



Search for a W' boson decaying to a muon and a neutrino in pp collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration*

Abstract

A new heavy gauge boson, W' , decaying to a muon and a neutrino, is searched for in pp collisions at a centre-of-mass of 7 TeV. The data, collected with the CMS detector at the LHC, correspond to an integrated luminosity of 36 pb^{-1} . No significant excess of events above the standard model expectation is found in the transverse mass distribution of the muon-neutrino system. Masses below 1.40 TeV are excluded at the 95% confidence level for a sequential standard-model-like W' . The W' mass lower limit increases to 1.58 TeV when the present analysis is combined with the CMS result for the electron channel.

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*See Appendix A for the list of collaboration members

New heavy gauge bosons, generally indicated as Z' and W' , are predicted in various extensions of the standard model (SM). Such extensions include Left-Right Symmetric Models [1–3], Compositeness models [4] and Little Higgs models [5]. The search for a W' is usually performed in the context of the benchmark model of Ref. [6], where the W' boson is considered a heavy analogue of the SM W boson with the same left-handed fermionic couplings. Thus the W' decay modes and branching fractions are similar to those of the W boson, with the notable exception of the $t\bar{b}$ channel, which opens up for W' masses above 180 GeV. No interaction with the SM gauge bosons or with other heavy gauge bosons such as Z' is assumed. In this context, CDF [7] and D0 [8] searched for a W' boson in the decay to an electron and a neutrino, and excluded W' masses below 1.1 TeV at the 95% confidence level (C.L.). Recently, a search in this decay channel by CMS extended the lower limit on the W' mass to 1.36 TeV [9].

In this letter, the W' decay to a muon and a neutrino with an assumed branching fraction of 8.5% (for all W' masses) is investigated and combined with a similar search in the electron channel [9]. The data sample, collected in 2010 by the CMS detector with pp collisions delivered by the LHC at centre-of-mass energy of 7 TeV, corresponds to 36 pb^{-1} .

A more detailed description of CMS can be found elsewhere [10]. The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter and the brass/scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel return yoke. Both barrel and endcap regions are instrumented with four muon stations combining high precision tracking detectors (drift tubes in the barrel and cathode strip chambers in the endcaps) with resistive plate chambers for triggering as well as contributing to the tracking. The muon transverse momentum, p_T , is measured through bending of its track when passing the magnetized return yoke. Each station consists of a multi-layer chamber, twelve and six layers for the drift and the cathode strip chambers, respectively. All muon stations contribute to the first level trigger and identify the bunch crossing from which the muon originated. A cylindrical coordinate system about the beam axis is used, in which the polar angle θ is measured with respect to the counterclockwise beam direction, and η is the pseudo-rapidity defined by $\eta = -\ln \tan \theta/2$.

Each muon track is matched to a tracker track, measured in the silicon tracker. A global track fit is performed [11], and the resulting global muon p_T resolution amounts to 1 to 10% for p_T values up to 1 TeV. The inner tracker measures charged particle trajectories within the pseudorapidity range $|\eta| < 2.5$. It provides an impact parameter resolution of about 15 μm and a transverse momentum p_T resolution of about 1.5% for $p_T = 100 \text{ GeV}$ particles.

The primary sources of background to the $W' \rightarrow \mu\nu$ search include standard model $W \rightarrow \mu\nu$ decays, QCD multijet events, $t\bar{t}$, Drell-Yan events and cosmic ray muons. Diboson processes (WW , WZ , ZZ) with decays to electrons, muons or taus are also considered. Monte Carlo (MC) simulation is used to obtain event samples that are employed to evaluate signal and background efficiencies. The generated events are processed through the full CMS GEANT4 [12, 13] based detector simulation, trigger emulation, and event reconstruction chain. The W' signal sample is produced with the PYTHIA 6.409 generator [14] and the CTEQ6L parton distribution functions (PDF) [15]. Events are generated for W' masses ranging between 0.6 TeV and 1.5 TeV in steps of 100 GeV and for a W' mass of 2 TeV. Next-to-next-to-leading order (NNLO) corrections to the W' production cross sections, called k -factors, are available [16, 17] and amount to 1.32 for $m_{W'} = 0.6 \text{ TeV}$ to 1.26 for $m_{W'} = 2 \text{ TeV}$.

The samples for the electroweak background processes $W \rightarrow \mu\nu$ and $Z \rightarrow \mu^+\mu^-$ are produced with POWHEG [18–20] interfaced with PYTHIA for showering and hadronization. Samples of

$W \rightarrow \mu\nu$, produced with PYTHIA with and without the simulation of pile-up effects, are used for cross-checks. The PYTHIA generator is also used for the production of $W \rightarrow \tau\nu$, $Z \rightarrow \tau^+\tau^-$, the diboson (ZZ, WZ, WW) samples, and QCD multijet events. For $t\bar{t}$ events, the MADGRAPH [21] generator is used in combination with PYTHIA for showering and hadronization. Most background processes are normalized to the integrated luminosity with NNLO cross section calculations. However, for $t\bar{t}$ and QCD multijet, the NLO and LO cross sections are used, respectively.

Candidate events with at least one high- p_T muon in the pseudorapidity range $|\eta| < 2.1$ are selected with a set of single-muon triggers. Only global muons reconstructed offline with $p_T > 25$ GeV in the range $|\eta| < 2.1$ are used in the analysis; the global muon track is required to have at least eleven hits in the silicon tracker and at least one hit in the pixel detector. The global track is also required to satisfy $\chi^2/N_{\text{dof}} < 10$ and to have at least two matching track segments in different muon stations. Since the segments have multiple hits and are typically found in different muon detectors separated by thick layers of iron, this requirement significantly reduces the amount of hadronic punch-through. The transverse impact parameter $|d_0|$ of a muon track with respect to the beam spot is required to be less than 0.02 cm, in order to reduce the cosmic muon background. Furthermore, the muon is required to be isolated with a combined relative isolation of less than 0.15. The latter variable is defined as the ratio between the addition (within a $\Delta R \equiv \sqrt{\Delta\phi^2 + \Delta\eta^2} < 0.3$ cone around the muon direction) of the deposited transverse energy in the calorimeters and the scalar sum of the transverse momenta of all tracks that originate from the interaction vertex, and the muon p_T . An additional requirement that there be no more than one muon in the event with $p_T > 25$ GeV is used to reduce the Z and Drell-Yan and cosmic ray muon backgrounds.

Muon reconstruction, identification, and selection efficiencies, along with their uncertainties, are determined from $Z \rightarrow \mu^+\mu^-$ decays using tag-and-probe techniques. One lepton candidate, called the “tag”, satisfies the trigger criteria and all identification and isolation requirements. The other lepton candidate, called the “probe”, is used to determine the efficiency of specific criteria under study.

The combined muon identification efficiency is measured to be 95%, including efficiencies for the muon reconstruction, the muon selection requirements, the isolation, and the inner track measured by the silicon strip tracker. The value for the combined efficiency is very similar in data and simulation, with the data/MC ratio being 99%. The trigger efficiency was studied with two complementary methods, the first one using tag-and-probe in dimuon events and the second one using a sample of jet-triggered data, which result in the trigger efficiencies of 92% and 91%, respectively, differing in data and simulation by 4%. Muons from a W' would have higher momenta than those used in the tag-and-probe studies. So far, only muons up to $p_T = 240$ GeV from pp collisions have been recorded and efficiency studies for O(500) GeV muons are done with simulated W' samples. The combined efficiency does not depend on p_T despite the fact that the showering probability in the iron yoke increases with the muon energy. This assumption has been checked with cosmic muons up to 1 TeV [11] and is a consequence of the redundancy of the muon system.

