 95% confidence level (CL) excluded region as a function of the W_R cross section multiplied by the $W_R \to \mu\mu jj$ branching fraction and W_R mass. The observed and expected limits are found to be in agreement. These results (available in tabular form in App. A) can be used for the evaluation of models other than those considered in this Letter.

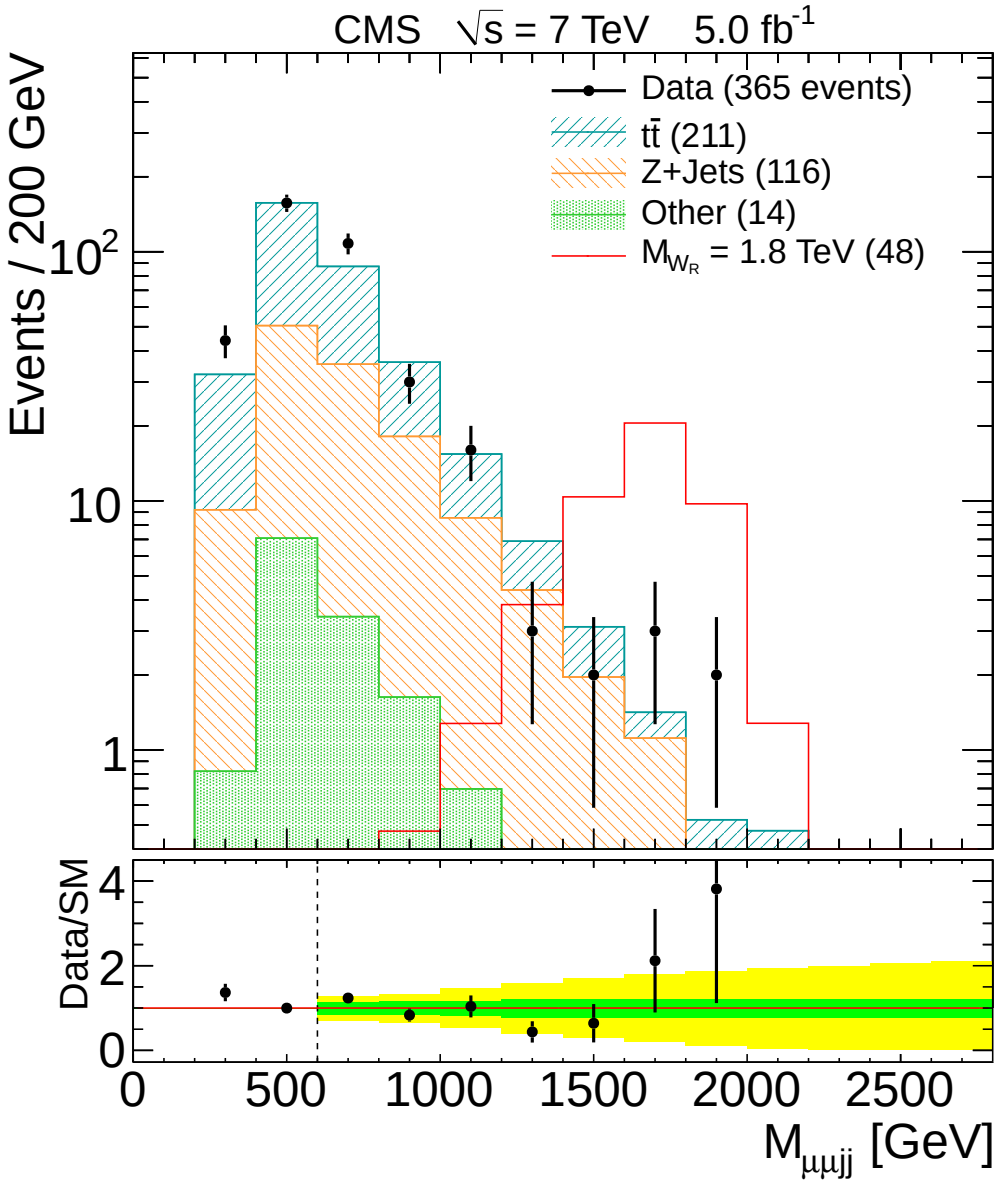

Figure 1: Distribution of the invariant mass $M_{\mu\mu jj}$ for events in data (points with error bars) with $M_{\mu\mu} > 200\,\text{GeV}$ and for simulated background contributions (hatched stacked histograms). The signal mass point $M_{W_R} = 1800\,\text{GeV}$, $M_{N_\mu} = 1000\,\text{GeV}$, is included for comparison (open red histogram). The number of events from each background process (and the expected number of signal events) is included in parentheses in the legend. The data are compared to SM expectations in the lower portion of the figure. The total background uncertainty (yellow band) and the background uncertainty after neglecting the uncertainty due to background modeling (green band) are included as a function of $M_{\mu\mu jj}$ for $M_{\mu\mu jj} > 600\,\text{GeV}$.

Limits as a function of W_R mass for a right-handed neutrino with $M_N = \frac{1}{2}M_{W_R}$ are presented in Fig. 2. The theoretical expectation in Fig. 2 assumes that only N_μ contributes to the W_R decay width, as mentioned previously. Assuming degenerate N_ℓ ($\ell = e, \mu, \tau$) masses allows $W_R \to eN_e$ and $W_R \to \tau N_\tau$ decays in addition to $W_R \to q\bar{q}'$ and $W_R \to \mu N_\mu$ and effectively decreases the expected $W_R \to \mu\mu jj$ production rate by approximately 15%.

For the model considered in this Letter, Fig. 3 indicates the range of excluded N_μ masses as a

