



First measurement of the cross section for top-quark pair production in proton–proton collisions at $\sqrt{s} = 7$ TeV[☆]

CMS Collaboration

CERN, Switzerland

ARTICLE INFO

Article history:

Received 30 October 2010

Received in revised form 18 November 2010

Accepted 26 November 2010

Available online 1 December 2010

Editor: M. Doser

Keywords:

CMS

LHC

Physics

Top quark

Cross section

ABSTRACT

The first measurement of the cross section for top-quark pair production in pp collisions at the Large Hadron Collider at center-of-mass energy $\sqrt{s} = 7$ TeV has been performed using a data sample corresponding to an integrated luminosity of $3.1 \pm 0.3 \text{ pb}^{-1}$ recorded by the CMS detector. This result utilizes the final state with two isolated, highly energetic charged leptons, large missing transverse energy, and two or more jets. Backgrounds from Drell-Yan and non-W/Z boson production are estimated from data. Eleven events are observed in the data with 2.1 ± 1.0 events expected from background. The measured cross section is $194 \pm 72(\text{stat.}) \pm 24(\text{syst.}) \pm 21(\text{lumi.}) \text{ pb}$, consistent with next-to-leading order predictions.

© 2010 CERN. Published by Elsevier B.V. All rights reserved.

Since its discovery [1,2], the properties of the top quark have been subject to numerous detailed studies [3], which until recently have only been possible at the Tevatron proton–antiproton collider. With the advent of the Large Hadron Collider (LHC) era [4], top-quark processes can be studied for the first time in multi-TeV proton–proton collisions. In both $p\bar{p}$ and pp collisions, top quarks are expected to be produced primarily via the strong interaction in top–antitop ($t\bar{t}$) pairs. At the LHC, the $t\bar{t}$ production mechanism is expected to be dominated by a gluon fusion process, whereas at the Tevatron, top-quark pairs are predominantly produced through quark–antiquark annihilation. Measurements of top-quark production at the LHC are therefore important new tests of our understanding of the $t\bar{t}$ production mechanism. This is a crucial component of the early LHC physics program, since many signatures of new physics models accessible at the LHC either suffer from top-quark production as a significant background or contain top quarks themselves.

In this Letter we present the first measurement of the cross section for $t\bar{t}$ production in proton–proton collisions at the LHC at center-of-mass energy $\sqrt{s} = 7$ TeV. The results are based on a data sample corresponding to an integrated luminosity of $3.1 \pm 0.3 \text{ pb}^{-1}$ [5] recorded by the CMS experiment [6] between March and August 2010. This measurement is an important milestone for

CMS, demonstrating the experiment's capabilities in extracting an intricate signature.

Within the standard model, the top quark decays via the weak process $t \rightarrow Wb$ almost exclusively. Experimentally, top-quark pair events are categorized according to the decay of the two W bosons: the all-hadronic channel, in which both W bosons decay into quarks; the lepton + jets channel, in which one W boson decays leptonically, the other into quarks; and the dilepton channel, in which both W bosons decay into leptons. The measurement described herein is performed using the e^+e^- , $\mu^+\mu^-$, and $e^\pm\mu^\mp$ dilepton $t\bar{t}$ modes. These modes comprise $(6.45 \pm 0.11)\%$ [7] of the total branching fraction for $t\bar{t}$ when including contributions from tau leptons that subsequently decay to electrons and muons, as is done here. Therefore, the final state studied in this analysis contains two oppositely charged leptons (electrons or muons), two neutrinos from the W boson decays, and at least two jets of particles resulting from the hadronization of the b quarks. Similar measurements have been performed recently at the Tevatron [8,9].

The central feature of the CMS apparatus is a superconducting solenoid, 13 m in length and 6 m in diameter, which provides an axial magnetic field of 3.8 T. The bore of the solenoid is outfitted with various particle detection systems. Charged particle trajectories are measured by the silicon pixel and strip tracker, covering $0 < \phi < 2\pi$ in azimuth and $|\eta| < 2.5$, where the pseudorapidity η is defined as $\eta = -\ln[\tan\theta/2]$, with θ being the polar angle of the trajectory of the particle with respect to the beam direction. A crystal electromagnetic calorimeter (ECAL)

[☆] © CERN, for the benefit of the CMS Collaboration.

