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Search for charge-asymmetric production of W' bosons in tt + jet events from pp collisions at $\sqrt{s} = 7$ TeV

CMS Collaboration

Ekaterina Avdeeva

University of Nebraska-Lincoln, tsukanovaeg@gmail.com

Kenneth A. Bloom

University of Nebraska-Lincoln, kbloom2@unl.edu

S. Bose

University of Nebraska-Lincoln, sbose2@unl.edu

J. Butt

University of Nebraska-Lincoln

See next page for additional authors

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Authors

CMS Collaboration, Ekaterina Avdeeva, Kenneth A. Bloom, S. Bose, J. Butt, Daniel R. Claes, Aaron Dominguez, Michael Eads, J. Keller, Ilya Kravchenko, J. Lazo-Flores, H. Malbouisson, Sudhir Malik, and Gregory Snow



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ABSTRACT

A search is presented for charge-asymmetric production of a W' boson that has been proposed to accommodate the forward–backward asymmetry observed in the production of top–antitop quark pairs at the Tevatron. The new heavy W' boson would be produced in association with a top quark and would decay into top and down quarks. The data correspond to an integrated luminosity of 5.0 fb^{-1} in pp collisions at a center-of-mass energy of 7 TeV, recorded by the CMS detector at the LHC. No significant excess above the standard model expectations is observed, and, from a combination of the electron-plus-jets and muon-plus-jets channels, a 95% confidence level lower limit of $840 \text{ GeV}/c^2$ is set on the W' boson mass for a W' boson model with values for coupling constants to top and down quarks $g_L = 0$ and $g_R = 2$. In addition, a kinematic reconstruction of the W' resonance mass using the inherent charge asymmetry of this model finds no indication of the presence of W' events in the data.

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1. Introduction

Many extensions to the standard model (SM) involve enhanced gauge symmetries that give rise to additional gauge bosons. Within these extensions, one of the additional bosons could be the W' boson, a proposed heavy partner to the W boson. There are many scenarios with a W' boson: a left–right symmetric model [1], a model based upon a new $SU(2)$ sector [1], a technicolor model [2], and a W' as the lowest Kaluza–Klein mode of the W boson [3].

A W' boson with a coupling to top (t) and down (d) quarks has been proposed [4] to explain the anomalous forward–backward asymmetry in $t\bar{t}$ events reported at the Tevatron [5–7]. The observed effect, which is particularly significant for large values of the $t\bar{t}$ mass, could be explained by the production of a W' boson with a mass in the range of $200\text{--}600 \text{ GeV}/c^2$ [4]. A search for a W' decaying to top and light quarks was conducted by the CDF experiment [8]. With a predicted cross section around 20 pb at 7 TeV and an assumed 100% branching fraction into t and d quarks, as illustrated in Fig. 1, the W' boson is potentially observable with the data already collected by the Compact Muon Solenoid (CMS) Collaboration at the Large Hadron Collider (LHC).

Because the LHC collides protons with protons, rather than with antiprotons, the valence d quarks have a much larger fraction of beam particle momentum than \bar{d} quarks, which come from the

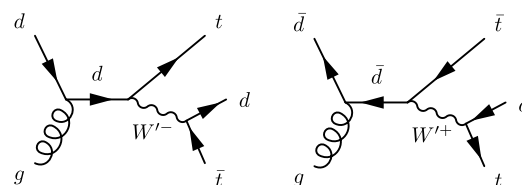


Fig. 1. Feynman diagrams for s -channel production of (left) W'^- and (right) W'^+ . Diagrams for t -channel production can be found in Ref. [9].

proton “sea”. The result is that, at leading order (LO), the W'^- (W'^+) contributes about 85% (15%) of the total W' production cross section, for W' masses in the range from $400\text{--}1200 \text{ GeV}/c^2$ [9]. This feature can be used to aid in the identification of the W' , as explained in Section 6.

The LO processes shown in Fig. 1 result in a final state of $t\bar{t}$ plus a d quark or antiquark. This final state can be classified according to how the W bosons from the top quarks decay: all hadronic (both W bosons decaying hadronically), partially leptonic (one decaying hadronically, the other leptonically), or fully leptonic (both decaying leptonically). We focus on the partially leptonic mode because it has a larger branching fraction than the fully leptonic mode and a cleaner signature than the all-hadronic mode. The event selection for this analysis requires one electron or muon accompanied by several jets and an imbalance in transverse momentum. The main background originates from SM $t\bar{t}$ production with initial- or final-state radiation. We conduct a search for the W' signal by comparing the number of observed events in data with the

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

total expected from SM sources. In addition, we utilize a kinematic reconstruction of the W' resonance mass and the inherent charge asymmetry of this model to perform an independent test for the presence of W' events in the data.

2. The CMS detector and data samples

The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a magnetic field of 3.8 T. A silicon pixel and strip tracker resides within the field volume, surrounded by a lead tungstate crystal electromagnetic calorimeter (ECAL) and a brass/scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the flux-return yoke of the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. CMS uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing to the center of the LHC ring, the y axis pointing up (perpendicular to the plane of the LHC ring), and the z axis along the counterclockwise beam direction. The polar angle, θ , is measured from the positive z axis and the azimuthal angle, ϕ , is measured in the x - y plane. The pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$. A more detailed description of the detector can be found in Ref. [10].

The data sample corresponds to an integrated luminosity of $5.0 \pm 0.1 \text{ fb}^{-1}$ in pp collisions at a center-of-mass energy $\sqrt{s} = 7 \text{ TeV}$, collected by the CMS detector at the LHC. We perform our search in both the electron-plus-jets ($e + \text{jets}$) and muon-plus-jets ($\mu + \text{jets}$) channels. For the $e + \text{jets}$ channel, about 0.2 fb^{-1} of data were initially collected by requiring one electron with transverse momentum (p_T) greater than $27 \text{ GeV}/c$. For the next 1 fb^{-1} of data, the p_T threshold had to be raised to $32 \text{ GeV}/c$. During the course of data taking, the maximum instantaneous luminosity increased by an order of magnitude, reaching up to $4 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, thereby requiring changes in the trigger configurations. For the remaining 3.8 fb^{-1} of data, it was necessary to include several jets in the electron trigger, resulting in an electron p_T threshold of $25 \text{ GeV}/c$ plus three jets with $p_T > 30 \text{ GeV}/c$. For the $\mu + \text{jets}$ channel, 2.2 fb^{-1} of data were initially collected by requiring a single muon with $p_T > 30 \text{ GeV}/c$, with this threshold later raised to $40 \text{ GeV}/c$ for the last 2.8 fb^{-1} of data.