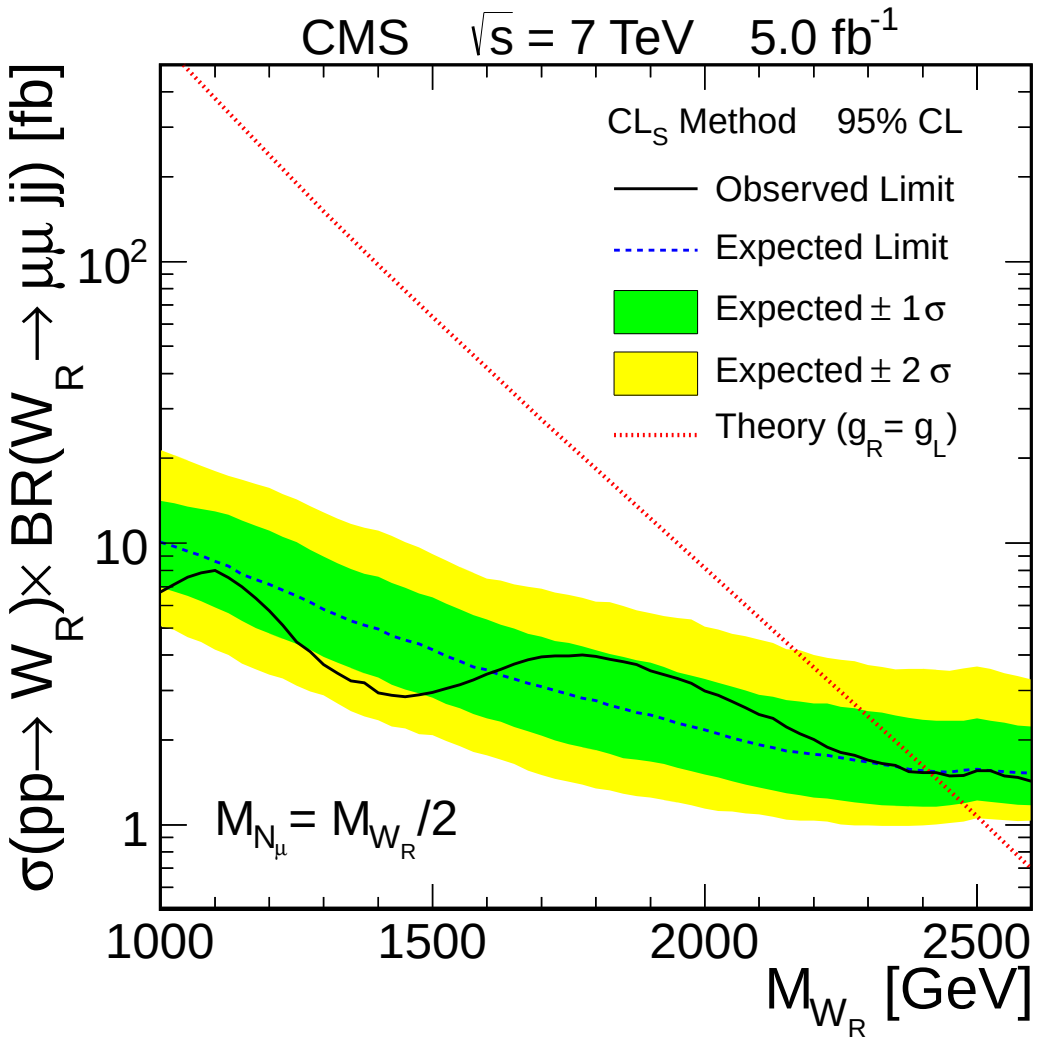

Figure 2: The 95% confidence level exclusion limit on the W_R production cross section times branching fraction for $W_R \to \mu\mu jj$ as a function of M_{W_R} for $M_{N_\mu} = \frac{1}{2} M_{W_R}$. This limit is compared to expectations given the theoretical model described in the text.

function of W_R mass by comparing the observed (expected) upper limit and the predicted cross section for each mass point. These limits extend to $M_{W_R} = 2.5\,\text{TeV}$, and exclude a wide range of heavy neutrino masses for W_R mass assumptions below this maximal value.

In summary, we have presented a search for the right-handed heavy muon neutrinos (N_μ) and bosons (W_R) of the left-right symmetric extension of the standard model. We find that our data sample is in agreement with expectations from standard model processes and therefore set a limit on the W_R and N_μ masses. For models with exact left-right symmetry (the same coupling to the right-handed and left-handed sectors), we exclude heavy right-handed neutrinos for a range of $M_{N_\mu} < M_{W_R}$, dependent on the value of M_{W_R}. For these models, the excluded region in the two-dimensional parameter space (M_{W_R},M_{N_μ}) extends to $M_{W_R} = 2.5\,\text{TeV}$. These results represent the most sensitive limits to date on W_R production assuming a single heavy neutrino flavor contributes significantly to the W_R decay width.

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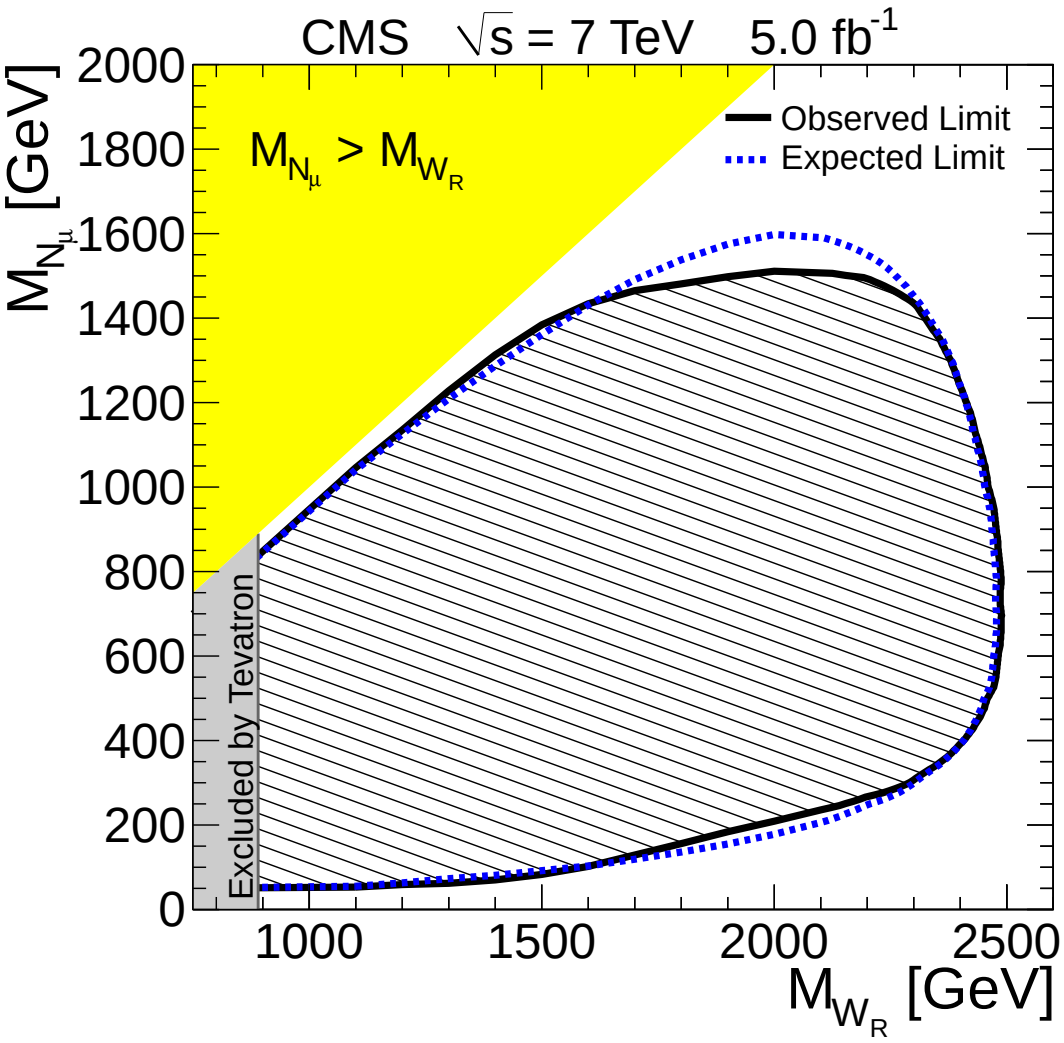

Figure 3: The 95% confidence level exclusion region in the (M_{W_R}, M_{N_μ}) plane, assuming the model described in the text. The Tevatron exclusion region for W_R production [16] is included in the figure.