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

and a brass/scintillator hadronic calorimeter (HCAL) surround the tracking volume; in this analysis the calorimetry provides high-resolution energy and direction measurements of electrons and hadronic jets. Muons are measured in gas detectors embedded in the steel return yoke outside the solenoid. The detector is nearly hermetic, allowing for energy balance measurements in the plane transverse to the beam directions. A two-tier trigger system selects the most interesting pp collision events for use in physics analysis. A more detailed description of the CMS detector can be found elsewhere [6].

The trigger providing the data sample used in this analysis is based on the presence of at least one charged lepton, either an electron or a muon, with a minimum transverse momentum p_T of 9 (15) GeV/c for the muon (electron). This data sample is used both for the selection of the signal and for signal-depleted control regions used for studies related to background processes. Simulated signal events that pass the event selection, as described below, satisfy the trigger requirements with an efficiency above 97% in the $\mu^+\mu^-$ decay mode and above 99% in the other two modes, in agreement with estimates from Z boson events in the data.

Before further consideration, events are required to have at least one good reconstructed pp interaction vertex [10]. Among these events, selection criteria are applied to reconstructed objects to identify candidates consistent with dilepton $t\bar{t}$ processes.

Muon candidates are reconstructed [11] using two algorithms that require consistent hits in the tracker and muon systems: one is an algorithm based on the matching of extrapolated trajectories from the silicon tracker to hits in the muon system (tracker-based muons); the second is an algorithm based on performing a global fit of consistent hits in the tracker and the muon system (globally-fitted muons). Candidates are required to have $p_T > 20$ GeV/c and $|\eta| < 2.5$. Additionally, the track associated with the muon candidate is required to have a minimum number of hits in the silicon tracker, to be consistent with originating from the beam spot, and to have a high-quality global fit including a minimum number of hits in the muon detector.

Electron candidates are reconstructed [12] starting from a cluster of energy deposits in the crystals of the ECAL, which is then matched to hits in the silicon tracker, used to initiate a special track reconstruction algorithm. The electron reconstruction algorithm takes into account the possibility of significant energy loss of the electron through bremsstrahlung as it traverses the material of the tracker. Electron candidates are required to have $p_T > 20$ GeV/c and pseudorapidity $|\eta| < 2.5$. The electron candidate track is required to be consistent with originating from the beam spot. Requirements on the values of electron identification variables based on shower shape and track-cluster matching are applied to the reconstructed candidates; the criteria are optimized for inclusive $W \rightarrow e\nu$ selection and are designed to maximize the rejection of electron candidates from QCD multijet production while maintaining 90% efficiency for electrons from the decay of W/Z bosons. Electron candidates within $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} < 0.1$ of a tracker-based or globally-fitted muon are rejected to remove fake electron candidates due to muon bremsstrahlung. In addition, electrons consistent with anomalous depositions in the ECAL or with photon conversions are rejected.

Charged leptons from the decay of W bosons are expected to be isolated from other activity in the event. For selected muon and electron candidates, a cone of $\Delta R < 0.3$ is constructed around the track direction at the origin and the scalar sum of the track transverse momenta and calorimeter energy deposits, projected onto a plane transverse to the beam, is calculated. The contribution from the candidate itself is excluded. If the value of this scalar sum is more than 15% of the candidate's transverse momentum, the candidate is considered to be non-isolated and is rejected.

Lepton trigger, identification, and isolation efficiencies are measured using inclusive Z events from data and are compared with simulation. All comparisons show good agreement, generally within 2%. The residual differences between the efficiencies estimated in data and simulation are treated as systematic uncertainties.

Events are required to have at least one pair of oppositely charged leptons. Both charged leptons are required to originate from within 1 cm along the beam line of the reconstructed pp interaction location. To veto contributions from Z production, the invariant mass of the dilepton system, $M_{\ell\ell}$, is required to be outside a ± 15 GeV/ c^2 window centered at the mass of the Z boson for the e^+e^- and $\mu^+\mu^-$ modes. Additionally, dilepton candidate events with $M_{\ell\ell} < 10$ GeV/ c^2 are removed, at essentially no penalty for the collected signal.