The neutrino from a potential W' signal is not detected, but gives rise to missing transverse energy (E_T^{miss}) in the detector, which is calculated using the particle flow technique [22]. The technique aims at reconstructing a complete, unique list of particles in each event using all the components of the CMS detector: muons, electrons, photons, and charged and neutral hadrons are all reconstructed individually. The E_T^{miss} for the event is given by the negative sum of the p_T of all the reconstructed particles in the event. The W' transverse mass, M_T , is thereafter

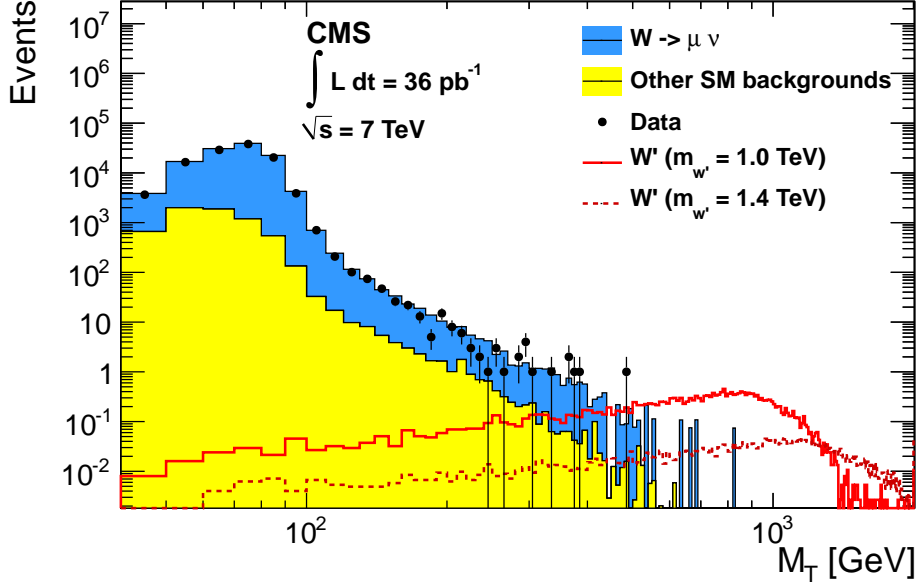


Figure 1: The M_T distribution after all the selection steps, in the data and in the simulation. A W' signal with two different hypothetical masses is shown.

calculated as:

$$M_T = \sqrt{2 \cdot p_T \cdot E_T^{\text{miss}} \cdot (1 - \cos \Delta\phi_{\mu,\nu})}$$

where $\Delta\phi_{\mu,\nu}$ is the opening azimuthal angle between the muon and the direction of E_T^{miss} measured in radians.

The two-body decay kinematics is exploited to further select events with signal-like topology where the muon and E_T^{miss} are expected to be nearly back-to-back in the transverse plane and also balanced in transverse energy. A selection on the ratio of the muon p_T and E_T^{miss} is then applied, $0.4 < p_T/E_T^{\text{miss}} < 1.5$. Further, the angular difference is required to be $\Delta\phi_{\mu,\nu} > 2.5$. After this selection, the W' signal efficiency for the explored W' mass range is found to be between 79% and 82.5% within the muon acceptance of $|\eta| < 2.1$.

Estimated SM backgrounds, based on MC simulations, are shown in Fig. 1 separately for W bosons and for smaller contributions due to QCD, $t\bar{t}$, Drell-Yan, and diboson production. The dominant background up to high transverse masses is the $W \rightarrow \mu\nu$ contribution, which is difficult to suppress as it also decays to a muon and a neutrino. The data are also shown in Fig. 1, in agreement with the SM expectation.

The background in the signal region is estimated using the lower $180 < M_T < 350$ GeV side band region of the high M_T part of the spectrum. A relativistic Breit-Wigner function is used as an ad-hoc empirical shape to fit the M_T distribution in the side band, both in the simulation and the data. The parameters of the fitting function are then used to calculate the number of expected background events in the different bins of M_T outside the side band. The choice of the side band lower and upper limits is made in order to minimize the contribution from a hypothetical W' signal and find a region that gives reliable extrapolations of the background in the signal region, based on simulation studies. According to the simulation, 71 ± 8 events are expected in the side band region for the combination of all SM backgrounds, for an integrated luminosity of 36 pb^{-1} . The signal contamination would be 1.63 ± 0.07 or 0.17 ± 0.01 W' events for a mass of 1.0 and 1.4 TeV, respectively. In the data, this region contains 52 events,

consistent with the prediction within the systematic uncertainties in luminosity, background composition and theoretical uncertainties. The difference between the background modeling in the data and the predicted SM background from simulation in various search windows is considered as systematic uncertainty in the determination of the expected background events in the signal region. The robustness of this method has been tested by varying the binning of the M_T distribution and the interval range defining the sideband region, and it was confirmed that it does not introduce any significant systematic uncertainties.

Unlike in the electron channel [9], high- p_T cosmic ray muons constitute an additional source of background for this analysis. Their spectrum shows a different M_T dependence from that of the dominant W boson contribution. Cosmic ray muons are identified with a transverse impact parameter with respect to the beam spot larger than 0.02 cm. The number of cosmic ray muons expected after this requirement is determined to be between 0.15 ± 0.04 for $M_T > 350$ GeV and 0.08 ± 0.03 for $M_T > 600$ GeV.

Table 1: Minimum M_T requirement for the search windows, along with the expected numbers of signal (N_{sig}) and background (N_{bkg}) events and data. Also shown are the theoretical, expected and observed excluded cross section \times BR limit for each W' signal sample, using a Bayesian method as discussed in the text.

$m_{W'}$ (GeV)	M_T (GeV)	N_{sig} (Events)	N_{bkg} (Events)	N_{data} (Events)	$\sigma \cdot \text{BR}$ (pb)	Expected limit (pb)	Observed limit (pb)
600	390	152 ± 16	2.54 ± 0.68	1	8.290	0.308	0.212
700	450	78 ± 8	1.54 ± 0.41	1	4.264	0.267	0.227
800	470	49 ± 5	1.33 ± 0.35	1	2.426	0.236	0.212
900	500	29 ± 3	1.09 ± 0.29	0	1.389	0.216	0.150
1000	530	18 ± 1.9	0.91 ± 0.23	0	0.849	0.204	0.147
1100	590	11 ± 1.2	0.65 ± 0.16	0	0.516	0.193	0.151
1200	610	7.1 ± 0.7	0.59 ± 0.15	0	0.334	0.188	0.150
1300	630	4.7 ± 0.5	0.54 ± 0.13	0	0.214	0.180	0.146
1400	630	3.0 ± 0.3	0.54 ± 0.13	0	0.141	0.175	0.139
1500	680	2.1 ± 0.2	0.42 ± 0.10	0	0.094	0.175	0.146
2000	690	0.29 ± 0.03	0.40 ± 0.10	0	0.014	0.185	0.153

The numbers of background events expected and observed are reported in Table 1. The uncertainties on the number of background events in Table 1 correspond to the statistical uncertainty of the side band fit itself, as the background is completely determined from data.

The number of signal events expected is evaluated from simulation and given in the third column of Table 1 for different W' masses along with the total uncertainty.

The following sources of systematic uncertainties have been considered.

- **Muon p_T resolution and muon momentum scale:** Systematic uncertainties due to the muon p_T resolution and momentum scale are evaluated from detailed studies of the $Z \rightarrow \mu^+ \mu^-$ mass distribution [23] and high- p_T cosmic ray muons [11]. In order to estimate the effect on the number of events expected, the data muon p_T spectrum is scaled and smeared using the values obtained from those studies, the missing transverse energy is recomputed, and finally a distorted M_T distribution is obtained. The fit in the side band is performed again with the new M_T distribution. From comparison with the background estimation obtained from the original undistorted sample, an uncertainty in the final number of expected background events for $M_T > 500$ GeV of approximately 3% is derived. For the signal yield, where higher

values of p_T should be considered, a conservative value of about 10% is assigned as systematic uncertainty due to this effect.