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A 95% C.L. Exclusion Limits as a function of W_R and N_μ mass (tabular format)

Table 2: The 95% confidence level observed (Obs.) and expected (Exp.) exclusion limits (in fb) on the W_R production cross section times branching fraction for $W_R \to \mu\mu jj$ as a function of W_R and N_μ mass (in GeV) for 800 GeV $\leq M_{W_R} \leq$ 1100 GeV. The 68% and 95% uncertainty bands for the expected limit (Exp. $\pm 1\sigma$ and Exp. $\pm 2\sigma$, respectively) are also included for each (M_{W_R}, M_{N_μ}) entry.

M_{W_R}	M_{N_μ}	Obs. Limit	Exp. Limit	Exp. -1σ	Exp. $+1\sigma$	Exp. -2σ	Exp. $+2\sigma$
800	100	164.05	117.93	83.22	174.17	59.49	238.37
800	200	48.16	34.62	24.43	51.13	17.47	69.98
800	300	34.80	25.02	17.66	36.95	12.62	50.57
800	400	30.14	21.67	15.29	32.00	10.93	43.80
800	500	28.54	20.52	14.48	30.30	10.35	41.47
800	600	29.96	21.54	15.20	31.81	10.86	43.53
800	700	40.88	29.39	20.74	43.41	14.83	59.41
900	100	51.43	83.52	58.94	114.27	43.95	143.72
900	200	13.52	21.96	15.49	30.04	11.55	37.78
900	300	9.50	15.43	10.89	21.11	8.12	26.55
900	400	8.00	12.98	9.16	17.77	6.83	22.34
900	500	7.35	11.93	8.42	16.32	6.28	20.53
900	600	7.28	11.83	8.35	16.19	6.23	20.36
900	700	7.81	12.68	8.95	17.35	6.67	21.82
900	800	10.19	16.54	11.67	22.63	8.70	28.46
1000	100	61.33	89.04	61.43	124.83	44.84	188.82
1000	200	13.85	20.11	13.88	28.20	10.13	42.65
1000	300	9.11	13.23	9.13	18.54	6.66	28.05
1000	400	7.62	11.07	7.64	15.52	5.57	23.47
1000	500	6.95	10.09	6.96	14.14	5.08	21.39
1000	600	6.67	9.68	6.68	13.58	4.88	20.54
1000	700	6.68	9.70	6.69	13.60	4.89	20.58
1000	800	7.19	10.44	7.20	14.63	5.26	22.14
1000	900	9.23	13.39	9.24	18.78	6.75	28.40
1100	100	75.54	90.83	62.35	136.58	44.07	190.23
1100	200	15.34	18.45	12.66	27.74	8.95	38.63
1100	300	10.11	12.16	8.34	18.28	5.90	25.46
1100	400	8.15	9.80	6.73	14.73	4.75	20.52
1100	500	7.36	8.85	6.07	13.30	4.29	18.53
1100	600	6.95	8.35	5.73	12.56	4.05	17.49
1100	700	6.82	8.20	5.63	12.34	3.98	17.18
1100	800	6.97	8.38	5.75	12.59	4.06	17.54
1100	900	7.38	8.88	6.10	13.35	4.31	18.60
1100	1000	9.18	11.04	7.58	16.60	5.36	23.12

Table 3: The 95% confidence level observed (Obs.) and expected (Exp.) exclusion limits (in fb) on the W_R production cross section times branching fraction for $W_R \to \mu\mu jj$ as a function of W_R and N_μ mass (in GeV) for 1200 GeV $\leq M_{W_R} \leq$ 1400 GeV. The 68% and 95% uncertainty bands for the expected limit (Exp. $\pm 1\sigma$ and Exp. $\pm 2\sigma$, respectively) are also included for each (M_{W_R}, M_{N_μ}) entry.

M_{W_R}	M_{N_μ}	Obs. Limit	Exp. Limit	Exp. -1σ	Exp. $+1\sigma$	Exp. -2σ	Exp. $+2\sigma$
1200	100	77.54	96.52	64.72	149.76	46.17	212.60
1200	200	14.31	17.81	11.94	27.63	8.52	39.22
1200	300	8.64	10.75	7.21	16.68	5.14	23.68
1200	400	6.92	8.62	5.78	13.37	4.12	18.98
1200	500	6.22	7.74	5.19	12.01	3.70	17.05
1200	600	5.73	7.13	4.78	11.06	3.41	15.70
1200	700	5.62	6.99	4.69	10.85	3.34	15.40
1200	800	5.57	6.94	4.65	10.76	3.32	15.28
1200	900	5.75	7.16	4.80	11.11	3.42	15.77
1200	1000	6.12	7.62	5.11	11.83	3.65	16.79
1200	1100	7.47	9.30	6.24	14.43	4.45	20.48
1300	100	56.46	83.58	56.80	128.85	41.46	184.69
1300	200	10.85	16.06	10.91	24.76	7.97	35.49
1300	300	6.16	9.12	6.20	14.06	4.52	20.15
1300	400	4.90	7.26	4.93	11.18	3.60	16.03
1300	500	4.31	6.39	4.34	9.84	3.17	14.11
1300	600	3.96	5.86	3.98	9.04	2.91	12.95
1300	700	3.86	5.71	3.88	8.80	2.83	12.61
1300	800	3.79	5.61	3.81	8.65	2.78	12.40
1300	900	3.79	5.62	3.82	8.66	2.79	12.41
1300	1000	3.88	5.74	3.90	8.85	2.85	12.69
1300	1100	4.15	6.14	4.18	9.47	3.05	13.58
1300	1200	4.91	7.27	4.94	11.21	3.61	16.06
1400	100	54.25	87.60	58.80	134.53	41.56	195.65
1400	200	9.42	15.20	10.20	23.35	7.21	33.95
1400	300	5.10	8.23	5.52	12.64	3.90	18.38
1400	400	3.93	6.35	4.26	9.75	3.01	14.18
1400	500	3.46	5.58	3.75	8.57	2.65	12.46
1400	600	3.18	5.14	3.45	7.89	2.44	11.48
1400	700	3.07	4.95	3.33	7.61	2.35	11.06
1400	800	3.00	4.85	3.25	7.44	2.30	10.83
1400	900	2.98	4.80	3.22	7.38	2.28	10.73
1400	1000	2.99	4.83	3.24	7.42	2.29	10.79
1400	1100	3.09	4.98	3.35	7.66	2.36	11.13
1400	1200	3.25	5.25	3.52	8.06	2.49	11.72
1400	1300	3.82	6.16	4.14	9.47	2.92	13.77