The data are compared with simulations of SM background contributions from leptonically enriched multijets, single top quark, $t\bar{t}$, W , and Z production, with all sources including additional jets. The $t\bar{t}$ background is dominant, and is simulated with up to three additional partons by the MADGRAPH 4.4.12 [11] event generator interfaced with the PYTHIA 6.4.22 [12] parton shower simulator. In the matching procedure for this parton showering [13], the k_T matrix element uses a matching scale of $30 \text{ GeV}/c$, according to the MLM scheme [14]. The W and Z background processes are produced with the MADGRAPH event generator. The W' signal samples are produced with MADGRAPH for masses $M_{W'} = 400, 600, 800, 900, 1000, \text{ and } 1200 \text{ GeV}/c^2$ with values of the W' coupling constants to top and down quarks $g_L = 0$ and $g_R = 2$ [9]. Additional W' benchmark points are produced for masses $M_{W'} = 600$ and $800 \text{ GeV}/c^2$ with $g_L = 0$ and $g_R = \sqrt{2}$. Compared to Ref. [8], the definition of g_R used here gives values smaller by a factor of $1/\sqrt{2}$. Single top quark production is simulated with the POWHEG [15] event generator and includes s - and t -channel production, along with tW associated production. The multijet background contribution is simulated using a combination of two sets of samples, one generated with MADGRAPH and the other with PYTHIA. The CTEQ6L1 parton distribution function (PDF) set [16], which contains LO PDFs, is used for generating all simulated events. The events for all samples are passed through a GEANT4-

based simulation [17] of the CMS detector and reconstructed with the same program used to reconstruct data.

3. Event selection and reconstruction

The particle-flow (PF) algorithm [18] is used to reconstruct and identify each particle based upon an optimized combination of information from all the sub-detectors. The particles are classified as charged hadrons, neutral hadrons, photons, muons, or electrons.

Charged leptons originating from W boson decays are expected to be isolated from other particles in the event. A variable to quantify this lepton isolation, I , is defined as a sum of momenta, divided by the lepton p_T , where the sum is of the transverse momenta of charged hadrons, neutral hadrons, and photons in a cone of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$ around the lepton direction, excluding the contribution from the lepton itself. Muons are reconstructed using information from the silicon tracker and the muon chambers. Muon candidates are required to be isolated, with $I < 0.125$, and to have $p_T > 42 \text{ GeV}/c$ and $|\eta| < 2.1$. Electrons are reconstructed using associated clusters of energy deposits in the ECAL that are then combined with tracks from the inner tracker [19]. The electron candidate is required to be isolated, with $I < 0.1$, and to have $p_T > 45 \text{ GeV}/c$ and $|\eta| < 2.5$. The p_T thresholds for the leptons are chosen so as to ensure a p_T -independent trigger efficiency, whose value is about 98%, for selected events. Electrons in the η range around the interface between the ECAL endcap and ECAL barrel ($1.444 < |\eta| < 1.566$) are excluded from the selection. From the high-quality vertices that are close to the beam spot, the vertex with the highest sum of p_T^2 of its constituent tracks is chosen as the primary vertex. To ensure the reconstructed muon or electron track is consistent with originating from the primary vertex, we require the longitudinal distance between the track and vertex to be less than 1 cm, and the point of closest approach to the primary vertex in the transverse direction to be less than 0.02 cm, as suggested by Ref. [20]. Selected events must contain exactly one electron or muon meeting the above requirements, and events are rejected if they have any additional muons with $p_T > 10 \text{ GeV}/c$, $|\eta| < 2.5$, and $I < 0.2$ or electrons with $p_T > 20 \text{ GeV}/c$, $|\eta| < 2.5$, and $I < 0.2$. To remove electrons resulting from photon conversions, we eliminate those events with a single electron candidate that has no hits in the innermost pixel layer or that is accompanied by a nearby track.

Jets are reconstructed from PF constituents with the FASTJET package [21], using the anti- k_T [22] clustering algorithm with a distance parameter 0.5 and a jet clustering recombination scheme that merges particles by summing their four-vectors [23]. Only charged PF jets that are consistent with originating from the primary vertex are considered. Correction factors [24] are applied to the jet energy to account for non-linearities in detector response.

Selected events must have at least five jets with a minimum p_T of $35 \text{ GeV}/c$ and $|\eta| < 2.4$. The highest- p_T jet is required to have $p_T > 180 \text{ GeV}/c$, and the second-highest- p_T jet must have $p_T > 90 \text{ GeV}/c$. The requirement for the highest- p_T jet is intended, in part, to select for the d -quark jet coming from the W' decay. We also require $H_T > 700 \text{ GeV}/c$, where H_T is the scalar sum of all jet p_T , the lepton p_T , and a quantity called E_T^{miss} , which is the absolute value of the vector sum of the transverse momenta of all particles found by the PF algorithm, with the particles being treated as massless. These H_T and jet p_T values are determined from optimizing the selection to suppress SM backgrounds while enhancing the signal significance, which is taken to be the expected number of signal events for a benchmark point with a W' mass of $600 \text{ GeV}/c^2$ divided by the square root of the number of expected background events. This benchmark corresponds to the highest mass point that is able to account well for the forward-

Table 1

Number of events in the $e + \text{jets}$ and $\mu + \text{jets}$ channels, for simulated background, a possible W' signal with a $600 \text{ GeV}/c^2$ mass, and data, corresponding to 5.0 fb^{-1} integrated luminosity. The uncertainties include both statistical and systematic contributions from all sources discussed in Section 4.

| Sample | Cross section [pb] | Number of events | |
|---|-----------------------|-------------------|---------------------|
| | | $e + \text{jets}$ | $\mu + \text{jets}$ |
| $t\bar{t}$ | 154 ± 17 [27] | 734 ± 204 | 888 ± 276 |
| Single top quark | 85 | 32 ± 16 | 40 ± 20 |
| $W + \text{jets}$ | 31 314 | 64 ± 32 | 49 ± 25 |
| $Z + \text{jets}$ | 3048 | 8 ± 4 | 12 ± 6 |
| Multijets | 6.7×10^6 | 5 ± 5 | – |
| Total background | | 843 ± 209 | 989 ± 279 |
| Signal ($M_{W'} = 600 \text{ GeV}/c^2$, $g_L = 0$, $g_R = 2$) | 18.2 | 723 ± 140 | 858 ± 120 |
| Data | | 726 | 904 |

backward asymmetry in $t\bar{t}$ events observed at the Tevatron [4]. We further require that at least one jet is identified as originating from a b quark. Jets from b quarks are identified by an algorithm [25] that reconstructs a displaced secondary vertex with high efficiency by combining two or more tracks and then assigns a likelihood of b-quark origin based upon the three-dimensional decay length of the vertex.

The leptonic decay of the W boson arising from a top quark produces a neutrino, which escapes the detector without interacting. The E_T^{miss} provides a measure of this missing energy, so we require $E_T^{\text{miss}} > 20 \text{ GeV}$.

The estimated background contribution from SM processes is obtained from simulation. After all selection requirements are applied, $t\bar{t}$ decays matching the signal topology are the dominant background source, with $W + \text{jets}$ events also contributing, but at a much smaller level.

Simulated events are corrected to account for effects of the trigger selection and differences between data and simulation in lepton and b-quark jet identification efficiency. The correction factors for leptons are obtained using a high-purity data sample of $Z \rightarrow \ell^+ \ell^-$ decays, where ℓ is an electron or muon. To account for the difference between data and simulation in the performance of the b-tagging algorithm, we follow the method described in Ref. [26], which entails adding or removing a b tag on each jet in simulated events, based upon p_T - and η -dependent correction factors [26].

Table 1 provides the cross sections used for each of the SM backgrounds, which, multiplied by the integrated luminosity of 5.0 fb^{-1} and selection efficiencies, give the expected number of background events. For $t\bar{t}$, we use the measured cross section from Ref. [27]. The single top quark next-to-next-to-leading-order (NNLO) cross section is obtained from Refs. [28–30]. The $W + \text{jets}$ and $Z + \text{jets}$ cross sections are computed to NNLO using the Fully Exclusive W, Z Production (FEWZ) pQCD generator [31]. Finally, the cross section for multijets is obtained, at LO, from PYTHIA [12].