- **E_T^{miss} resolution:** An uncertainty of 10% [24] is assumed on the hadronic component of the E_T^{miss} resolution, and used to smear the x and y components of the reconstructed E_T^{miss} . The impact on the number of W' signal events (averaged over all masses) in the M_T search window with respect to the unsmeared distribution is found to be below 1%.
- **Muon trigger and identification efficiency:** An uncertainty close to 4% on the combined muon identification and trigger efficiency is considered for the signal yield.
- **Uncertainty on luminosity:** The uncertainty on the absolute value of the integrated luminosity is taken as 11% [25].

The high M_T region is then used to search for $W' \rightarrow \mu\nu$ which would manifest itself as an excess of events in the TeV region of the M_T distribution. No significant excess is observed (Fig. 1). The highest transverse mass event observed has $M_T = 487$ GeV and is displayed in Fig. 2.

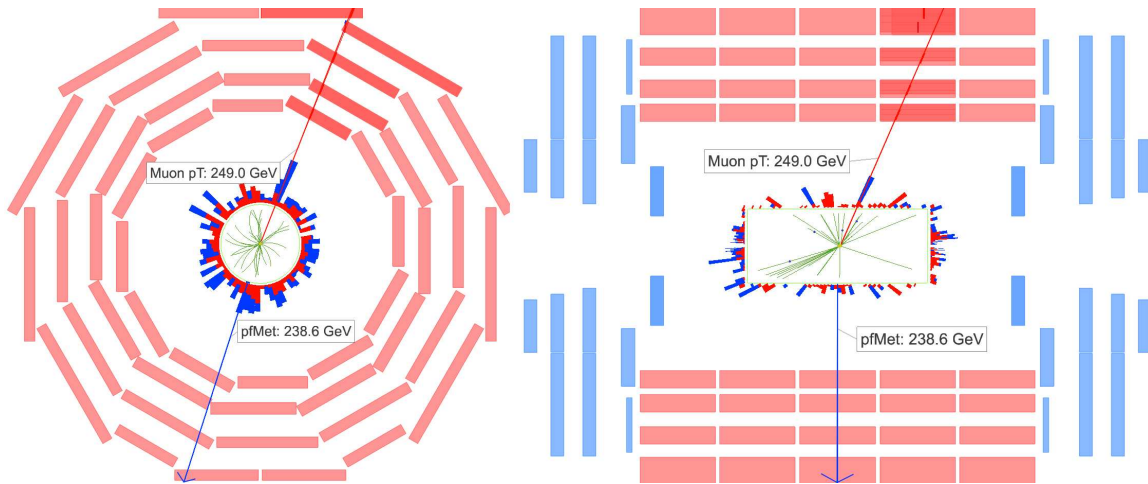


Figure 2: Display of the highest- M_T event in transverse view (left) and longitudinal view (right). The four barrel muon stations are shown in red, the forward muon stations in blue. Charged particle tracks as well as the deposited energy per calorimeter cell are displayed. The muon with $p_T = 249$ GeV is symbolized by a red line moving upward, and the $E_T^{\text{miss}} = 238.6$ GeV (“pfMet”) by a blue line moving downward.

An upper limit is set on the production cross section times the branching ratio into $\mu\nu$, $\sigma \cdot \text{BR}(W' \rightarrow \mu\nu)$. The limit is derived using the RooStats [26] interface to BAT [27] to calculate the limits with the help of Markov Chain Monte Carlo methods. A flat prior probability distribution is assumed for the signal cross section. The number of data events above an optimized M_T threshold are counted and compared to the expected number of background events. Systematic uncertainties on the signal efficiency and background events are treated as nuisance parameters with a log-normal prior distribution and integrated over. The M_T threshold is optimized for the best expected limit and defines the lower bound of the search window for each value of the W' mass. The expected and observed 95% C.L. limits for $\sigma \cdot \text{BR}$ are shown in Table 1. The value of the theoretical cross section, shown in Table 1, is used to translate the excluded cross section into a W' mass limit. The existence of a W' with SM-like couplings and masses below 1.40 TeV is excluded at 95% C.L. with an expected limit of 1.35 TeV. Inclusion of $W' \rightarrow \tau\nu$ decays does not appreciably add to the acceptance of the $W' \rightarrow \mu\nu$ signal process.

Finally, the results of this search are combined with those of the $W' \rightarrow e\nu$ analysis [9]. The

muon channel exhibits slightly higher sensitivity (due to the larger efficiency of about 79-82%, compared to 64-67% in the electron channel). In either channels, no events are seen at high transverse masses. Identical NNLO signal cross sections with the same k -factors and the same PDF uncertainties are used for both channels under the assumption of lepton universality. The search windows are optimized individually for each channel based on the best expected limit. The search windows for both channels can be found in Table 2. For each channel the likelihood function is determined and the two likelihood functions are combined.

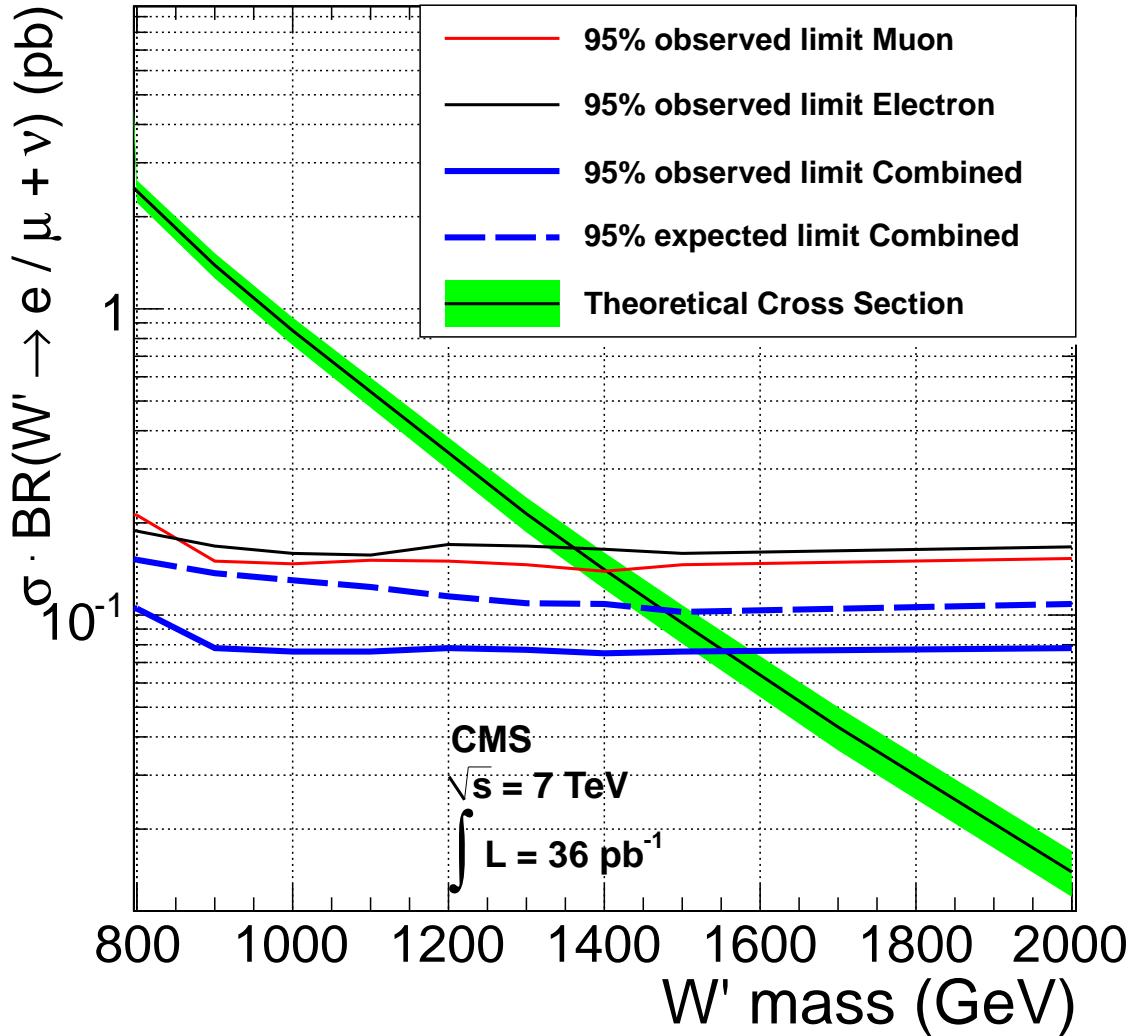


Figure 3: Individual limits as observed for the electron (black line) and the muon channel (red line). Their combination is shown as a solid blue line for the observed limit (expected as dashed blue line), using a Bayesian technique with only the luminosity uncertainty correlated.