Table 4: The 95% confidence level observed (Obs.) and expected (Exp.) exclusion limits (in fb) on the W_R production cross section times branching fraction for $W_R \to \mu\mu jj$ as a function of W_R and N_μ mass (in GeV) for 1500 GeV $\leq M_{W_R} \leq$ 1700 GeV. The 68% and 95% uncertainty bands for the expected limit (Exp. $\pm 1\sigma$ and Exp. $\pm 2\sigma$, respectively) are also included for each (M_{W_R}, M_{N_μ}) entry.

M_{W_R}	M_{N_μ}	Obs. Limit	Exp. Limit	Exp. -1σ	Exp. $+1\sigma$	Exp. -2σ	Exp. $+2\sigma$
1500	100	62.08	86.59	58.31	132.45	42.98	188.68
1500	200	10.60	14.78	9.96	22.62	7.34	32.22
1500	300	5.26	7.34	4.94	11.23	3.64	16.00
1500	400	4.00	5.58	3.76	8.54	2.77	12.16
1500	500	3.50	4.89	3.29	7.48	2.43	10.65
1500	600	3.22	4.48	3.02	6.86	2.23	9.77
1500	700	3.02	4.21	2.83	6.44	2.09	9.17
1500	800	2.95	4.12	2.77	6.29	2.04	8.97
1500	900	2.93	4.09	2.75	6.25	2.03	8.90
1500	1000	2.94	4.10	2.76	6.27	2.03	8.93
1500	1100	2.92	4.08	2.75	6.24	2.02	8.89
1500	1200	3.01	4.20	2.83	6.42	2.08	9.15
1500	1300	3.21	4.48	3.01	6.85	2.22	9.75
1500	1400	3.71	5.17	3.48	7.91	2.57	11.27
1600	100	77.66	80.27	54.11	121.06	39.92	169.10
1600	200	13.31	13.75	9.27	20.74	6.84	28.97
1600	300	6.35	6.57	4.43	9.91	3.27	13.84
1600	400	4.77	4.93	3.33	7.44	2.45	10.39
1600	500	4.10	4.24	2.86	6.39	2.11	8.93
1600	600	3.72	3.84	2.59	5.79	1.91	8.09
1600	700	3.52	3.64	2.45	5.49	1.81	7.66
1600	800	3.43	3.55	2.39	5.35	1.76	7.47
1600	900	3.35	3.46	2.33	5.22	1.72	7.29
1600	1000	3.33	3.44	2.32	5.19	1.71	7.25
1600	1100	3.35	3.47	2.34	5.23	1.72	7.30
1600	1200	3.37	3.49	2.35	5.26	1.73	7.35
1600	1300	3.47	3.59	2.42	5.42	1.79	7.57
1600	1400	3.66	3.78	2.55	5.70	1.88	7.96
1600	1500	4.21	4.35	2.93	6.56	2.16	9.16
1700	100	98.67	79.48	53.20	119.50	38.65	176.76
1700	200	16.24	13.08	8.75	19.66	6.36	29.09
1700	300	7.66	6.17	4.13	9.28	3.00	13.73
1700	400	5.48	4.42	2.96	6.64	2.15	9.82
1700	500	4.66	3.75	2.51	5.64	1.83	8.35
1700	600	4.26	3.43	2.29	5.16	1.67	7.62
1700	700	4.00	3.22	2.16	4.85	1.57	7.17
1700	800	3.85	3.10	2.08	4.67	1.51	6.91
1700	900	3.75	3.02	2.02	4.54	1.47	6.72
1700	1000	3.73	3.01	2.01	4.52	1.46	6.69
1700	1100	3.72	3.00	2.01	4.51	1.46	6.67
1700	1200	3.75	3.02	2.02	4.54	1.47	6.72
1700	1300	3.76	3.03	2.03	4.56	1.47	6.74
1700	1400	3.91	3.15	2.11	4.73	1.53	7.00
1700	1500	4.09	3.29	2.21	4.95	1.60	7.33
1700	1600	4.64	3.74	2.50	5.62	1.82	8.31

Table 5: The 95% confidence level observed (Obs.) and expected (Exp.) exclusion limits (in fb) on the W_R production cross section times branching fraction for $W_R \to \mu\mu jj$ as a function of W_R and N_μ mass (in GeV) for 1800 GeV $\leq M_{W_R} \leq$ 1900 GeV. The 68% and 95% uncertainty bands for the expected limit (Exp. $\pm 1\sigma$ and Exp. $\pm 2\sigma$, respectively) are also included for each (M_{W_R}, M_{N_μ}) entry.