The neutrinos from the W boson decays do not interact with the detector and escape without depositing any of their energy. The presence of a neutrino manifests itself as an imbalance in the measured energy depositions; the imbalance in the projection perpendicular to the beam line (missing transverse energy, $\cancel{E}_T$) is an important distinguishing feature of $t\bar{t}$ events in this channel. At CMS there are several techniques for calculating $\cancel{E}_T$ [13]; here, the raw $\cancel{E}_T$, calculated from calorimeter signals, is made more accurate through a series of corrections taking into account the contribution from the minimally interacting muons and, most importantly, a per-track correction for the expected imperfect response of the calorimeter, derived from simulation. This track correction results in an improved energy resolution, especially for low-energy charged particles. Neither the dominant background processes, Drell–Yan $Z/\gamma^* \rightarrow e^+e^-$ and $\mu^+\mu^-$, nor the difficult-to-model background from isolated lepton candidates produced in QCD multijet events, contain a natural source of large $\cancel{E}_T$. Hence, in the e^+e^- and $\mu^+\mu^-$ modes, $\cancel{E}_T > 30$ GeV is required; in the $e^\pm\mu^\mp$ mode a looser requirement of $\cancel{E}_T > 20$ GeV is used due to the significantly smaller contribution of Drell–Yan background.

Dilepton $t\bar{t}$ events will have at least two hadronic jets from the hadronization of the two b quarks. The anti- k_T clustering algorithm [14] with $R = 0.5$ is used for jet clustering. Jets are reconstructed using calorimeter information and corrected using reconstructed tracks [15]. Further corrections are applied to the raw jet momenta to establish a relative uniform response of the calorimeter in jet η and an absolute uniform response in jet p_T . The jet energy scale uncertainty for these track-corrected jets is 5%. Jet candidates are required to have $p_T > 30$ GeV/c, $|\eta| < 2.5$, and must not overlap with any electron or muon candidate within $\Delta R < 0.4$. Events with fewer than two jets are not used in the measurement.

The selection efficiency of signal events is evaluated in a simulated $t\bar{t}$ event sample modeled with the MADGRAPH event generator version 4.4.12 [16] with up to three additional hadronic jets. The events are subsequently processed with PYTHIA (v. 6.420) [17] to provide showering of generated particles, and then processed with a full CMS detector simulation based on GEANT4 (v. 9.2 Rev01) [18]. The total next-to-leading order (NLO) cross section for top-quark pair production used here to scale simulated signal distributions is $\sigma_{t\bar{t}} = 158_{-24}^{+23}$ pb, as obtained with MCFM [19–22] for a top-quark mass of 172.5 GeV/ c^2 . Approximate next-to-next-to-leading order (NNLO) calculations for the $t\bar{t}$ cross section have been completed (see for example [23–29]) but are not used here. The theoretical uncertainty on the cross section includes the scale uncertainties, determined by varying the factorization and renormalization scales by factors of 2 and 0.5 around the central scale, corresponding to the assumed top-quark mass, and the uncertainties from the parton distribution functions (PDFs) and the value of α_s ,

Table 1

The expected number of dilepton $t\bar{t}$ signal and background events passing the full selection criteria, compared to the number of observed events. The procedures for estimating the expected numbers of events and their uncertainties are described in the text. For the backgrounds estimated from data, the statistical and systematic uncertainties are quoted separately. The expected signal yield assumes a $t\bar{t}$ cross section of $\sigma_{t\bar{t}} = 158^{+23}_{-24}$ pb.

Source	Number of events
Expected $t\bar{t}$	7.7 ± 1.5
Dibosons (VV)	0.13 ± 0.07
Single top (tW)	0.25 ± 0.13
Drell–Yan $Z/\gamma^* \rightarrow \tau^+\tau^-$	0.18 ± 0.09
Drell–Yan $Z/\gamma^* \rightarrow e^+e^-, \mu^+\mu^-$	$1.4 \pm 0.5 \pm 0.5$
Events with non-W/Z leptons	$0.1 \pm 0.5 \pm 0.3$
Total backgrounds	2.1 ± 1.0
Expected total, including $t\bar{t}$	9.8 ± 1.8
Data	11

following the procedures from the MSTW2008 [30], CTEQ6.6 [31], and NNPDF2.0 [32] sets. From the simulated $t\bar{t}$ sample, the total signal acceptance, including geometric acceptance and event reconstruction and selection efficiencies, is found to be $(23.0 \pm 1.4)\%$ for events contributing to the e^+e^- , $\mu^+\mu^-$, and $e^\pm\mu^\mp$ modes combined, where the systematic uncertainty on the acceptance is described later in the text. The expected yield of events passing the selection criteria, assuming the NLO production cross section, is 1.5 ± 0.3 , 1.7 ± 0.3 , and 4.5 ± 0.9 for the e^+e^- , $\mu^+\mu^-$, and $e^\pm\mu^\mp$ decay modes, respectively. The uncertainties on these predicted event yields combine the systematic uncertainties on the event selection, the theoretical production cross section, and the integrated luminosity of the sample, where the contribution from the last two sources dominates the total. Note that the simulated $t\bar{t}$ signal sample used for the estimate of the expected signal events was generated with the $W \rightarrow \ell\nu$ branching fraction set to 1/9, which is different from the standard value (0.1080 ± 0.0009) [7] used in the cross section measurement.