The uncertainties quoted in Table 1 reflect statistical and systematic sources, which are elaborated in Section 4. Although large, the estimated background is comparable to the predicted signal for a W' with a mass of $600 \text{ GeV}/c^2$ and with $g_L = 0$ and $g_R = 2$ [9,32], given in the next-to-last row in Table 1. The numbers of observed events in data in the $e + \text{jets}$ and $\mu + \text{jets}$ channels are presented in the last row in Table 1. For W' signal events, the total selection efficiency is roughly 2%, while for the main background, $t\bar{t}$, it is roughly 0.2%.

4. Systematic uncertainties

The following sources of systematic uncertainty are evaluated for their effect on simulated signal and background yields: jet

energy corrections, b-tagging corrections, lepton charge misidentification, lepton trigger and identification efficiencies, and the integrated luminosity measurement. In addition, the parameters used in generating simulated events have associated systematic uncertainties, as does the procedure to make the distribution of additional interaction vertices from pileup match simulation to data.

Uncertainties from corrections on the jet energy scale are taken into account by shifting the energy of each jet by ± 1 standard deviation [24]. The E_T^{miss} is corrected simultaneously since it is almost fully correlated with the jet energies. The effect on yields is about 10% for both signal and background. Similarly, with simulated events, varying the b-tagging corrections by their estimated uncertainty leads to a 2% change in the event yields.

A wrong charge assignment for a reconstructed lepton could also cause its momentum determination to be incorrect. As a check of the significance of this effect, study of the charge-misidentification rate with a sample of simulated $t\bar{t}$ events shows the effect to be negligible. To match the trigger and lepton identification efficiencies in simulated samples and data, correction factors are applied. The uncertainty on these corrections is approximately 2% of event yields in signal and background.

The uncertainty in the luminosity determination is 2.2% [33] and affects the overall scaling of signal and background samples.

The uncertainty in the choice of PDFs used for generating simulated events is evaluated following the PDF4LHC recommendation [34]. We calculate an uncertainty of around 13% in the number of expected events, for both signal and $t\bar{t}$ background. We also evaluate the uncertainty associated with the choice of renormalization and factorization scales and the initial- and final-state radiation used in simulation. Varying the q^2 scale by a factor of 4 or 0.25 results in a 7% change in the estimated signal yield. For $t\bar{t}$, the yield changes by about 20%. This systematic uncertainty is the dominant one for the background prediction, and it reflects uncertainties in modeling events with five or more jets, as our selection requires.

All simulated background samples are scaled using their corresponding cross sections. For $t\bar{t}$ we use the CMS measured value of $154 \pm 17 \text{ pb}$ [27]. We conservatively treat the systematic uncertainty on the $t\bar{t}$ cross section as uncorrelated with the systematic uncertainties on the $t\bar{t}$ acceptance because the cross-section measurement employs techniques and simulated samples significantly different from those we use. The other backgrounds are small, and their uncertainties do not make a significant contribution to the total background uncertainty, so conservative estimates of their uncertainties are used. A 50% uncertainty in the event yield is assumed for the electroweak backgrounds (W, Z) as well as for single top quark production, and a 100% uncertainty is assigned to the multijet background [27].

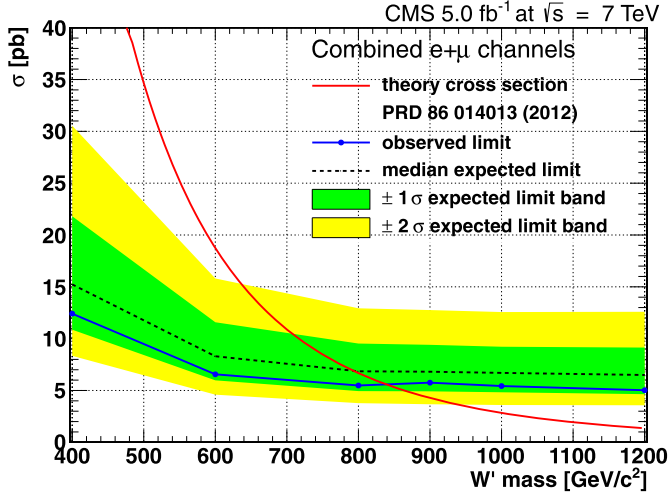


Fig. 2. The 95% CL expected and observed limits on LO W' production for $g_L = 0$ and $g_R = 2$ as a function of the W' boson mass for $e + \text{jets}$ and $\mu + \text{jets}$ channels combined.

Simulated samples are produced with a generic distribution describing additional interactions in the same bunch crossing at high instantaneous luminosities (event pileup). A reweighting procedure is applied to match the pileup conditions in the data. The uncertainty in the reweighting procedure has an effect of about 1% on the event yields for both simulated signal and background.

5. Limits on W' production

We perform a counting experiment where the number of observed events (N_{obs}) is compared with the number of expected events from background (N_{exp}). From Table 1, we have $N_{\text{obs}} = 726$ and $N_{\text{exp}} = 843 \pm 209$ for the $e + \text{jets}$ channel, and $N_{\text{obs}} = 904$ and $N_{\text{exp}} = 989 \pm 279$ for the $\mu + \text{jets}$ channel. We observe no significant excess above the SM background expectation in the two channels.

From a comparison of the observed and estimated numbers of events, we calculate an upper limit on the cross section of W' production as a function of mass. A 95% confidence level (CL) upper limit is calculated using the CL_s technique [35,36]. Any theoretical uncertainty in the LO W' cross section is not included. Systematic uncertainties in the luminosity, jet energy scale, b-tagging efficiency, pileup, and lepton ID efficiency are taken to be 100% correlated between signal and background. Systematic uncertainties due to PDFs and factorization scales are taken to be uncorrelated for signal and the leading $t\bar{t}$ background. All systematic uncertainties are assumed to follow log-normal distributions.

The 95% CL upper limit on the number of selected signal events is 581 for the combination of the $e + \text{jets}$ and $\mu + \text{jets}$ channels with W' coupling constant values $g_L = 0$ and $g_R = 2$. Fig. 2 shows the corresponding 95% CL upper limit on the W' production. For this W' model, we exclude W' masses below 840 GeV/c^2 .

To provide comparison between two important theoretical benchmark points of the W' model, we also calculate limits on the cross section for W' masses of 600 and 800 GeV/c^2 and g_R values of 2 and $\sqrt{2}$, as shown in Table 2.

6. Search for W' asymmetry

As an independent cross check, we attempt the reconstruction of the W' mass and derive an asymmetry to check whether there is any indication of signal in the data, as suggested by Ref. [9]. We

Table 2

W' cross-section limits for $g_R = 2$ and $\sqrt{2}$ (with $g_L = 0$) for the combined $e + \text{jets}$ and $\mu + \text{jets}$ channels. The W' model includes both s- and t-channel production. Thus, the acceptance changes with the coupling, and the cross section does not simply scale with the coupling.

| W' mass | 600 GeV/c^2 | $\sqrt{2}$ | 800 GeV/c^2 | $\sqrt{2}$ |
|---------------------|----------------------|------------|----------------------|------------|
| Coupling g_R | 2 | $\sqrt{2}$ | 2 | $\sqrt{2}$ |
| Cross section [pb] | 18.2 | 6.3 | 6.5 | 2.1 |
| Acceptance (comb.) | 1.8% | 2.2% | 2.1% | 2.8% |
| Expected limit [pb] | 8.3 | 6.3 | 6.9 | 5.3 |
| Observed limit [pb] | 6.6 | 5.0 | 5.5 | 4.3 |

exploit the charge asymmetry in W' production, a key feature of this theoretical model.