M_{W_R}	M_{N_μ}	Obs. Limit	Exp. Limit	Exp. -1σ	Exp. $+1\sigma$	Exp. -2σ	Exp. $+2\sigma$
1800	100	111.90	79.36	53.08	120.16	38.73	178.56
1800	200	17.80	12.62	8.44	19.12	6.16	28.41
1800	300	8.40	5.96	3.99	9.03	2.91	13.41
1800	400	5.84	4.14	2.77	6.27	2.02	9.32
1800	500	4.91	3.48	2.33	5.27	1.70	7.84
1800	600	4.44	3.15	2.11	4.77	1.54	7.09
1800	700	4.13	2.93	1.96	4.43	1.43	6.58
1800	800	4.01	2.84	1.90	4.30	1.39	6.40
1800	900	3.89	2.76	1.84	4.17	1.34	6.20
1800	1000	3.85	2.73	1.83	4.13	1.33	6.14
1800	1100	3.82	2.71	1.81	4.11	1.32	6.10
1800	1200	3.82	2.71	1.81	4.11	1.32	6.10
1800	1300	3.83	2.72	1.82	4.11	1.33	6.11
1800	1400	3.90	2.76	1.85	4.18	1.35	6.22
1800	1500	4.00	2.83	1.90	4.29	1.38	6.38
1800	1600	4.21	2.99	2.00	4.53	1.46	6.73
1800	1700	4.70	3.33	2.23	5.04	1.63	7.49
1900	100	106.11	73.41	50.20	113.01	37.43	169.08
1900	200	17.65	12.21	8.35	18.80	6.23	28.13
1900	300	8.14	5.63	3.85	8.67	2.87	12.98
1900	400	5.55	3.84	2.63	5.91	1.96	8.85
1900	500	4.54	3.14	2.15	4.84	1.60	7.24
1900	600	4.12	2.85	1.95	4.39	1.45	6.57
1900	700	3.85	2.66	1.82	4.10	1.36	6.13
1900	800	3.66	2.53	1.73	3.90	1.29	5.83
1900	900	3.57	2.47	1.69	3.80	1.26	5.68
1900	1000	3.53	2.44	1.67	3.76	1.25	5.63
1900	1100	3.48	2.41	1.64	3.70	1.23	5.54
1900	1200	3.46	2.39	1.64	3.68	1.22	5.51
1900	1300	3.46	2.39	1.64	3.69	1.22	5.51
1900	1400	3.48	2.41	1.65	3.71	1.23	5.55
1900	1500	3.53	2.44	1.67	3.76	1.24	5.62
1900	1600	3.61	2.50	1.71	3.84	1.27	5.75
1900	1700	3.84	2.65	1.81	4.08	1.35	6.11
1900	1800	4.25	2.94	2.01	4.53	1.50	6.77

Table 6: The 95% confidence level observed (Obs.) and expected (Exp.) exclusion limits (in fb) on the W_R production cross section times branching fraction for $W_R \to \mu\mu jj$ as a function of W_R and N_μ mass (in GeV) for 2000 GeV $\leq M_{W_R} \leq$ 2100 GeV. The 68% and 95% uncertainty bands for the expected limit (Exp. $\pm 1\sigma$ and Exp. $\pm 2\sigma$, respectively) are also included for each (M_{W_R}, M_{N_μ}) entry.

M_{W_R}	M_{N_μ}	Obs. Limit	Exp. Limit	Exp. -1σ	Exp. $+1\sigma$	Exp. -2σ	Exp. $+2\sigma$
2000	100	98.21	70.58	49.13	107.35	37.07	164.39
2000	200	16.04	11.53	8.02	17.53	6.05	26.85
2000	300	7.32	5.26	3.66	8.00	2.76	12.26
2000	400	4.92	3.53	2.46	5.37	1.86	8.23
2000	500	3.99	2.86	1.99	4.36	1.50	6.67
2000	600	3.56	2.56	1.78	3.90	1.35	5.96
2000	700	3.31	2.38	1.65	3.61	1.25	5.53
2000	800	3.16	2.27	1.58	3.46	1.19	5.30
2000	900	3.08	2.21	1.54	3.37	1.16	5.16
2000	1000	3.02	2.17	1.51	3.30	1.14	5.05
2000	1100	2.97	2.14	1.49	3.25	1.12	4.98
2000	1200	2.96	2.13	1.48	3.24	1.12	4.96
2000	1300	2.95	2.12	1.47	3.22	1.11	4.93
2000	1400	2.94	2.12	1.47	3.22	1.11	4.93
2000	1500	2.99	2.15	1.50	3.27	1.13	5.01
2000	1600	3.02	2.17	1.51	3.30	1.14	5.06
2000	1700	3.11	2.24	1.56	3.40	1.17	5.21
2000	1800	3.28	2.36	1.64	3.58	1.24	5.49
2000	1900	3.64	2.61	1.82	3.98	1.37	6.09
2100	100	82.38	64.00	45.12	96.25	36.23	151.27
2100	200	13.88	10.78	7.60	16.21	6.10	25.48
2100	300	6.33	4.92	3.47	7.40	2.79	11.63
2100	400	4.26	3.31	2.33	4.98	1.87	7.82
2100	500	3.43	2.67	1.88	4.01	1.51	6.30
2100	600	3.00	2.33	1.64	3.51	1.32	5.51
2100	700	2.78	2.16	1.52	3.24	1.22	5.10
2100	800	2.67	2.07	1.46	3.12	1.17	4.90
2100	900	2.57	1.99	1.41	3.00	1.13	4.72
2100	1000	2.50	1.94	1.37	2.92	1.10	4.59
2100	1100	2.46	1.91	1.35	2.88	1.08	4.52
2100	1200	2.45	1.90	1.34	2.86	1.08	4.50
2100	1300	2.45	1.91	1.34	2.87	1.08	4.51
2100	1400	2.45	1.91	1.34	2.87	1.08	4.50
2100	1500	2.45	1.91	1.34	2.87	1.08	4.51
2100	1600	2.47	1.92	1.35	2.89	1.09	4.53
2100	1700	2.52	1.96	1.38	2.94	1.11	4.62
2100	1800	2.56	1.99	1.40	3.00	1.13	4.71
2100	1900	2.68	2.09	1.47	3.14	1.18	4.93
2100	2000	2.96	2.30	1.62	3.46	1.30	5.44

Table 7: The 95% confidence level observed (Obs.) and expected (Exp.) exclusion limits (in fb) on the W_R production cross section times branching fraction for $W_R \to \mu\mu jj$ as a function of W_R and N_μ mass (in GeV) for 2200 GeV $\leq M_{W_R} \leq$ 2300 GeV. The 68% and 95% uncertainty bands for the expected limit (Exp. $\pm 1\sigma$ and Exp. $\pm 2\sigma$, respectively) are also included for each (M_{W_R}, M_{N_μ}) entry.