The limits for the two individual channels as well as the limit obtained by combining them are shown in Fig. 3. The systematic uncertainties for resolution, trigger and lepton identification efficiencies are assumed to be fully uncorrelated between both channels. The uncertainty on the luminosity is taken as fully correlated, as well as the k -factors and PDF uncertainties on the theoretical cross section. When all background uncertainties are assumed to be fully correlated between the two channels, the combined limit remains unchanged. From this combination, a W' with SM-like couplings and with mass below 1.58 TeV is excluded at the 95% confidence

level.

Table 2: The first two columns show the channel-independent theoretical NNLO cross section for various W' mass points. Columns three and five show the individually optimized minimum M_T thresholds for the electron and muon channels, respectively, along with the excluded cross section \times BR per channel in columns four and six. Finally, the right-most column is the combined limit by using a Bayesian method.

$m_{W'}$ GeV	$\sigma \cdot \text{BR}$ (pb) per channel	M_T (e) (GeV)	Obs. limit electron (pb)	M_T (μ) (GeV)	Obs. limit muon (pb)	Obs. limit combined (pb)
600	8.290	400	0.289	390	0.212	0.134
700	4.264	500	0.215	450	0.227	0.116
800	2.426	500	0.188	470	0.212	0.105
900	1.389	500	0.168	500	0.150	0.078
1000	0.849	500	0.159	530	0.147	0.076
1100	0.516	500	0.157	590	0.151	0.076
1200	0.334	650	0.170	610	0.150	0.078
1300	0.214	675	0.168	630	0.146	0.077
1400	0.141	675	0.164	630	0.139	0.075
1500	0.094	675	0.159	680	0.146	0.076
2000	0.014	675	0.167	690	0.153	0.078

In summary, a search for a new heavy gauge boson W' that decays to a muon and a neutrino has been performed with 36 pb^{-1} of data collected by the CMS experiment. No evidence has been found for W' boson production assuming SM-like couplings and 95% C.L. upper limits have been set on $\sigma \cdot \text{BR}(W' \rightarrow \mu\nu)$. Additionally, a 95% C.L. lower bound on the mass of a W' boson is set at 1.40 TeV. This lower bound is increased to 1.58 TeV when this analysis is combined with a similar search for $W' \rightarrow e\nu$. This result represents 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, M. Friedl, R. Frühwirth, V.M. Ghete, J. Hammer¹, S. Häsnel, M. Hoch, N. Hörmann, J. Hrubec, M. Jeitler, G. Kasieczka, W. Kiesenhofer, M. Krammer, D. Liko, I. Mikulec, M. Pernicka, H. Rohringer, R. Schöfbeck, J. Strauss, F. Teischinger, P. Wagner, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz

National Centre for Particle and High Energy Physics, Minsk, Belarus

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium

L. Benucci, E.A. De Wolf, X. Janssen, T. Maes, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, M. Selvaggi, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium

F. Blekman, S. Blyweert, J. D'Hondt, O. Devroede, R. Gonzalez Suarez, A. Kalogeropoulos, J. Maes, M. Maes, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Vilella

Université Libre de Bruxelles, Bruxelles, Belgium

O. Charaf, B. Clerbaux, G. De Lentdecker, V. Dero, A.P.R. Gay, G.H. Hammad, T. Hreus, P.E. Marage, L. Thomas, C. Vander Velde, P. Vanlaer

Ghent University, Ghent, Belgium

V. Adler, A. Cimmino, S. Costantini, M. Grunewald, B. Klein, A. Marinov, J. Mccartin, D. Ryckbosch, F. Thyssen, M. Tytgat, L. Vanelderen, P. Verwilligen, S. Walsh, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

S. Basegmez, G. Bruno, J. Caudron, L. Ceard, E. Cortina Gil, J. De Favereau De Jeneret, C. Delaere, D. Favart, A. Giammanco, G. Grégoire, J. Hollar, V. Lemaitre, J. Liao, O. Militaru, S. Oryn, D. Pagano, A. Pin, K. Piotrkowski, N. Schul

Université de Mons, Mons, Belgium

N. Bely, T. Caebergs, E. Daubie

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G.A. Alves, D. De Jesus Damiao, M.E. Pol, M.H.G. Souza

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

W. Carvalho, E.M. Da Costa, C. De Oliveira Martins, S. Fonseca De Souza, L. Mundim, H. Nogima, V. Oguri, W.L. Prado Da Silva, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, F. Torres Da Silva De Araujo

Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil

F.A. Dias, T.R. Fernandez Perez Tomei, E. M. Gregores², C. Lagana, F. Marinho, P.G. Mercadante², S.F. Novaes, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

N. Darmenov¹, L. Dimitrov, V. Genchev¹, P. Iaydjiev¹, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, I. Vankov

University of Sofia, Sofia, Bulgaria

A. Dimitrov, M. Dyulendarova, R. Hadjiiska, A. Karadzhinova, V. Kozhuharov, L. Litov, E. Marinova, M. Mateev, 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, 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

Y. Ban, S. Guo, Y. Guo, W. Li, Y. Mao, S.J. Qian, H. Teng, L. Zhang, B. Zhu, W. Zou

Universidad de Los Andes, Bogota, Colombia

A. Cabrera, B. Gomez Moreno, A.A. Ocampo Rios, A.F. Osorio Oliveros, J.C. Sanabria

Technical University of Split, Split, Croatia

N. Godinovic, D. Lelas, K. Lelas, R. Plestina³, D. Polic, I. Puljak

University of Split, Split, Croatia

Z. Antunovic, M. Dzelalija

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, S. Duric, K. Kadija, S. Morovic

University of Cyprus, Nicosia, Cyprus

A. Attikis, M. Galanti, 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. Assran⁴, S. Khalil⁵, M.A. Mahmoud⁶

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

A. Hektor, M. Kadastik, M. Müntel, M. Raidal, L. Rebane

Department of Physics, University of Helsinki, Helsinki, Finland

V. Azzolini, P. Eerola

Helsinki Institute of Physics, Helsinki, Finland

S. Czellar, J. Härkönen, A. Heikkinen, V. Karimäki, R. Kinnunen, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, E. Tuominen, J. Tuominiemi, E. Tuovinen, D. Ungaro, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland

K. Banzuzi, A. Korpela, T. Tuuva

Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France

D. Sillou

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, F.X. Gentit, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, M. Marionneau, L. Millischer, J. Rander, A. Rosowsky, I. Shreyber, M. Titov, P. Verrecchia

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj⁷, C. Broutin, P. Busson, C. Charlot, T. Dahms, L. Dobrzynski, S. Elgammal, R. Granier de Cassagnac, M. Haguenaer, P. Miné, C. Mironov, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Thiebaut, B. Wyslouch⁸, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

J.-L. Agram⁹, J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte⁹, F. Drouhin⁹, C. Ferro, J.-C. Fontaine⁹, D. Gelé, U. Goerlach, S. Greder, P. Juillot, M. Karim⁹, A.-C. Le Bihan, Y. Mikami, P. Van Hove

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules (IN2P3), Villeurbanne, France