To reconstruct the W' , we first reconstruct two top quarks. Three jets in the event are used to reconstruct one top quark, with the jets being considered to match the decay chain $t \rightarrow W + b$, $W \rightarrow j + j$, where j is a jet resulting from the hadronic decay of the W boson. Out of the many three-jet combinations possible in each event, we choose the one in which a pair of jets gives an invariant mass closest to the W boson mass [37] and the three jets give an invariant mass closest to the top quark mass [37]. From the lepton, one jet, and E_T^{miss} , we reconstruct the second top quark, following the decay chain $t \rightarrow W + b$, $W \rightarrow \ell + \nu$. Again, out of the several combinations with the jets in each event, we choose the one giving an invariant mass closest to the top quark mass. Though the event selection requires at least one b-tagged jet, b tagging is not considered when choosing the jets used for top reconstruction. Next, the highest- p_T , non-b-tagged jet not used in the top reconstruction is labeled as the candidate d-quark jet.

Each of the two top candidates are combined in turn with the d-quark jet so that two W' candidates are reconstructed for each selected event. The charge of the W' candidate that has the lepton in its decay chain is determined by the charge of the lepton, while the other W' candidate has the opposite charge. In a true W' event, only the W' candidate that matches the true W' charge could possibly be correctly reconstructed, and thus, because of the charge asymmetry in W' production, the W'^- candidate is more likely to be correctly reconstructed than the W'^+ candidate. Fig. 3 shows the invariant mass distributions for both W' candidates reconstructed from every selected event in data and the simulated background. Included with both distributions is the expected signal for a W' boson with a mass of 600 GeV/c^2 . The invariant mass distribution for the W'^- candidates shows a high peak around the W' mass, while the distribution for the W'^+ candidates has a lower, more rounded peak. The simulated W' events provide this shape difference, since, for these events, W'^- candidates cluster more around the W' mass while W'^+ candidates, likely to be mis-reconstructed, create a broader distribution. A window of 200 GeV/c^2 width around the W' mass contains, for W' signal with a mass of 600 GeV/c^2 , about 42% of W'^- candidates compared with only about 34% of W'^+ candidates. The background components of both distributions look identical since the additional jet originates from initial- or final-state radiation and there is no preference in combining it with either top candidate. The data distributions agree within the uncertainties with the background model.

To illustrate the asymmetry of the W' model, we calculate the difference in yields for the W'^- and W'^+ invariant mass distributions. The result is shown in Fig. 4. The data are represented by black points, and blue X's show the expected difference for a combination of background and a simulated W' signal at a mass of 600 GeV/c^2 . The shaded blue band represents the statistical uncertainty for the combined signal and background. The predicted signature of W' events, as seen in Fig. 4 is a bump at the W' mass

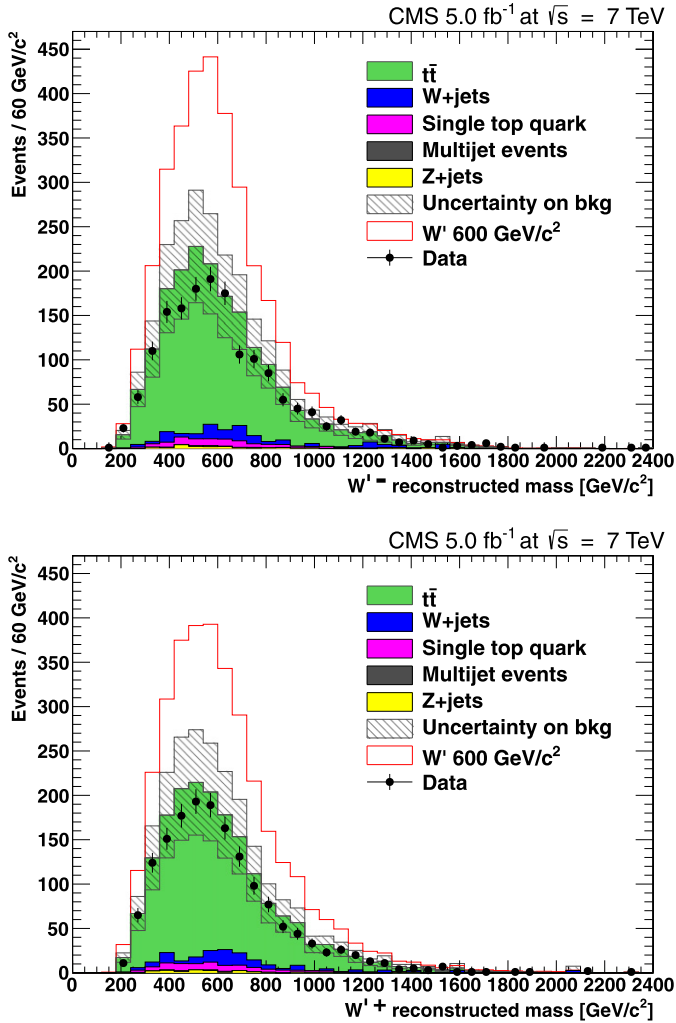


Fig. 3. Invariant mass distributions for (top) W^- candidates and (bottom) W^+ candidates. The figures show a comparison between the background prediction, with candidates reconstructed from simulated signal events stacked on top, and data. Uncertainty bands represent statistical and systematic uncertainties on the background prediction.

and a dip at higher mass, due to the fact that the W^- mass distribution is more tightly concentrated within a narrow peak compared with the broader distribution seen for W^+ . In contrast, the data are statistically consistent with a flat distribution.

7. Summary

A search has been performed by the CMS Collaboration for a W' boson via the process $d + g \rightarrow t + W'$, $W' \rightarrow \bar{t} + d$. This model represents one possible explanation for the $t\bar{t}$ forward–backward asymmetry seen at the Tevatron. The data showed no significant deviation from the standard model prediction. A counting experiment set a 95% CL limit on the W' production cross section as a function of mass. This W' model with $g_L = 0$ and $g_R = 2$ has been excluded below a mass of $840 \text{ GeV}/c^2$ in the combined $e + \text{jets}$ and $\mu + \text{jets}$ channels. In addition, no statistically significant indication of the predicted W' mass distribution asymmetry has been observed in the data.