M_{W_R}	M_{N_μ}	Obs. Limit	Exp. Limit	Exp. -1σ	Exp. $+1\sigma$	Exp. -2σ	Exp. $+2\sigma$
2200	100	61.55	53.90	37.83	81.66	31.30	121.24
2200	200	11.83	10.36	7.27	15.69	6.01	23.30
2200	300	5.58	4.89	3.43	7.41	2.84	11.00
2200	400	3.58	3.13	2.20	4.74	1.82	7.04
2200	500	2.89	2.53	1.77	3.83	1.47	5.68
2200	600	2.51	2.20	1.54	3.33	1.28	4.94
2200	700	2.32	2.03	1.42	3.07	1.18	4.56
2200	800	2.17	1.90	1.34	2.88	1.10	4.28
2200	900	2.12	1.86	1.30	2.82	1.08	4.18
2200	1000	2.07	1.81	1.27	2.74	1.05	4.07
2200	1100	2.03	1.78	1.25	2.69	1.03	4.00
2200	1200	2.03	1.78	1.25	2.70	1.03	4.00
2200	1300	2.00	1.75	1.23	2.66	1.02	3.95
2200	1400	2.00	1.75	1.23	2.66	1.02	3.94
2200	1500	2.00	1.75	1.23	2.65	1.02	3.94
2200	1600	2.00	1.75	1.23	2.66	1.02	3.94
2200	1700	2.02	1.77	1.24	2.68	1.03	3.99
2200	1800	2.06	1.81	1.27	2.73	1.05	4.06
2200	1900	2.10	1.84	1.29	2.79	1.07	4.14
2200	2000	2.20	1.93	1.35	2.92	1.12	4.34
2200	2100	2.40	2.11	1.48	3.19	1.22	4.74
2300	100	53.75	52.32	37.28	79.45	31.13	115.64
2300	200	10.63	10.34	7.37	15.71	6.15	22.86
2300	300	4.68	4.55	3.24	6.91	2.71	10.06
2300	400	3.18	3.09	2.20	4.69	1.84	6.83
2300	500	2.45	2.38	1.70	3.61	1.42	5.26
2300	600	2.15	2.09	1.49	3.18	1.25	4.63
2300	700	1.97	1.92	1.37	2.91	1.14	4.24
2300	800	1.84	1.79	1.28	2.72	1.07	3.96
2300	900	1.78	1.73	1.23	2.62	1.03	3.82
2300	1000	1.73	1.69	1.20	2.56	1.00	3.73
2300	1100	1.71	1.66	1.18	2.53	0.99	3.68
2300	1200	1.69	1.64	1.17	2.49	0.98	3.63
2300	1300	1.68	1.63	1.16	2.48	0.97	3.61
2300	1400	1.67	1.62	1.16	2.46	0.97	3.59
2300	1500	1.67	1.63	1.16	2.47	0.97	3.60
2300	1600	1.66	1.62	1.15	2.46	0.96	3.58
2300	1700	1.69	1.64	1.17	2.49	0.98	3.63
2300	1800	1.69	1.65	1.18	2.51	0.98	3.65
2300	1900	1.72	1.67	1.19	2.54	1.00	3.70
2300	2000	1.75	1.71	1.22	2.59	1.02	3.77
2300	2100	1.84	1.79	1.27	2.72	1.06	3.95
2300	2200	2.02	1.96	1.40	2.98	1.17	4.34

Table 8: The 95% confidence level observed (Obs.) and expected (Exp.) exclusion limits (in fb) on the W_R production cross section times branching fraction for $W_R \to \mu\mu jj$ as a function of W_R and N_μ mass (in GeV) for 2400 GeV $\leq M_{W_R} \leq$ 2500 GeV. The 68% and 95% uncertainty bands for the expected limit (Exp. $\pm 1\sigma$ and Exp. $\pm 2\sigma$, respectively) are also included for each (M_{W_R}, M_{N_μ}) entry.

M_{W_R}	M_{N_μ}	Obs. Limit	Exp. Limit	Exp. -1σ	Exp. $+1\sigma$	Exp. -2σ	Exp. $+2\sigma$
2400	100	43.94	43.82	32.64	66.42	28.01	100.50
2400	200	9.52	9.49	7.07	14.38	6.07	21.76
2400	300	4.59	4.58	3.41	6.94	2.93	10.50
2400	400	2.95	2.94	2.19	4.45	1.88	6.74
2400	500	2.34	2.33	1.74	3.54	1.49	5.35
2400	600	2.00	1.99	1.49	3.02	1.27	4.57
2400	700	1.83	1.82	1.36	2.77	1.17	4.18
2400	800	1.72	1.72	1.28	2.61	1.10	3.94
2400	900	1.65	1.65	1.23	2.50	1.05	3.78
2400	1000	1.62	1.62	1.21	2.45	1.03	3.71
2400	1100	1.59	1.58	1.18	2.40	1.01	3.63
2400	1200	1.56	1.56	1.16	2.36	1.00	3.57
2400	1300	1.54	1.54	1.15	2.33	0.98	3.53
2400	1400	1.54	1.53	1.14	2.32	0.98	3.51
2400	1500	1.53	1.53	1.14	2.31	0.98	3.50
2400	1600	1.52	1.52	1.13	2.30	0.97	3.49
2400	1700	1.54	1.53	1.14	2.33	0.98	3.52
2400	1800	1.56	1.55	1.16	2.35	0.99	3.56
2400	1900	1.57	1.56	1.16	2.37	1.00	3.59
2400	2000	1.59	1.58	1.18	2.40	1.01	3.63
2400	2100	1.62	1.62	1.21	2.45	1.04	3.71
2400	2200	1.69	1.69	1.26	2.56	1.08	3.87
2400	2300	1.83	1.83	1.36	2.77	1.17	4.19
2500	100	42.22	44.33	34.29	67.02	29.64	102.78
2500	200	9.04	9.49	7.34	14.35	6.35	22.01
2500	300	4.56	4.78	3.70	7.23	3.20	11.09
2500	400	2.98	3.13	2.42	4.73	2.09	7.25
2500	500	2.31	2.43	1.88	3.67	1.62	5.63
2500	600	1.97	2.07	1.60	3.12	1.38	4.79
2500	700	1.79	1.88	1.45	2.84	1.26	4.36
2500	800	1.67	1.76	1.36	2.66	1.18	4.08
2500	900	1.62	1.70	1.31	2.57	1.14	3.94
2500	1000	1.58	1.66	1.28	2.51	1.11	3.85
2500	1100	1.54	1.61	1.25	2.44	1.08	3.74
2500	1200	1.51	1.58	1.22	2.39	1.06	3.67
2500	1300	1.50	1.57	1.22	2.38	1.05	3.65
2500	1400	1.48	1.55	1.20	2.35	1.04	3.60
2500	1500	1.48	1.56	1.20	2.35	1.04	3.61
2500	1600	1.48	1.55	1.20	2.34	1.04	3.59
2500	1700	1.48	1.56	1.20	2.35	1.04	3.61
2500	1800	1.48	1.55	1.20	2.35	1.04	3.61
2500	1900	1.49	1.56	1.21	2.36	1.04	3.62
2500	2000	1.50	1.58	1.22	2.38	1.05	3.66
2500	2100	1.52	1.60	1.24	2.42	1.07	3.71
2500	2200	1.56	1.64	1.27	2.48	1.10	3.80
2500	2300	1.62	1.70	1.32	2.57	1.14	3.94
2500	2400	1.77	1.86	1.44	2.82	1.25	4.32