F. Fassi, D. Mercier

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

C. Baty, S. Beauceron, N. Beaupere, M. Bedjidian, O. Bondu, G. Boudoul, D. Boumediene, H. Brun, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, A. Falkiewicz, J. Fay, S. Gascon, B. Ille, T. Kurca, T. Le Grand, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, S. Tosi, Y. Tschudi, P. Verdier

E. Andronikashvili Institute of Physics, Academy of Science, Tbilisi, Georgia

L. Megrelidze

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

D. Lomidze

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

G. Anagnostou, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, N. Mohr, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, M. Weber, B. Wittmer

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

M. Ata, W. Bender, M. Erdmann, J. Frangenheim, T. Hebbeker, A. Hinzmann, K. Hoepfner, T. Klimkovich, D. Klingebiel, P. Kreuzer, D. Lanske[†], C. Magass, M. Merschmeyer, A. Meyer, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier, S. Thüer, M. Tonutti

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

M. Bontenackels, M. Davids, M. Duda, G. Flügge, H. Geenen, M. Giffels, W. Haj Ahmad, D. Heydhausen, T. Kress, Y. Kuessel, A. Linn, A. Nowack, L. Perchalla, O. Pooth, J. Rennefeld, P. Sauerland, A. Stahl, M. Thomas, D. Tornier, M.H. Zoeller

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, W. Behrenhoff, U. Behrens, M. Bergholz¹⁰, K. Borrás, A. Cakir, A. Campbell, E. Castro, D. Dammann, G. Eckerlin, D. Eckstein, A. Flossdorf, G. Flucke, A. Geiser, J. Hauk, H. Jung¹, M. Kasemann, I. Katkov¹¹, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann¹⁰, R. Mankel, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, J. Olzem, D. Pitzl, A. Raspereza, A. Raval, M. Rosin, R. Schmidt¹⁰, T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, J. Tomaszewska, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany

C. Autermann, V. Blobel, S. Bobrovskiy, J. Draeger, H. Enderle, U. Gebbert, K. Kaschube, G. Kaussen, R. Klanner, J. Lange, B. Mura, S. Naumann-Emme, F. Nowak, N. Pietsch, C. Sander, H. Schettler, P. Schleper, M. Schröder, T. Schum, J. Schwandt, H. Stadie, G. Steinbrück, J. Thomsen

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

C. Barth, J. Bauer, V. Buege, T. Chwalek, W. De Boer, A. Dierlamm, G. Dirkes, M. Feindt, J. Gruschke, C. Hackstein, F. Hartmann, S.M. Heindl, M. Heinrich, H. Held, K.H. Hoffmann, S. Honc, J.R. Komaragiri, T. Kuhr, D. Martschei, S. Mueller, Th. Müller, M. Niegel, O. Oberst, A. Oehler, J. Ott, T. Peiffer, D. Piparo, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, M. Renz, C. Saout, A. Scheurer, P. Schieferdecker, F.-P. Schilling, M. Schmanau, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, J. Wagner-Kuhr, T. Weiler, M. Zeise, V. Zhukov¹¹, E.B. Ziebarth

Institute of Nuclear Physics "Demokritos", Aghia Paraskevi, Greece

G. Daskalakis, T. Geralis, K. Karafasoulis, S. Kesisoglou, A. Kyriakis, D. Loukas, I. Manolakos, A. Markou, C. Markou, C. Mavrommatis, E. Ntomari, E. Petrakou

University of Athens, Athens, Greece

L. Gouskos, T.J. Mertzimekis, A. Panagiotou, E. Stiliaris

University of Ioánnina, Ioánnina, Greece

I. Evangelou, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras, F.A. Triantis

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary

A. Aranyi, G. Bencze, L. Boldizsar, C. Hajdu¹, P. Hidas, D. Horvath¹², A. Kapusi, K. Krajczar¹³, B. Radics, F. Sikler, G.I. Veres¹³, G. Vesztergombi¹³

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, J. Molnar, J. Palinkas, Z. Szillasi, V. Veszpremi

University of Debrecen, Debrecen, Hungary

P. Raics, Z.L. Trocsanyi, B. Ujvari

Panjab University, Chandigarh, India

S. Bansal, S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Jindal, M. Kaur, J.M. Kohli, M.Z. Mehta, N. Nishu, L.K. Saini, A. Sharma, A.P. Singh, J.B. Singh, S.P. Singh

University of Delhi, Delhi, India

S. Ahuja, S. Bhattacharya, B.C. Choudhary, P. Gupta, S. Jain, S. Jain, A. Kumar, K. Ranjan, R.K. Shivpuri

Bhabha Atomic Research Centre, Mumbai, India

R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, A.K. Mohanty¹, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research - EHEP, Mumbai, India

T. Aziz, M. Guchait¹⁴, A. Gurtu, M. Maity¹⁵, D. Majumder, G. Majumder, K. Mazumdar, G.B. Mohanty, A. Saha, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research - HECR, Mumbai, India

S. Banerjee, S. Dugad, N.K. Mondal

Institute for Research and Fundamental Sciences (IPM), Tehran, Iran

H. Arfaei, H. Bakhshiansohi¹⁶, S.M. Etesami, A. Fahim¹⁶, M. Hashemi, A. Jafari¹⁶, M. Khakzad, A. Mohammadi¹⁷, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh, M. Zeinali¹⁸

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}, A. Colaleo^a, D. Creanza^{a,c}, N. De Filippis^{a,c,1}, M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, L. Lusito^{a,b}, G. Maggi^{a,c}, M. Maggi^a, N. Manna^{a,b}, B. Marangelli^{a,b}, S. My^{a,c}, S. Nuzzo^{a,b}, N. Pacifico^{a,b}, G.A. Pierro^a, A. Pompili^{a,b}, G. Pugliese^{a,c}, F. Romano^{a,c}, G. Roselli^{a,b}, G. Selvaggi^{a,b}, L. Silvestris^a, R. Trentadue^a, S. Tuppiti^{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, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^a, 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}, P. Giacomelli^a, M. Giunta^a, C. Grandi^a, S. Marcellini^a, G. Masetti, M. Meneghelli^{a,b}, A. Montanari^a, F.L. Navarra^{a,b}, F. Odorici^a, A. Perrotta^a, F. Primavera^a, 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,1}, S. Costa^{a,b}, A. Tricomi^{a,b}, C. Tuve^a

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}, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, A. Tropiano^{a,1}

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, S. Colafranceschi¹⁹, F. Fabbri, D. Piccolo

INFN Sezione di Genova, Genova, Italy

P. Fabbriatore, R. Musenich

INFN Sezione di Milano-Bicocca ^a, Università di Milano-Bicocca ^b, Milano, Italy

A. Benaglia^{a,b}, F. De Guio^{a,b,1}, L. Di Matteo^{a,b}, A. Ghezzi^{a,b}, M. Malberti^{a,b}, S. Malvezzi^a, 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}, V. Tancini^{a,b}

INFN Sezione di Napoli ^a, Università di Napoli "Federico II" ^b, Napoli, Italy

S. Buontempo^a, C.A. Carrillo Montoya^{a,1}, N. Cavallo^{a,20}, A. De Cosa^{a,b}, F. Fabozzi^{a,20}, A.O.M. Iorio^a, L. Lista^a, M. Merola^{a,b}, P. Noli^{a,b}, P. Paolucci^a

INFN Sezione di Padova ^a, Università di Padova ^b, Università di Trento (Trento) ^c, Padova, Italy

P. Azzi^a, N. Bacchetta^a, P. Bellan^{a,b}, D. Bisello^{a,b}, A. Branca^a, R. Carlin^{a,b}, P. Checchia^a, M. De Mattia^{a,b}, T. Dorigo^a, U. Dosselli^a, F. Fanzago^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, S. Lacaprara^{a,21}, I. Lazzizzera^{a,c}, M. Margoni^{a,b}, M. Mazzucato^a, A.T. Meneguzzo^{a,b}, M. Nespolo^{a,1}, L. Perrozzi^{a,1}, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, M. Tosi^{a,b}, S. Vanini^{a,b}, P. Zotto^{a,b}, G. Zumerle^{a,b}

INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy

P. Baesso^{a,b}, U. Berzano^a, S.P. Ratti^{a,b}, C. Riccardi^{a,b}, P. Torre^{a,b}, P. Vitulo^{a,b}, C. Viviani^{a,b}

INFN Sezione di Perugia ^a, Università di Perugia ^b, Perugia, Italy

M. Biasini^{a,b}, G.M. Bilei^a, B. Caponeri^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,b}, A. Lucaroni^{a,b,1}, G. Mantovani^{a,b}, M. Menichelli^a, A. Nappi^{a,b}, F. Romeo^{a,b}, A. Santocchia^{a,b}, S. Taroni^{a,b,1}, M. Valdata^{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, J. Bernardini^{a,b}, T. Boccali^{a,1}, G. Broccolo^{a,c}, R. Castaldi^a, R.T. D'Agnolo^{a,c}, R. Dell'Orso^a, F. Fiori^{a,b}, L. Foà^{a,c}, A. Giassi^a, A. Kraan^a, F. Ligabue^{a,c},

T. Lomtadze^a, L. Martini^{a,22}, A. Messineo^{a,b}, F. Palla^a, F. Palmonari^a, G. Segneri^a, A.T. Serban^a, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b,1}, A. Venturi^{a,1}, 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}, E. Di Marco^{a,b}, M. Diemoz^a, D. Franci^{a,b}, M. Grassi^{a,1}, E. Longo^{a,b}, S. Nourbakhsh^a, G. Organtini^{a,b}, F. Pandolfi^{a,b,1}, R. Paramatti^a, S. Rahatlou^{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, C. Botta^{a,b,1}, N. Cartiglia^a, R. Castello^{a,b}, M. Costa^{a,b}, N. Demaria^a, A. Graziano^{a,b,1}, C. Mariotti^a, M. Marone^{a,b}, S. Maselli^a, E. Migliore^{a,b}, G. Mila^{a,b}, V. Monaco^{a,b}, M. Musich^{a,b}, M.M. Obertino^{a,c}, N. Pastrone^a, M. Pelliccioni^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, V. Sola^{a,b}, A. Solano^{a,b}, A. Staiano^a, D. Trocino^{a,b}, A. Vilela Pereira^{a,b}

INFN Sezione di Trieste ^a, Università di Trieste ^b, Trieste, Italy

S. Belforte^a, F. Cossutti^a, G. Della Ricca^{a,b}, B. Gobbo^a, D. Montanino^{a,b}, A. Penzo^a

Kangwon National University, Chunchon, Korea

S.G. Heo, S.K. Nam

Kyungpook National University, Daegu, Korea

S. Chang, J. Chung, D.H. Kim, G.N. Kim, J.E. Kim, D.J. Kong, H. Park, S.R. Ro, D. Son, D.C. Son

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea

Zero Kim, J.Y. Kim, S. Song

Korea University, Seoul, Korea

S. Choi, B. Hong, M.S. Jeong, M. Jo, H. Kim, J.H. Kim, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park, H.B. Rhee, E. Seo, S. Shin, K.S. Sim

University of Seoul, Seoul, Korea

M. Choi, S. Kang, 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, J. Lee, S. Lee, H. Seo, I. Yu

Vilnius University, Vilnius, Lithuania

M.J. Bilinskas, I. Grigelionis, M. Janulis, D. Martisiute, P. Petrov, T. Sabonis

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

H. Castilla-Valdez, E. De La Cruz-Burelo, R. Lopez-Fernandez, 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, J. Tam

University of Canterbury, Christchurch, New Zealand

P.H. Butler, R. Doesburg, H. Silverwood

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

M. Ahmad, I. Ahmed, M.I. Asghar, H.R. Hoorani, W.A. Khan, T. Khurshid, S. Qazi

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

Soltan Institute for Nuclear Studies, Warsaw, Poland

T. Frueboes, R. Gokieli, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, G. Wrochna, P. Zalewski

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

N. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, P. Musella, A. Nayak, J. Seixas, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia

S. Afanasiev, I. Belotelov, P. Bunin, I. Golutvin, A. Kamenev, V. Karjavin, G. Kozlov, A. Lanev, P. Moisenz, V. Palichik, V. Perehygin, S. Shmatov, V. Smirnov, A. Volodko, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St Petersburg), Russia

V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, V. Matveev, A. Pashenkov, A. Toropin, S. Troitsky

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Epshteyn, V. Gavrilov, V. Kaftanov[†], M. Kossov¹, A. Krokhotin, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Moscow State University, Moscow, Russia

E. Boos, M. Dubinin²³, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, L. Sarycheva, V. Savrin, A. Snigirev

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, S.V. Rusakov, A. Vinogradov

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

I. Azhgirey, S. Bitioukov, V. Grishin¹, V. Kachanov, D. Konstantinov, A. Korablev, V. Krychkine, V. Petrov, R. Ryutin, S. Slabospitsky, 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. Adzic²⁴, M. Djordjevic, D. Krpic²⁴, 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. Cepeda, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, C. Diez Pardos, 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, 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

J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J.M. Vizan Garcia

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. Felcini²⁵, M. Fernandez, G. Gomez, J. Gonzalez Sanchez, C. Jorda, P. Lobelle Pardo, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez²⁶, 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, A.J. Bell²⁷, D. Benedetti, C. Bernet³, W. Bialas, P. Bloch, A. Bocci, S. Bolognesi, M. Bona, H. Breuker, G. Brona, K. Bunkowski, T. Camporesi, G. Cerminara, J.A. Coarasa Perez, B. Curé, D. D'Enterria, A. De Roeck, S. Di Guida, A. Elliott-Peisert, B. Frisch, W. Funk, A. Gaddi, S. Gennai, G. Georgiou, H. Gerwig, D. Gigi, K. Gill, D. Giordano, F. Glege, R. Gomez-Reino Garrido, M. Gouzevitch, P. Govoni, S. Gowdy, L. Guiducci, M. Hansen, C. Hartl, J. Harvey, J. Hegeman, B. Hegner, H.F. Hoffmann, A. Honma, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, P. Lecoq, C. Lourenço, T. Mäki, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, E. Nesvold¹, M. Nguyen, T. Orimoto, L. Orsini, E. Perez, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, G. Polese, A. Racz, J. Rodrigues Antunes, G. Rolandi²⁸, T. Rommerskirchen, C. Rovelli²⁹, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, I. Segoni, A. Sharma, P. Siegrist, M. Simon, P. Sphicas³⁰, M. Spiropulu²³, F. Stöckli, M. Stoye, P. Tropea, A. Tsiros, P. Vichoudis, M. Voutilainen, 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. Sibille³¹, A. Starodumov³²

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

P. Bortignon, L. Caminada³³, Z. Chen, S. Cittolin, G. Dissertori, M. Dittmar, J. Eugster, K. Freudenreich, C. Grab, A. Hervé, W. Hintz, P. Lecomte, W. Lustermann, C. Marchica³³, P. Martinez Ruiz del Arbol, P. Meridiani, P. Milenovic³⁴, F. Moortgat, P. Nef, F. Nessi-Tedaldi, L. Pape, F. Pauss, T. Punz, A. Rizzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, M.-C. Sawley, B. Stieger, L. Tauscher[†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, M. Weber, L. Wehrli, J. Weng

Universität Zürich, Zurich, Switzerland

E. Aguiló, C. Amsler, V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, P. Otiougova, C. Regenfus, P. Robmann, A. Schmidt, H. Snoek

National Central University, Chung-Li, Taiwan

Y.H. Chang, E.A. Chen, K.H. Chen, W.T. Chen, C.M. Kuo, S.W. Li, W. Lin, M.H. Liu, Z.K. Liu, Y.J. Lu, D. Mekterovic, R. Volpe, J.H. Wu, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, R.-S. Lu, J.G. Shiu, Y.M. Tzeng, M. Wang