During the final stages of publication of this work, a related article has appeared [38], suggesting that interference effects were not properly taken into account in the theoretical model used in our analysis, with a possible result being the alteration of the lim-

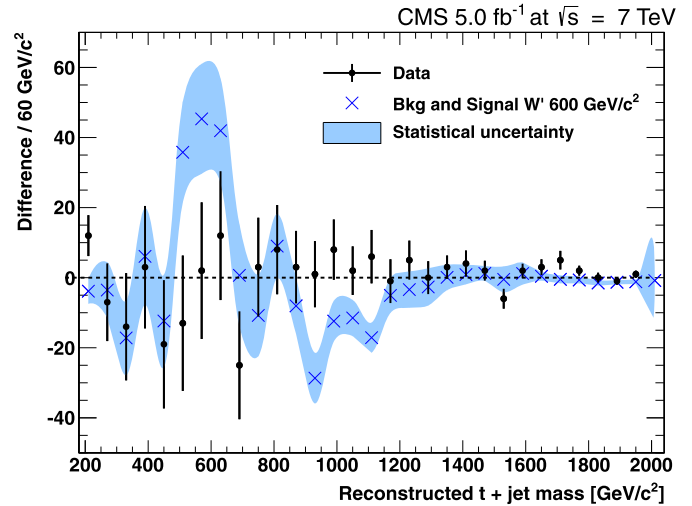


Fig. 4. Difference in yields for W^- and W^+ candidate invariant mass distributions. Data are compared with the combination of background and a simulated W' signal with a mass of $600 \text{ GeV}/c^2$ and $g_L = 0$ and $g_R = 2$. The shaded blue band indicates the statistical uncertainty of the signal and background combination. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

its we quote. The interference effects discussed in Ref. [38] arise mainly in diagrams with t -channel W' exchange, but these effects do not contribute significantly in the region of phase space chosen by our full selection.

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CMS Collaboration

S. Chatrchyan, V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan¹, M. Friedl, R. Frühwirth¹, V.M. Ghete, J. Hammer, N. Hörmann, J. Hrubec, M. Jeitler¹, W. Kiesenhofer, V. Knünz, M. Krammer¹, D. Liko, I. Mikulec, M. Pernicka[†], B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, P. Wagner, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz¹

Institut für Hochenergiephysik der OeAW, Wien, Austria

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

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

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

Universiteit Antwerpen, Antwerpen, 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

Vrije Universiteit Brussel, Brussel, Belgium

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

Université Libre de Bruxelles, Bruxelles, Belgium

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

Ghent University, Ghent, Belgium

S. Basegmez, G. Bruno, R. Castello, A. Caudron, L. Ceard, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco², J. Hollar, V. Lemaître, J. Liao, O. Militaru, C. Nuttens, D. Pagano, L. Perrini, A. Pin, K. Piotrkowski, N. Schul, J.M. Vizán García

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

N. Beliy, T. Caebergs, E. Daubie, G.H. Hammad

Université de Mons, Mons, Belgium

G.A. Alves, M. Correa Martins Junior, D. De Jesus Damiao, T. Martins, M.E. Pol, M.H.G. Souza

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, W. Carvalho, A. Custódio, E.M. Da Costa, C. De Oliveira Martins, S. Fonseca De Souza, D. Matos Figueiredo, L. Mundim, H. Nogima, V. Oguri, W.L. Prado Da Silva, A. Santoro, L. Soares Jorge, A. Sznajder

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

C.A. Bernardes³, F.A. Dias⁴, T.R. Fernandez Perez Tomei, E.M. Gregores³, C. Lagana, F. Marinho, P.G. Mercadante³, S.F. Novaes, Sandra S. Padula

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

V. Genchev⁵, P. Iaydjiev⁵, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, M. Vutova

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

A. Dimitrov, R. Hadjiiska, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

University of Sofia, Sofia, Bulgaria

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

Institute of High Energy Physics, Beijing, China

C. Asawatangtrakuldee, Y. Ban, S. Guo, Y. Guo, W. Li, S. Liu, Y. Mao, S.J. Qian, H. Teng, S. Wang, B. Zhu, W. Zou

State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China

C. Avila, J.P. Gomez, B. Gomez Moreno, A.F. Osorio Oliveros, J.C. Sanabria

Universidad de Los Andes, Bogota, Colombia

N. Godinovic, D. Lelas, R. Plestina⁶, D. Polic, I. Puljak⁵

Technical University of Split, Split, Croatia

Z. Antunovic, M. Kovac

University of Split, Split, Croatia

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

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

M. Finger, M. Finger Jr.

Charles University, Prague, Czech Republic

Y. Assran⁷, S. Elgammal⁸, A. Ellithi Kamel⁹, S. Khalil⁸, M.A. Mahmoud¹⁰, A. Radi^{11,12}

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

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

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

V. Azzolini, P. Eerola, G. Fedi, M. Voutilainen

Department of Physics, University of Helsinki, 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

Helsinki Institute of Physics, Helsinki, Finland

K. Banzuzi, A. Karjalainen, A. Korpela, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, S. Choudhury, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, L. Millischer, A. Nayak, J. Rander, A. Rosowsky, I. Shreyber, M. Titov

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj¹³, C. Broutin, P. Busson, C. Charlot, N. Daci, T. Dahms, L. Dobrzynski, R. Granier de Cassagnac, M. Haguenaue, P. Miné, C. Mironov, M. Nguyen, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Veelken, A. Zabi

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

J.-L. Agram¹⁴, J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte¹⁴, F. Drouhin¹⁴, C. Ferro, J.-C. Fontaine¹⁴, D. Gelé, U. Goerlach, P. Juillot, A.-C. Le Bihan, P. Van Hove

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

F. Fassi, D. Mercier

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

S. Beauceron, N. Beaupere, O. Bondu, G. Boudoul, J. Chasserat, R. Chierici⁵, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, S. Tosi, Y. Tschudi, P. Verdier, S. Viret

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

Z. Tsamalaidze¹⁵

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

G. Anagnostou, S. Beranek, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, B. Wittmer, V. Zhukov¹⁶

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

M. Ata, J. Caudron, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, P. Kreuzer, J. Lingemann, C. Magass, M. Merschmeyer, A. Meyer, M. Olschewski, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier, M. Weber

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

M. Bontenackels, V. Cherepanov, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Nowack, L. Perchalla, O. Pooth, J. Rennefeld, P. Sauerland, A. Stahl

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

M. Aldaya Martin, J. Behr, W. Behrenhoff, U. Behrens, M. Bergholz¹⁷, A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, E. Castro, F. Costanza, D. Dammann, C. Diez Pardos, G. Eckerlin, D. Eckstein, G. Flucke, A. Geiser, I. Glushkov, P. Gunnellini, S. Habib, J. Hauk, G. Hellwig, H. Jung, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann¹⁷, B. Lutz, R. Mankel, I. Marfin, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Musgiller, S. Naumann-Emme, J. Olzem, H. Perrey, A. Petrukhin, D. Pitzl, A. Raspereza, P.M. Ribeiro Cipriano, C. Riedl, E. Ron, M. Rosin, J. Salfeld-Nebgen, R. Schmidt¹⁷, T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, R. Walsh, C. Wissing

Deutsches Elektronen-Synchrotron, Hamburg, Germany

C. Autermann, V. Blobel, J. Draeger, H. Enderle, J. Erfle, U. Gebbert, M. Görner, T. Hermanns, R.S. Höing, K. Kaschube, G. Kaussen, H. Kirschenmann, R. Klanner, J. Lange, B. Mura, F. Nowak, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, J. Thomsen, L. Vanelderren

University of Hamburg, Hamburg, Germany

C. Barth, J. Berger, C. Böser, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, M. Guthoff⁵, C. Hackstein, F. Hartmann, T. Hauth⁵, M. Heinrich, H. Held, K.H. Hoffmann, S. Honc, I. Katkov¹⁶, 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. Ratnikova, N. Ratnikova, S. Röcker, A. Scheurer, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, M. Zeise

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

G. Daskalakis, T. Geralis, S. Kesisoglou, A. Kyriakis, D. Loukas, I. Manolagos, A. Markou, C. Markou, C. Mavrommatis, E. Ntomari