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, E. Aguilo, 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], I. Krätschmer, D. Liko, I. Mikulec, M. Pernicka†, B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, W. Waltenberger, 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
M. Bansal, S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, S. Luyckx, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, M. Selvaggi, 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, A. Mohammadi, 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, S. Walsh, E. Yazgan, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Basegmez, G. Bruno, R. Castello, 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, A. Pin, K. Piotrzkowski, 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, 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, A. Santoro, L. Soares Jorge, A. Sznajder, A. Vilela Pereira

Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil
T.S. Anjos[3], 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, Y. Guo, W. Li, S. Liu, Y. Mao, S.J. Qian, H. Teng, D. Wang, L. Zhang, W. Zou

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

Technical University of Split, Split, Croatia
N. Godinovic, D. 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, D. Mekterovic, 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
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, 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, M. Dalchenko, L. Dobrzynski, A. Florent, R. Granier de Cassagnac, M. Haguenauer, P. Miné, C. Mironov, I.N. Naranjo, 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], 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, L. Sgandurra, V. Sordini, 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
C. Autermann, S. Beranek, B. Calpas, 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, M. Merschmeyer, A. Meyer, M. Olschewski, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier, S. Thüer, M. Weber

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
M. Bontenackels, V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, J. Lingemann[5], A. Nowack, L. Perchalla, O. Pooth, P. Sauerland, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, J. Behr, W. Behrenhoff, U. Behrens, M. Bergholz[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, J. Leonard, 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, O. Novgorodova, J. Olzem, H. Perrey, A. Petrukhin, D. Pitzl, A. Raspereza, P.M. Ribeiro Cipriano, C. Riedl, E. Ron, M. Rosin, J. Salfeld-Nebgen, R. Schmidt[17], T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany
V. Blobel, H. Enderle, J. Erfle, U. Gebbert, M. Görner, M. Gosselink, J. Haller, T. Hermanns, R.S. Höing, K. Kaschube, G. Kaussen, H. Kirschenmann, R. Klanner, J. Lange, F. Nowak, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, M. Seidel, J. Sibille[18], 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[5], T. Hauth[5], M. Heinrich, H. Held, K.H. Hoffmann, U. Husemann, 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, 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. Anagnostou, G. Daskalakis, T. Geralis, S. Kesisoglou, A. Kyriakis, D. Loukas, I. Manolakos, A. Markou, C. Markou, C. Mavrommatis, E. Ntomari

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

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

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
G. Bencze, C. Hajdu, P. Hidas, D. Horvath[19], F. Sikler, V. Veszpremi, G. Vesztergombi[20]

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

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

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

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

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

Bhabha Atomic Research Centre, Mumbai, India
A. Abdulsalam, D. Dutta, S. Kailas, V. Kumar, A.K. Mohanty[5], L.M. Pant, P. Shukla

Tata Institute of Fundamental Research - EHEP, Mumbai, India
T. Aziz, S. Ganguly, M. Guchait[21], A. Gurtu[22], M. Maity[23], 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[24], H. Bakhshiansohi, S.M. Etesami[25], A. Fahim[24], M. Hashemi[26], H. Hesari, A. Jafari, M. Khakzad, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh[27], M. Zeinali

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], G. Maggi[a,c], M. Maggi[a], B. Marangelli[a,b],

S. My[a,c], S. Nuzzo[a,b], N. Pacifico[a], A. Pompili[a,b], G. Pugliese[a,c], G. Selvaggi[a,b], L. Silvestris[a], G. Singh[a,b], R. Venditti[a,b], P. Verwilligen, 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], 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.P. Siroli[a,b], N. Tosi, 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,b]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, S. Colafranceschi[28], F. Fabbri, D. Piccolo

INFN Sezione di Genova [a], Università di Genova [b], Genova, Italy
P. Fabbricatore[a], R. Musenich[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca [a], Università di Milano-Bicocca [b], Milano, Italy
A. Benaglia[a], 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], 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], N. Cavallo[a,29], A. De Cosa[a,b,5], O. Dogangun[a,b], F. Fabozzi[a,29], A.O.M. Iorio[a,b], L. Lista[a], S. Meola[a,30], M. Merola[a], 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], P. Bellan[a,b], D. Bisello[a,b], A. Branca[a,5], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a], U. Dosselli[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], M. Nespolo[a,5], J. Pazzini[a,b], P. Ronchese[a,b], F. Simonetto[a,b], E. Torassa[a], S. Vanini[a,b], P. Zotto[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], G. Mantovani[a,b], M. Menichelli[a], A. Nappi[a,b†], F. Romeo[a,b], A. Saha[a], A. Santocchia[a,b], A. Spiezia[a,b], S. Taroni[a,b]

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,5], 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,31], A. Messineo[a,b], F. Palla[a], A. Rizzi[a,b], A.T. Serban[a,32], P. Spagnolo[a], P. Squillacioti[a,5], R. Tenchini[a], G. Tonelli[a,b], A. Venturi[a], 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], M. Diemoz[a], C. Fanelli, 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], S. Casasso[a,b], M. Costa[a,b], N. Demaria[a], 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], M. Ruspa[a,c], R. Sacchi[a,b], A. Solano[a,b], A. Staiano[a]

INFN Sezione di Trieste [a], Università di Trieste [b], Trieste, Italy
S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], 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
T.Y. Kim, S.K. Nam

Kyungpook National University, Daegu, Korea
S. Chang, D.H. Kim, G.N. Kim, D.J. Kong, H. Park, 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. 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, 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, J. Butt, H.R. Hoorani, S. Khalid, W.A. Khan, T. Khurshid, S. Qazi, M.A. Shah, M. Shoaib

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, B. Boimska, T. Frueboes, M. Górski, 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

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

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

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
S. 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, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, I. Shreyber, V. Stolin, E. Vlasov, A. Zhokin

Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, M. Dubinin[4], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, S. Petrushanko, A. Popov, L. Sarycheva†, V. Savrin, A. Snigirev

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

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, V. Grishin[5], V. Kachanov, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic[33], M. Djordjevic, M. Ekmedzic, D. Krpic[33], 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[34], M. Fernandez, G. Gomez, J. Gonzalez Sanchez, A. Graziano, C. Jorda, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, T. Rodrigo, A.Y. Rodríguez-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.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. Girone, M. Giunta, F. Glege, R. Gomez-Reino Garrido, P. Govoni, S. Gowdy, R. Guida, S. Gundacker, 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, N. Magini, 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[35], C. Rovelli[36], M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas[37], D. Spiga, A. Tsirou, G.I. Veres[20], J.R. Vlimant, H.K. Wöhri, S.D. Worm[38], 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