Cukurova University, Adana, Turkey

A. Adiguzel, M.N. Bakirci³⁵, S. Cerci³⁶, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal, T. Karaman, A. Kayis Topaksu, A. Nart, G. Onengut, K. Ozdemir, S. Ozturk, A. Polatoz, K. Sogut³⁷, D. Sunar Cerci³⁶, B. Tali, H. Topakli³⁵, D. Uzun, L.N. Vergili, M. Vergili, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

I.V. Akin, T. Aliev, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, E. Yildirim, M. Zeyrek

Bogazici University, Istanbul, Turkey

M. Deliomeroğlu, D. Demir³⁸, E. Gülmez, B. Isildak, M. Kaya³⁹, O. Kaya³⁹, S. Ozkorucuklu⁴⁰, N. Sonmez⁴¹

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

L. Levchuk

University of Bristol, Bristol, United Kingdom

P. Bell, F. Bostock, J.J. Brooke, T.L. Cheng, E. Clement, D. Cussans, R. Frazier, J. Goldstein, M. Grimes, M. Hansen, D. Hartley, G.P. Heath, H.F. Heath, B. Huckvale, J. Jackson, L. Kreczko, S. Metson, D.M. Newbold⁴², K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, S. Ward

Rutherford Appleton Laboratory, Didcot, United Kingdom

L. Basso⁴³, K.W. Bell, A. Belyaev⁴³, C. Brew, R.M. Brown, B. Camanzi, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley, S.D. Worm

Imperial College, London, United Kingdom

R. Bainbridge, G. Ball, J. Ballin, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, G. Davies, M. Della Negra, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, G. Karapostoli, L. Lyons, B.C. MacEvoy, A.-M. Magnan, J. Marrouche, R. Nandi, J. Nash, A. Nikitenko³², A. Papageorgiou, M. Pesaresi, K. Petridis, M. Pioppi⁴⁴, D.M. Raymond, N. Rompotis, A. Rose, M.J. Ryan, C. Seez, P. Sharp, A. Sparrow, A. Tapper, S. Tourneur, M. Vazquez Acosta, T. Virdee, S. Wakefield, D. Wardrope, T. Whyntie

Brunel University, Uxbridge, United Kingdom

M. Barrett, M. Chadwick, J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leslie, W. Martin, I.D. Reid, L. Teodorescu

Baylor University, Waco, USA

K. Hatakeyama

Boston University, Boston, USA

T. Bose, E. Carrera Jarrin, C. Fantasia, A. Heister, J. St. John, P. Lawson, D. Lazic, J. Rohlf, D. Sperka, L. Sulak

Brown University, Providence, USA

A. Avetisyan, S. Bhattacharya, J.P. Chou, D. Cutts, A. Ferapontov, U. Heintz, S. Jabeen, G. Kukartsev, G. Landsberg, M. Narain, D. Nguyen, M. Segala, T. Speer, K.V. Tsang

University of California, Davis, Davis, USA

R. Breedon, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, P.T. Cox, J. Dolen, R. Erbacher, E. Friis, W. Ko, A. Kopecky, R. Lander, H. Liu, S. Maruyama, T. Miceli, M. Nikolic, D. Pellett, J. Robles, S. Salur, T. Schwarz, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra, C. Veelken

University of California, Los Angeles, Los Angeles, USA

V. Andreev, K. Arisaka, D. Cline, R. Cousins, A. Deisher, J. Duris, S. Erhan, C. Farrell, J. Hauser, M. Ignatenko, C. Jarvis, C. Plager, G. Rakness, P. Schlein[†], J. Tucker, V. Valuev

University of California, Riverside, Riverside, USA

J. Babb, A. Chandra, R. Clare, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng, S.C. Kao, F. Liu, H. Liu, O.R. Long, A. Luthra, H. Nguyen, B.C. Shen[†], R. Stringer, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, San Diego, La Jolla, USA

W. Andrews, J.G. Branson, G.B. Cerati, E. Dusinger, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, B. Mangano, S. Padhi, C. Palmer, G. Petrucciani, H. Pi, M. Pieri, R. Ranieri, M. Sani, V. Sharma¹, S. Simon, Y. Tu, A. Vartak, S. Wasserbaech, F. Würthwein, A. Yagil

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, J.R. Vlimant

California Institute of Technology, Pasadena, USA

A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, M. Gataullin, Y. Ma, A. Mott, H.B. Newman, C. Rogan, K. Shin, 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, S.Y. Jun, Y.F. Liu, M. Paulini, J. Russ, H. Vogel, I. Vorobiev

University of Colorado at Boulder, Boulder, USA

J.P. Cumalat, M.E. Dinardo, B.R. Drell, C.J. Edelmaier, W.T. Ford, A. Gaz, B. Heyburn, E. Luiggi Lopez, U. Nauenberg, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner, S.L. Zang

Cornell University, Ithaca, USA

L. Agostino, J. Alexander, D. Cassel, A. Chatterjee, S. Das, N. Eggert, L.K. Gibbons, B. Heltsley, W. Hopkins, A. Khukhunaishvili, B. Kreis, G. Nicolas Kaufman, J.R. Patterson, D. Puigh, A. Ryd, X. Shi, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Vaughan, Y. Weng, L. Winstrom, P. Wittich

Fairfield University, Fairfield, USA

A. Biselli, G. Cirino, D. Winn

Fermi National Accelerator Laboratory, Batavia, USA

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, M. Atac, J.A. Bakken, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, F. Borchering, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, S. Cihangir, W. Cooper, D.P. Eartly, V.D. Elvira, S. Esen, I. Fisk, J. Freeman, Y. Gao, E. Gottschalk, D. Green, K. Gunthoti, O. Gutsche, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, H. Jensen, M. Johnson, U. Joshi, R. Khatiwada, B. Klima, K. Kousouris, S. Kunori, S. Kwan, C. Leonidopoulos,

P. Limon, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, T. Miao, K. Mishra, S. Mrenna, Y. Musienko⁴⁵, C. Newman-Holmes, V. O'Dell, R. Pordes, O. Prokofyev, N. Saoulidou, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, P. Tan, L. Taylor, S. Tkaczyk, 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, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, K. Matchev, G. Mitselmakher, L. Muniz, Y. Pakhotin, C. Prescott, R. Remington, M. Schmitt, B. Scurlock, P. Sellers, N. Skhirtladze, M. Snowball, D. Wang, J. Yelton, M. Zakaria

Florida International University, Miami, USA

C. Ceron, V. Gaultney, L. Kramer, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, D. Mesa, J.L. Rodriguez

Florida State University, Tallahassee, USA

T. Adams, A. Askew, D. Bandurin, J. Bochenek, J. Chen, B. Diamond, S.V. Gleyzer, J. Haas, S. Hagopian, V. Hagopian, M. Jenkins, K.F. Johnson, H. Prosper, L. Quertenmont, S. Sekmen, V. Veeraraghavan

Florida Institute of Technology, Melbourne, USA

M.M. Baarmand, B. Dorney, S. Guragain, M. Hohlmann, H. Kalakhety, R. Ralich, I. Vodopiyarov

University of Illinois at Chicago (UIC), Chicago, USA

M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, J. Callner, R. Cavanaugh, C. Dragoiu, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, G.J. Kunde⁴⁶, F. Lacroix, M. Malek, C. O'Brien, C. Silvestre, A. Smoron, D. Strom, N. Varelas

The University of Iowa, Iowa City, USA

U. Akgun, E.A. Albayrak, B. Bilki, W. Clarida, F. Duru, C.K. Lae, E. McCliment, J.-P. Merlo, H. Mermerkaya, A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, J. Olson, Y. Onel, F. Ozok, S. Sen, J. Wetzell, T. Yetkin, K. Yi