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

L. Gouskos, T.J. Mertzimekis, A. Panagiotou, N. Saoulidou

University of Athens, Athens, Greece

I. Evangelou, C. Foudas⁵, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras

University of Ioánnina, Ioánnina, Greece

G. Bencze, C. Hajdu⁵, P. Hidas, D. Horvath¹⁸, F. Sikler, V. Veszpremi, G. Vesztergombi¹⁹

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

N. Beni, S. Czellar, J. Molnar, J. Palinkas, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

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

University of Debrecen, Debrecen, Hungary

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

Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India

S. Banerjee, S. Bhattacharya, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, S. Sarkar, M. Sharan

Saha Institute of Nuclear Physics, Kolkata, India

A. Abdulsalam, R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, P. Mehta, A.K. Mohanty⁵, L.M. Pant, P. Shukla

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Ganguly, M. Guchait²⁰, M. Maity²¹, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research - EHEP, Mumbai, India

S. Banerjee, S. Dugad

Tata Institute of Fundamental Research - HECR, Mumbai, India

H. Arfaei, H. Bakhshiansohi²², S.M. Etesami²³, A. Fahim²², M. Hashemi, H. Hesari, A. Jafari²², M. Khakzad, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh²⁴, M. Zeinali²³

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

M. Abbrescia^{a,b}, L. Barbone^{a,b}, C. Calabria^{a,b,5}, S.S. Chhibra^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, N. De Filippis^{a,c,5}, M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, L. Lusito^{a,b}, G. Maggi^{a,c}, M. Maggi^a, B. Marangelli^{a,b}, S. My^{a,c}, S. Nuzzo^{a,b}, N. Pacifico^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, G. Selvaggi^{a,b}, L. Silvestris^a, G. Singh^{a,b}, R. Venditti, G. Zito^a

^a INFN Sezione di Bari, Bari, Italy

^b Università di Bari, Bari, Italy

^c Politecnico di Bari, Bari, Italy

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

^a INFN Sezione di Bologna, Bologna, Italy

^b Università di Bologna, Bologna, 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}

^a INFN Sezione di Catania, Catania, Italy

^b Università di Catania, Catania, Italy

G. Barbagli ^a, V. Ciulli ^{a,b}, C. Civinini ^a, R. D'Alessandro ^{a,b}, E. Focardi ^{a,b}, S. Frosali ^{a,b}, E. Gallo ^a, S. Gonzi ^{a,b}, M. Meschini ^a, S. Paoletti ^a, G. Sguazzoni ^a, A. Tropiano ^{a,5}

^a INFN Sezione di Firenze, Firenze, Italy

^b Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, S. Colafranceschi ²⁵, F. Fabbri, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

P. Fabbriatore, R. Musenich

INFN Sezione di Genova, Genova, Italy

A. Benaglia ^{a,b,5}, F. De Guio ^{a,b}, L. Di Matteo ^{a,b,5}, S. Fiorendi ^{a,b}, S. Gennai ^{a,5}, A. Ghezzi ^{a,b}, S. Malvezzi ^a, R.A. Manzoni ^{a,b}, A. Martelli ^{a,b}, A. Massironi ^{a,b,5}, D. Menasce ^a, L. Moroni ^a, M. Paganoni ^{a,b}, D. Pedrini ^a, S. Ragazzi ^{a,b}, N. Redaelli ^a, S. Sala ^a, T. Tabarelli de Fatis ^{a,b}

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

^b Università di Milano-Bicocca, Milano, Italy

S. Buontempo ^a, C.A. Carrillo Montoya ^{a,5}, N. Cavallo ^{a,26}, A. De Cosa ^{a,b,5}, O. Dogangun ^{a,b}, F. Fabozzi ^{a,26}, A.O.M. Iorio ^a, L. Lista ^a, S. Meola ^{a,27}, M. Merola ^{a,b}, P. Paolucci ^{a,5}

^a INFN Sezione di Napoli, Napoli, Italy

^b Università di Napoli "Federico II", Napoli, Italy

P. Azzi ^a, N. Bacchetta ^{a,5}, A. Branca ^{a,5}, R. Carlin ^{a,b}, P. Checchia ^a, T. Dorigo ^a, F. Gasparini ^{a,b}, U. Gasparini ^{a,b}, A. Gozzelino ^a, K. Kanishchev ^{a,c}, S. Lacaprara ^a, I. Lazzizzera ^{a,c}, M. Margoni ^{a,b}, A.T. Meneguzzo ^{a,b}, M. Passaseo ^a, J. Pazzini ^a, M. Pegoraro ^a, N. Pozzobon ^{a,b}, P. Ronchese ^{a,b}, F. Simonetto ^{a,b}, E. Torassa ^a, M. Tosi ^{a,b,5}, S. Vanini ^{a,b}, S. Ventura ^a, P. Zotto ^{a,b}, A. Zucchetta ^a

^a INFN Sezione di Padova, Padova, Italy

^b Università di Padova, Padova, Italy

^c Università di Trento (Trento), Padova, Italy

M. Gabusi ^{a,b}, S.P. Ratti ^{a,b}, C. Riccardi ^{a,b}, P. Torre ^{a,b}, P. Vitulo ^{a,b}

^a INFN Sezione di Pavia, Pavia, Italy

^b Università di Pavia, Pavia, Italy

M. Biasini ^{a,b}, G.M. Bilei ^a, L. Fanò ^{a,b}, P. Lariccia ^{a,b}, A. Lucaroni ^{a,b,5}, G. Mantovani ^{a,b}, M. Menichelli ^a, A. Nappi ^{a,b}, F. Romeo ^{a,b}, A. Saha ^a, A. Santocchia ^{a,b}, S. Taroni ^{a,b,5}

^a INFN Sezione di Perugia, Perugia, Italy

^b Università di Perugia, Perugia, Italy

P. Azzurri ^{a,c}, G. Bagliesi ^a, T. Boccali ^a, G. Broccolo ^{a,c}, R. Castaldi ^a, R.T. D'Agnolo ^{a,c}, R. Dell'Orso ^a, F. Fiori ^{a,b,5}, L. Foà ^{a,c}, A. Giassi ^a, A. Kraan ^a, F. Ligabue ^{a,c}, T. Lomtadze ^a, L. Martini ^{a,28}, A. Messineo ^{a,b}, F. Palla ^a, A. Rizzi ^{a,b}, A.T. Serban ^{a,29}, P. Spagnolo ^a, P. Squillacioti ^{a,5}, R. Tenchini ^a, G. Tonelli ^{a,b,5}, A. Venturi ^{a,5}, P.G. Verdini ^a

^a INFN Sezione di Pisa, Pisa, Italy

^b Università di Pisa, Pisa, Italy

^c Scuola Normale Superiore di Pisa, Pisa, Italy

L. Barone ^{a,b}, F. Cavallari ^a, D. Del Re ^{a,b,5}, M. Diemoz ^a, M. Grassi ^{a,b,5}, E. Longo ^{a,b}, P. Meridiani ^{a,5}, F. Micheli ^{a,b}, S. Nourbakhsh ^{a,b}, G. Organtini ^{a,b}, R. Paramatti ^a, S. Rahatlou ^{a,b}, M. Sigamani ^a, L. Soffi ^{a,b}