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
L. Bäni, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, J. Eugster, K. Freudenreich, C. Grab, D. Hits, P. Lecomte, W. Lustermann, A.C. Marini, P. Martinez Ruiz del Arbol, N. Mohr, F. Moortgat, C. Nägeli[39], 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[40], B. Stieger, M. Takahashi, L. Tauscher†, A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H.A. Weber, L. Wehrli

Universität Zürich, Zurich, Switzerland
C. Amsler[41], V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Kilminster, 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. Ferro, C.M. Kuo, S.W. Li, W. Lin, Y.J. Lu, A.P. Singh, R. Volpe, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, C. Dietz, U. Grundler, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, R.-S. Lu, D. Majumder, E. Petrakou, X. Shi, J.G. Shiu, Y.M. Tzeng, X. Wan, M. Wang

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

Cukurova University, Adana, Turkey
A. Adiguzel, M.N. Bakirci[42], S. Cerci[43], C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, T. Karaman, G. Karapinar[44], A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk[45], A. Polatoz, K. Sogut[46], D. Sunar Cerci[43], B. Tali[43], H. Topakli[42], 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[47], M. Kaya[48], O. Kaya[48], S. Ozkorucuklu[49], N. Sonmez[50]

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

Rutherford Appleton Laboratory, Didcot, United Kingdom
L. Basso[51], K.W. Bell, A. Belyaev[51], 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[40], A. Papageorgiou, J. Pela, M. Pesaresi, K. Petridis, M. Pioppi[52], 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, G. Christopher, D. Cutts, Z. Demiragli, A. Ferapontov, A. Garabedian, U. Heintz, S. Jabeen, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, D. Nguyen, M. Segala, T. Sinthuprasith, T. Speer

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

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, G. Rakness, P. Schlein†, P. Traczyk, V. Valuev, M. Weber

University of California, Riverside, Riverside, USA
J. Babb, R. Clare, M.E. Dinardo, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng[53], 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, 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[54], 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, F. Golf, J. Incandela, C. Justus, P. Kalavase, D. Kovalskyi, V. Krutelyov, S. Lowette, R. Magaña Villalba, N. Mccoll, V. Pavlunin, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, C. West

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

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

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

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

Fairfield University, Fairfield, USA
D. Winn

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, J. Anderson, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, 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. Klima, S. Kunori, S. Kwan, C. Leonidopoulos[55], J. Linacre, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko[56], C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, J.C. Yun

University of Florida, Gainesville, USA
D. Acosta, P. Avery, D. Bourilkov, M. Chen, T. Cheng, S. Das, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, J. Hugon, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic[57], G. Mitselmakher, L. Muniz, M. Park, R. Remington, A. Rinkevicius, P. Sellers, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

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

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

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

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

The University of Iowa, Iowa City, USA
U. Akgun, E.A. Albayrak, B. Bilki[58], W. Clarida, F. Duru, J.-P. Merlo, H. Mermerkaya[59], A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, Y. Onel, F. Ozok[60], S. Sen, P. Tan, E. Tiras, J. Wetzel, T. Yetkin, K. Yi

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

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

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, F. Rebassoo, D. Wright

University of Maryland, College Park, USA
A. Baden, 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. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar

Massachusetts Institute of Technology, Cambridge, USA
A. Apyan, G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, G. Gomez Ceballos, M. Goncharov, Y. Kim, M. Klute, K. Krajczar[61], A. Levin, 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, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti, V. Zhukova

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, Oxford, 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, D.R. Claes, A. Dominguez, M. Eads, J. Keller, I. Kravchenko, J. Lazo-Flores, S. Malik, G.R. Snow

State University of New York at Buffalo, Buffalo, USA
A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S. Rappoccio

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, K.A. Hahn, A. Kubik, L. Lusito, 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, K.M. Chan, M. Hildreth, C. Jessop, D.J. Karmgard, J. Kolb, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, M. Planer, R. Ruchti, J. Slaunwhite, N. Valls, M. Wayne, M. Wolf

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

Princeton University, Princeton, USA
E. Berry, P. Elmer, V. Halyo, P. Hebda, J. Hegeman, A. Hunt, P. Jindal, S.A. Koay, D. Lopes Pegna, 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, A. Zuranski

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

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, B. Akgun, C. Boulahouache, K.M. Ecklund, F.J.M. Geurts, W. Li, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

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

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

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

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[62], V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, S. Sengupta, I. Suarez, A. Tatarinov, D. Toback

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

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

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

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, 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, 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 National Centre for Nuclear Research, Swierk, Poland
14: Also at Université de Haute-Alsace, Mulhouse, France
15: Also 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 The University of Kansas, Lawrence, USA
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: Now at King Abdulaziz University, Jeddah, Saudi Arabia
23: Also at University of Visva-Bharati, Santiniketan, India
24: Also at Sharif University of Technology, Tehran, Iran
25: Also at Isfahan University of Technology, Isfahan, Iran
26: Also at Shiraz University, Shiraz, Iran
27: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
28: Also at Facoltà Ingegneria Università di Roma, Roma, Italy
29: Also at Università della Basilicata, Potenza, Italy
30: Also at Università degli Studi Guglielmo Marconi, Roma, Italy
31: Also at Università degli Studi di Siena, Siena, Italy
32: Also at University of Bucharest, Faculty of Physics, Bucuresti-Magurele, Romania
33: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
34: Also at University of California, Los Angeles, Los Angeles, USA
35: Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy
36: Also at INFN Sezione di Roma; Università di Roma "La Sapienza", Roma, Italy
37: Also at University of Athens, Athens, Greece
38: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
39: Also at Paul Scherrer Institut, Villigen, Switzerland
40: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
41: Also at Albert Einstein Center for Fundamental Physics, BERN, SWITZERLAND
42: Also at Gaziosmanpasa University, Tokat, Turkey
43: Also at Adiyaman University, Adiyaman, Turkey
44: Also at Izmir Institute of Technology, Izmir, Turkey
45: Also at The University of Iowa, Iowa City, USA
46: Also at Mersin University, Mersin, Turkey
47: Also at Ozyegin University, Istanbul, Turkey
48: Also at Kafkas University, Kars, Turkey
49: Also at Suleyman Demirel University, Isparta, Turkey
50: Also at Ege University, Izmir, Turkey
51: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
52: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
53: Also at University of Sydney, Sydney, Australia
54: Also at Utah Valley University, Orem, USA

55: Now at University of Edinburgh, Scotland, Edinburgh, United Kingdom
56: Also at Institute for Nuclear Research, Moscow, Russia
57: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
58: Also at Argonne National Laboratory, Argonne, USA
59: Also at Erzincan University, Erzincan, Turkey
60: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
61: Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
62: Also at Kyungpook National University, Daegu, Korea