The selected sample is not 100% pure in dilepton $t\bar{t}$ events. There are two types of background estimation techniques used in this analysis. One strategy utilizes simulated pp collision events to model background processes. There are, however, some pathological backgrounds that are harder to model accurately. In such cases, it is preferred to estimate the yields of these events from the data.

Contributions from diboson production (VV, where $V = W$ or Z/γ^*), based on a leading-order production cross section of $\sigma_{VV} = 4.8$ pb [16], and electroweak single-top production in the tW channel ($\sigma_{tW} = 10.6$ pb [33]) are modeled with the MADGRAPH event generator and are processed in an equivalent fashion as the simulated $t\bar{t}$ sample used to assess the signal yield. The Drell–Yan $Z/\gamma^* \rightarrow \tau\tau$ process ($\sigma_{Z/\gamma^* \rightarrow \tau\tau} = 1666$ pb [34]) is modeled with PYTHIA and MADGRAPH. The uncertainties on these production cross sections are well within the total systematic uncertainty of 50% used for each of these backgrounds. Table 1 gives the simulation-based predictions for the event yields from these processes.

The contributions from two important background sources are estimated from the data: exceptional Drell–Yan events that evade the Z veto and are accompanied by significant missing transverse energy; and dilepton candidate events from multijet and W + jets production. Difficult-to-simulate instrumental effects influence both topologies and hence it is preferable to use calibration samples from the data in these estimations.

The events rejected by the Z veto are used to estimate the residual contributions from Drell–Yan $Z/\gamma^* \rightarrow e^+e^-$ and $\mu^+\mu^-$ in the surviving selected sample. In the $\mu^+\mu^-$ final state the rate of events surviving the Z veto is equal to an estimate of the Drell–

Yan contribution near the $M_{\ell\ell}$ peak, scaled by the expected ratio of off-peak to near-peak events derived from simulation. The near-peak Drell–Yan Z/γ^* contribution is estimated from the number of all events failing the Z veto, after subtraction of the non-Drell–Yan contribution estimated from $e^\pm\mu^\mp$ events passing the same selection and corrected for the differences between the electron and muon identification efficiencies. The estimate in the e^+e^- mode is done in a similar fashion; the summed contribution is shown in Table 1. The systematic uncertainty of this method, evaluated in each mode separately, is estimated to be 50%. This is dominated by detector calibration effects and changes of the fraction of Z-vetoed Drell–Yan Z/γ^* events with increasingly stringent requirements (additional jets and missing transverse energy) as estimated from simulation.

Dilepton candidate events from multijet and W + jets production mostly arise from jets that are able to satisfy the tight lepton identification criteria. These contributions to the selected sample from isolated lepton candidates from non-W/Z decays are also derived from data. A superset of dilepton candidate events is chosen by loosening the lepton identification criteria in the data samples used for the measurement. The number of these candidates passing the loosened selection criteria from non-W/Z leptons can be weighted by the ratio of yields of tight-to-loose lepton candidates (R_{TL}) to produce an estimate of non-W/Z leptons passing the tight selections. The ratio R_{TL} is measured as a function of candidate transverse momentum and pseudorapidity in a multijet-dominated data sample containing events with one lepton candidate passing loose selection criteria. Additional selection criteria, based on the missing transverse energy and on the transverse mass of the system defined by the $\cancel{E}_T$ and charged lepton candidate p_T , are applied to suppress the residual contribution to the loose lepton sample from electroweak processes. We assume this R_{TL} is appropriate for use in the dilepton signal sample, and we also consider R_{TL} to be independent from the other lepton in events with two leptons. In this measurement, the value of R_{TL} changes slightly as a function of candidate p_T and $|\eta|$; for both muon and electron candidates, R_{TL} is in the interval between 0.2 and 0.4.

Estimates for the contributions from lepton candidates in pure multijet QCD, with two such non-W/Z candidates, and in W + jets, with one such candidate beyond that from the decay of the W, are derived separately. A sample of loose dilepton events both failing the tight selections is used to estimate the multijet QCD contribution. Loose dilepton events with only one lepton failing the tight requirements include contributions from W + jets events, but are contaminated by multijets and leptons from W/Z decays. The multijet QCD contamination is subtracted using the previous estimate, while the contamination from W/Z leptons is measured from a sample of Z events fulfilling loose selection requirements.