^a INFN Sezione di Roma, Roma, Italy

^b Università di Roma "La Sapienza", Roma, Italy

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

^a INFN Sezione di Torino, Torino, Italy

^b Università di Torino, Torino, Italy

^c Università del Piemonte Orientale (Novara), Torino, Italy

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

^a INFN Sezione di Trieste, Trieste, Italy

^b Università di Trieste, Trieste, Italy

S.G. Heo, T.Y. Kim, S.K. Nam

Kangwon National University, Chunchon, Republic of Korea

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

Kyungpook National University, Daegu, Republic of Korea

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

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

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

Korea University, Seoul, Republic of Korea

M. Choi, J.H. Kim, C. Park, I.C. Park, S. Park, G. Ryu

University of Seoul, Seoul, Republic of Korea

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

Sungkyunkwan University, Suwon, Republic of Korea

M.J. Bilinskas, I. Grigelionis, M. Janulis, A. Juodagalvis

Vilnius University, Vilnius, Lithuania

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, R. Lopez-Fernandez, R. Magaña Villalba, J. Martínez-Ortega, A. Sánchez-Hernández, L.M. Villasenor-Cendejas

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

S. Carrillo Moreno, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

H.A. Salazar Ibarguen

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

D. Krofcheck

University of Auckland, Auckland, New Zealand

A.J. Bell, P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood

University of Canterbury, Christchurch, New Zealand

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

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

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

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

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

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

V. Epshteyn, M. Erofeeva, V. Gavrilo, M. Kossov⁵, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov,
V. Stolin, E. Vlasov, A. Zhokin
Institute for Theoretical and Experimental Physics, Moscow, Russia

A. Belyaev, E. Boos, M. Dubinin⁴, 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
Moscow State University, Moscow, Russia

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

I. Azhgirey, I. Bayshev, S. Bitiukov, V. Grishin⁵, V. Kachanov, D. Konstantinov, A. Korablev, V. Krychkin,
V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov
State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

P. Adzic³⁰, M. Djordjevic, M. Ekmedzic, D. Krpic³⁰, J. Milosevic
University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

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
Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

C. Albajar, G. Codispoti, J.F. de Trocóniz

Universidad Autónoma de Madrid, Madrid, Spain

H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J. Piedra Gomez³¹

Universidad de Oviedo, Oviedo, Spain

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini³², M. Fernandez, G. Gomez, J. Gonzalez Sanchez, C. Jorda, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, M. Sobron Sanudo, I. Vila, R. Vilar Cortabitarte

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

D. Abbaneo, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, J.F. Benitez, C. Bernet⁶, G. Bianchi, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, D. D'Enterria, A. Dabrowski, A. De Roeck, S. Di Guida, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, B. Frisch, W. Funk, G. Georgiou, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Giunta, F. Glege, R. Gomez-Reino Garrido, P. Govoni, S. Gowdy, R. Guida, M. Hansen, P. Harris, C. Hartl, J. Harvey, B. Hegner, A. Hinzmann, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, K. Kousouris, P. Lecoq, Y.-J. Lee, P. Lenzi, C. Lourenço, T. Mäki, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, P. Musella, E. Nesvold, T. Orimoto, L. Orsini, E. Palencia Cortezon, E. Perez, L. Perrozzi, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, G. Polese, L. Quertenmont, A. Racz, W. Reece, J. Rodrigues Antunes, G. Rolandi³³, T. Rommerskirchen, C. Rovelli³⁴, M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas^{*,35}, D. Spiga, M. Spiropulu⁴, A. Tsiros, G.I. Veres¹⁹, J.R. Vlimant, H.K. Wöhri, S.D. Worm³⁶, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, 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. Sibille³⁷

Paul Scherrer Institut, Villigen, Switzerland

L. Bäni, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Dünser, J. Eugster, K. Freudenreich, C. Grab, D. Hits, P. Lecomte, W. Luster, A.C. Marini, P. Martinez Ruiz del Arbol, N. Mohr, F. Moortgat, C. Nägeli³⁸, P. Nef, F. Nessi-Tedaldi, F. Pandolfi, L. Pape, F. Pauss, M. Peruzzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, A. Starodumov³⁹, B. Stieger, M. Takahashi, L. Tauscher[†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H.A. Weber, L. Wehrli

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

E. Aguilo, C. AMSler, V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, P. Otiougova, P. Robmann, H. Snoek, S. Tuppiti, M. Verzetti

Universität Zürich, Zurich, Switzerland

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

National Central University, Chung-Li, 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

National Taiwan University (NTU), Taipei, Taiwan

A. Adiguzel, M.N. Bakirci⁴⁰, S. Cerci⁴¹, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, G. Karapinar⁴², A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk⁴³, A. Polatoz, K. Sogut⁴⁴, D. Sunar Cerci⁴¹, B. Tali⁴¹, H. Topakli⁴⁰, L.N. Vergili, M. Vergili

Cukurova University, Adana, 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

Middle East Technical University, Physics Department, Ankara, Turkey

E. Gülmez, B. Isildak⁴⁵, M. Kaya⁴⁶, O. Kaya⁴⁶, S. Ozkorucuklu⁴⁷, N. Sonmez⁴⁸

Bogazici University, Istanbul, Turkey

K. Cankocak

Istanbul Technical University, Istanbul, Turkey

L. Levchuk

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

F. Bostock, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, L. Kreczko, S. Metson, D.M. Newbold³⁶, K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, T. Williams

University of Bristol, Bristol, United Kingdom

L. Basso⁴⁹, K.W. Bell, A. Belyaev⁴⁹, 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

Rutherford Appleton Laboratory, Didcot, 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. Nikitenko³⁹, A. Papageorgiou, J. Pela⁵, M. Pesaresi, K. Petridis, M. Pioppi⁵⁰, 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

Imperial College, London, 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

Brunel University, Uxbridge, United Kingdom

K. Hatakeyama, H. Liu, T. Scarborough

Baylor University, Waco, USA

O. Charaf, C. Henderson, P. Rumerio

The University of Alabama, Tuscaloosa, USA

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

Boston University, Boston, USA

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

Brown University, Providence, USA

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, J. Dolen, R. Erbacher, M. Gardner, R. Houtz, W. Ko, A. Kopecky, R. Lander, T. Miceli, D. Pellett, B. Rutherford, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra

University of California, Davis, Davis, USA

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

University of California, Los Angeles, Los Angeles, USA

J. Babb, R. Clare, M.E. Dinardo, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng⁵¹, H. Liu, O.R. Long, A. Luthra, H. Nguyen, S. Paramesvaran, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, Riverside, Riverside, USA

W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, I. Macneill, B. Mangano, S. Padhi, C. Palmer, G. Petrucciani, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech⁵², F. Würthwein, A. Yagil, J. Yoo

University of California, San Diego, La Jolla, USA

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

University of California, Santa Barbara, Santa Barbara, USA

A. Apresyan, A. Bornheim, Y. Chen, E. Di Marco, J. Duarte, M. Gataullin, Y. Ma, A. Mott, H.B. Newman, C. Rogan, V. Timciuc, P. Traczyk, J. Veverka, R. Wilkinson, Y. Yang, R.Y. Zhu

California Institute of Technology, Pasadena, USA

B. Akgun, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, Y.F. Liu, M. Paulini, H. Vogel, I. Vorobiev

Carnegie Mellon University, Pittsburgh, USA

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

University of Colorado at Boulder, Boulder, USA

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

Cornell University, Ithaca, USA

D. Winn

Fairfield University, Fairfield, USA

S. Abdullin, M. Albrow, J. Anderson, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, V.D. Elvira, I. Fisk, J. Freeman, Y. Gao, D. Green, O. Gutsche, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, B. Kilminster, B. Klima, S. Kunori, S. Kwan, C. Leonidopoulos, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko⁵³, C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, P. Tan, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, F. Yumiceva, J.C. Yun