Johns Hopkins University, Baltimore, USA

B.A. Barnett, B. Blumenfeld, A. Bonato, C. Eskew, D. Fehling, G. Giurgiu, A.V. Gritsan, G. Hu, P. Maksimovic, S. Rappoccio, M. Swartz, N.V. Tran, A. Whitbeck

The University of Kansas, Lawrence, USA

P. Baringer, A. Bean, G. Benelli, O. Grachov, M. Murray, D. Noonan, S. Sanders, 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, Z. Wan

Lawrence Livermore National Laboratory, Livermore, USA

J. Gronberg, D. Lange, D. Wright

University of Maryland, College Park, USA

A. Baden, M. Boutemour, S.C. Eno, D. Ferencek, J.A. Gomez, N.J. Hadley, R.G. Kellogg, M. Kirn, Y. Lu, A.C. Mignerey, K. Rossato, P. Rumerio, F. Santanastasio, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, E. Twedt

Massachusetts Institute of Technology, Cambridge, USA

B. Alver, G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, P. Everaerts, G. Gomez Ceballos, M. Goncharov, K.A. Hahn, P. Harris, Y. Kim, M. Klute, Y.-J. Lee, W. Li, C. Loizides, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephans, K. Sumorok, K. Sung, E.A. Wenger, S. Xie, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

University of Minnesota, Minneapolis, USA

P. Cole, S.I. Cooper, P. Cushman, B. Dahmes, A. De Benedetti, P.R. Duderø, G. Franzoni, J. Haupt, K. Klapoetke, Y. Kubota, J. Mans, V. Rekovic, R. Rusack, M. Sasseville, A. Singovsky

University of Mississippi, University, USA

L.M. Cremaldi, R. Godang, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders, D. Summers

University of Nebraska-Lincoln, Lincoln, USA

K. Bloom, S. Bose, J. Butt, D.R. Claes, A. Dominguez, M. Eads, J. Keller, T. Kelly, 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, O. Boeriu, M. Chasco, S. Reucroft, J. Swain, D. Wood, J. Zhang

Northwestern University, Evanston, USA

A. Anastassov, A. Kubik, 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, M. Hildreth, C. Jessop, D.J. Karmgard, J. Kolb, T. Kolberg, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, R. Ruchti, J. Slaunwhite, N. Valls, M. Wayne, J. Ziegler

The Ohio State University, Columbus, USA

B. Bylsma, L.S. Durkin, J. Gu, C. Hill, P. Killewald, K. Kotov, T.Y. Ling, M. Rodenburg, G. Williams

Princeton University, Princeton, USA

N. Adam, E. Berry, P. Elmer, D. Gerbaudo, V. Halyo, P. Hebda, A. Hunt, J. Jones, E. Laird, D. Lopes Pegna, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

University of Puerto Rico, Mayaguez, USA

J.G. Acosta, 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, G. Bolla, L. Borrello, D. Bortoletto, A. Everett, A.F. Garfinkel, L. Gutay, Z. Hu, M. Jones, O. Koybasi, M. Kress, A.T. Laasanen, N. Leonardo, C. Liu, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, I. Shipsey, D. Silvers, A. Svyatkovskiy, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University Calumet, Hammond, USA

P. Jindal, N. Parashar

Rice University, Houston, USA

C. Boulahouache, V. Cuplov, 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, H. Flacher, A. Garcia-Bellido, P. Goldenzweig, Y. Gotra, J. Han, A. Harel, D.C. Miner, D. Orbaker, G. Petrillo, D. Vishnevskiy, M. Zielinski

The Rockefeller University, New York, USA

A. Bhatti, R. Ciesielski, L. Demortier, K. Goulianos, G. Lungu, C. Mesropian, M. Yan

Rutgers, the State University of New Jersey, Piscataway, USA

O. Atramentov, A. Barker, D. Duggan, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, D. Hits, A. Lath, S. Panwalkar, R. Patel, A. Richards, K. Rose, S. Schnetzer, 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

J. Asaadi, R. Eusebi, J. Gilmore, A. Gurrola, T. Kamon, V. Khotilovich, R. Montalvo, C.N. Nguyen, I. Osipenkov, J. Pivarski, A. Safonov, S. Sengupta, A. Tatarinov, D. Toback, M. Weinberger

Texas Tech University, Lubbock, USA

N. Akchurin, J. Damgov, C. Jeong, K. Kovitanggoon, S.W. Lee, Y. Roh, A. Sill, I. Volobouev, R. Wigmans, E. Yazgan

Vanderbilt University, Nashville, USA

E. Appelt, E. Brownson, D. Engh, C. Florez, W. Gabella, M. Issah, W. Johns, P. Kurt, C. Maguire, A. Melo, P. Sheldon, S. Tuo, J. Velkovska

University of Virginia, Charlottesville, USA

M.W. Arenton, M. Balazs, S. Boutle, M. Buehler, B. Cox, B. Francis, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, R. Yohay

Wayne State University, Detroit, USA

S. Gollapinni, R. Harr, P.E. Karchin, P. Lamichhane, M. Mattson, C. Milstène, A. Sakharov

University of Wisconsin, Madison, USA

M. Anderson, M. Bachtis, J.N. Bellinger, D. Carlsmith, S. Dasu, J. Efron, K. Flood, L. Gray, K.S. Grogg, M. Grothe, R. Hall-Wilton, M. Herndon, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, J. Leonard, R. Loveless, A. Mohapatra, D. Reeder, I. Ross, A. Savin, W.H. Smith, J. Swanson, M. Weinberg

†: Deceased

1: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

2: Also at Universidade Federal do ABC, Santo Andre, Brazil

3: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

4: Also at Suez Canal University, Suez, Egypt

5: Also at British University, Cairo, Egypt

6: Also at Fayoum University, El-Fayoum, Egypt

7: Also at Soltan Institute for Nuclear Studies, Warsaw, Poland

8: Also at Massachusetts Institute of Technology, Cambridge, USA

- 9: Also at Université de Haute-Alsace, Mulhouse, France
- 10: Also at Brandenburg University of Technology, Cottbus, Germany
- 11: Also at Moscow State University, Moscow, Russia
- 12: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 13: Also at Eötvös Loránd University, Budapest, Hungary
- 14: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
- 15: Also at University of Visva-Bharati, Santiniketan, India
- 16: Also at Sharif University of Technology, Tehran, Iran
- 17: Also at Shiraz University, Shiraz, Iran
- 18: Also at Isfahan University of Technology, Isfahan, Iran
- 19: Also at Facoltà Ingegneria Università di Roma "La Sapienza", Roma, Italy
- 20: Also at Università della Basilicata, Potenza, Italy
- 21: Also at Laboratori Nazionali di Legnaro dell' INFN, Legnaro, Italy
- 22: Also at Università degli studi di Siena, Siena, Italy
- 23: Also at California Institute of Technology, Pasadena, USA
- 24: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
- 25: Also at University of California, Los Angeles, Los Angeles, USA
- 26: Also at University of Florida, Gainesville, USA
- 27: Also at Université de Genève, Geneva, Switzerland
- 28: Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy
- 29: Also at INFN Sezione di Roma; Università di Roma "La Sapienza", Roma, Italy
- 30: Also at University of Athens, Athens, Greece
- 31: Also at The University of Kansas, Lawrence, USA
- 32: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 33: Also at Paul Scherrer Institut, Villigen, Switzerland
- 34: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 35: Also at Gaziosmanpasa University, Tokat, Turkey
- 36: Also at Adiyaman University, Adiyaman, Turkey
- 37: Also at Mersin University, Mersin, Turkey
- 38: Also at Izmir Institute of Technology, Izmir, Turkey
- 39: Also at Kafkas University, Kars, Turkey
- 40: Also at Suleyman Demirel University, Isparta, Turkey
- 41: Also at Ege University, Izmir, Turkey
- 42: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 43: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 44: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
- 45: Also at Institute for Nuclear Research, Moscow, Russia
- 46: Also at Los Alamos National Laboratory, Los Alamos, USA