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, D. Bourilkov, M. Chen, S. Das, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, J. Hugon, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic⁵⁴, G. Mitselmakher, L. Muniz, R. Remington, A. Rinkevicius, P. Sellers, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

University of Florida, Gainesville, USA

V. Gaultney, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida International University, Miami, USA

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

Florida State University, Tallahassee, USA

M.M. Baarmand, B. Dorney, M. Hohlmann, H. Kalakhety, I. Vodopiyanov

Florida Institute of Technology, Melbourne, USA

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

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

U. Akgun, E.A. Albayrak, B. Bilki⁵⁵, W. Clarida, F. Duru, S. Griffiths, J.-P. Merlo, H. Mermerkaya⁵⁶, A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, Y. Onel, F. Ozok, S. Sen, E. Tiras, J. Wetzel, T. Yetkin, K. Yi

The University of Iowa, Iowa City, USA

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

Johns Hopkins University, Baltimore, USA

P. Baringer, A. Bean, G. Benelli, O. Grachov, R.P. Kenny Iii, M. Murray, D. Noonan, S. Sanders, R. Stringer, G. Tinti, J.S. Wood, V. Zhukova

The University of Kansas, Lawrence, USA

A.F. Barfuss, T. Bolton, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze

Kansas State University, Manhattan, USA

J. Gronberg, D. Lange, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

A. Baden, M. Boutemour, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, R.G. Kellogg, M. Kirn, T. Kolberg, Y. Lu, M. Marionneau, A.C. Mignerey, K. Pedro, A. Peterman, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, E. Twedt

University of Maryland, College Park, USA

G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, G. Gomez Ceballos, M. Goncharov, K.A. Hahn, Y. Kim, M. Klute, K. Krajczar⁵⁷, W. Li, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephans, F. Stöckli, K. Sumorok, K. Sung, D. Velicanu, E.A. Wenger, R. Wolf, B. Wyslouch, S. Xie, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

Massachusetts Institute of Technology, Cambridge, 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 Minnesota, Minneapolis, USA

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

University of Mississippi, University, USA

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

University of Nebraska-Lincoln, Lincoln, USA

U. Baur, A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S.P. Shipkowski, K. Smith

State University of New York at Buffalo, Buffalo, USA

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

Northeastern University, Boston, USA

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

Northwestern University, Evanston, USA

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

University of Notre Dame, Notre Dame, USA

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

The Ohio State University, Columbus, USA

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

Princeton University, Princeton, USA

J.G. Acosta, E. Brownson, X.T. Huang, A. Lopez, H. Mendez, S. Oliveros, J.E. Ramirez Vargas, A. Zatserklyaniy

University of Puerto Rico, Mayaguez, 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, West Lafayette, USA

S. Guragain, N. Parashar

Purdue University Calumet, Hammond, USA

A. Adair, C. Boulahouache, K.M. Ecklund, F.J.M. Geurts, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

Rice University, Houston, USA

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

University of Rochester, Rochester, USA

A. Bhatti, R. Ciesielski, L. Demortier, K. Goulianos, G. Lungu, S. Malik, C. Mesropian

The Rockefeller University, New York, 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

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

G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

University of Tennessee, Knoxville, USA

R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon⁵⁸, 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 A&M University, College Station, USA

N. Akchurin, J. Damgov, P.R. Duerdo, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, Y. Roh, I. Volobouev

Texas Tech University, Lubbock, USA

E. Appelt, C. Florez, S. Greene, A. Gurrola, W. Johns, C. Johnston, P. Kurt, C. Maguire, A. Melo, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

Vanderbilt University, Nashville, USA

M.W. Arenton, M. Balazs, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirsosky, A. Ledovskoy, C. Lin, C. Neu, J. Wood, R. Yohay

University of Virginia, Charlottesville, USA

S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, A. Sakharov

Wayne State University, Detroit, USA

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

University of Wisconsin, Madison, USA

* Corresponding author.

† 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 Ain Shams University, Cairo, Egypt.

¹² Now at British University, Cairo, Egypt.

¹³ Also at Soltan Institute for Nuclear Studies, Warsaw, Poland.

¹⁴ Also at Université de Haute-Alsace, Mulhouse, France.

¹⁵ Now at Joint Institute for Nuclear Research, Dubna, Russia.

¹⁶ Also at Moscow State University, Moscow, Russia.

¹⁷ Also at Brandenburg University of Technology, Cottbus, Germany.

¹⁸ Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

¹⁹ Also at Eötvös Loránd University, Budapest, Hungary.

²⁰ Also at Tata Institute of Fundamental Research - HECR, Mumbai, India.

²¹ Also at University of Visva-Bharati, Santiniketan, India.

- ²² Also at Sharif University of Technology, Tehran, Iran.
- ²³ Also at Isfahan University of Technology, Isfahan, Iran.
- ²⁴ Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Teheran, Iran.
- ²⁵ Also at Facoltà Ingegneria Università di Roma, Roma, Italy.
- ²⁶ Also at Università della Basilicata, Potenza, Italy.
- ²⁷ Also at Università degli Studi Guglielmo Marconi, Roma, Italy.
- ²⁸ Also at Università degli studi di Siena, Siena, Italy.
- ²⁹ Also at University of Bucharest, Faculty of Physics, Bucuresti-Magurele, Romania.
- ³⁰ Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia.
- ³¹ Also at University of Florida, Gainesville, USA.
- ³² Also at University of California, Los Angeles, Los Angeles, USA.
- ³³ Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
- ³⁴ Also at INFN Sezione di Roma; Università di Roma "La Sapienza", Roma, Italy.
- ³⁵ Also at University of Athens, Athens, Greece.
- ³⁶ Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- ³⁷ Also at The University of Kansas, Lawrence, USA.
- ³⁸ Also at Paul Scherrer Institut, Villigen, Switzerland.
- ³⁹ Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
- ⁴⁰ Also at Gaziosmanpasa University, Tokat, Turkey.
- ⁴¹ Also at Adiyaman University, Adiyaman, Turkey.
- ⁴² Also at Izmir Institute of Technology, Izmir, Turkey.
- ⁴³ Also at The University of Iowa, Iowa City, USA.
- ⁴⁴ Also at Mersin University, Mersin, Turkey.
- ⁴⁵ Also at Ozyegin University, Istanbul, Turkey.
- ⁴⁶ Also at Kafkas University, Kars, Turkey.
- ⁴⁷ Also at Suleyman Demirel University, Isparta, Turkey.
- ⁴⁸ Also at Ege University, Izmir, Turkey.
- ⁴⁹ Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- ⁵⁰ Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy.
- ⁵¹ Also at University of Sydney, Sydney, Australia.
- ⁵² Also at Utah Valley University, Orem, USA.
- ⁵³ Also at Institute for Nuclear Research, Moscow, Russia.
- ⁵⁴ Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
- ⁵⁵ Also at Argonne National Laboratory, Argonne, USA.
- ⁵⁶ Also at Erzincan University, Erzincan, Turkey.
- ⁵⁷ Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.
- ⁵⁸ Also at Kyungpook National University, Daegu, Republic of Korea.