The prediction for these non-W/Z leptons is shown in Table 1. The systematic uncertainty on the non-W/Z lepton estimate is primarily from differences in the jet momentum spectrum and flavor composition between the QCD-dominated sample in which R_{TL} is measured and the sample where it is applied. Other subdominant contributions to the systematic uncertainties include the R_{TL} measurement biases due to electroweak signal contribution, the dissimilarity in the trigger between the R_{TL} calibration sample and the signal sample to which it is applied, and from the statistical limitations on the R_{TL} calibration sample. The systematic uncertainty on the electron R_{TL} is 50%, which corresponds to a 50% (100%) uncertainty on a raw estimate of the W + jets (QCD multijets) non-W/Z isolated lepton contribution, prior to accounting for the signal contribution to the estimate. Similarly, the systematic uncertainty on the muon R_{TL} is $^{+50}_{-100}\%$, which corresponds to a $^{+50}_{-100}\%$ ($^{+100}_{-100}\%$) uncertainty on the estimate of the W + jets (QCD multijets) non-W/Z isolated lepton contribution.

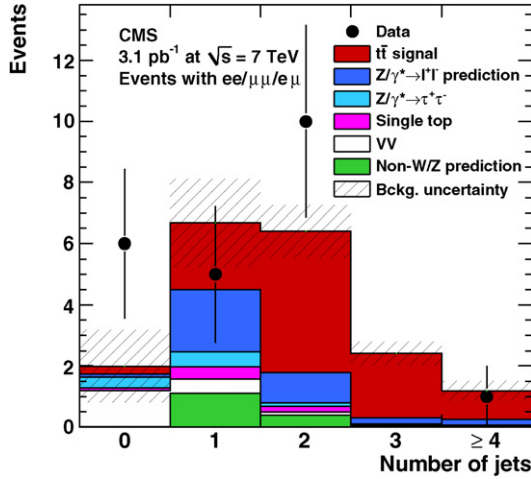


Fig. 1. Number of jets in events passing all dilepton selection criteria before the ≥ 2 -jet requirement for all three dilepton modes combined, compared to signal and background predictions. The hatched bands reflect the uncertainties on the background predictions.

Expected yields from simulated signal and background processes, normalized to estimates from data where appropriate, are shown in Fig. 1 as a function of jet multiplicity for events satisfying the complete dilepton event selection criteria except the ≥ 2 -jet requirement; the $t\bar{t}$ signal dominates the bins with at least two jets.

Eleven dilepton events ($3 e^+e^-$, $3 \mu^+\mu^-$, $5 e^\pm\mu^\mp$) are observed in the data after applying the event selection criteria, with a total of 2.1 ± 1.0 background events expected. We attribute the excess of events above the background expectation to top-quark pair production.

The top-quark mass reconstruction methods of [35] (KIN, i.e., KINematic, method) and [36] (MWT, i.e., Matrix Weighting Technique) are applied to the selected events. In both methods, numerical solutions to the kinematic equations appropriate for a $t\bar{t}$ decay with two charged leptons in the final state are found for each event. The solutions are based on an ensemble of values of jet momenta and missing energy, generated corresponding to their expected resolution around the measured values. In the KIN method the underconstrained system is solved by introducing an additional constraint on the longitudinal momentum of the $t\bar{t}$ system, whose probability distribution is expected to have a negligible dependence on the top-quark mass and is therefore assumed from simulation. The top-quark mass value corresponding to the largest number of solutions is the reconstructed mass for each event. In the MWT method the system is solved for a range of top-quark mass values, and weights, dependent on the momentum of the initial partons and the lepton energies in the top-quark rest frame, are assigned based on the likelihood of each solution. The mass for which the sum of the weights of all solutions is maximized is used as the mass estimator. Fig. 2 shows that the kinematics of the selected events are statistically compatible with predictions based on a top-quark mass of $172.5 \text{ GeV}/c^2$, demonstrating the consistency of the selected sample with top-quark pair production.

Further, beyond the complete event selection described above, the property that the two jets expected in dilepton $t\bar{t}$ events both originate from b quarks is exploited to further confirm the top-quark signal. A b-quark jet identification algorithm that relies on the presence of charged particle tracks displaced from the primary pp interaction location, as expected from the decay products of long-lived b hadrons [37], is used. A jet is identified to be from

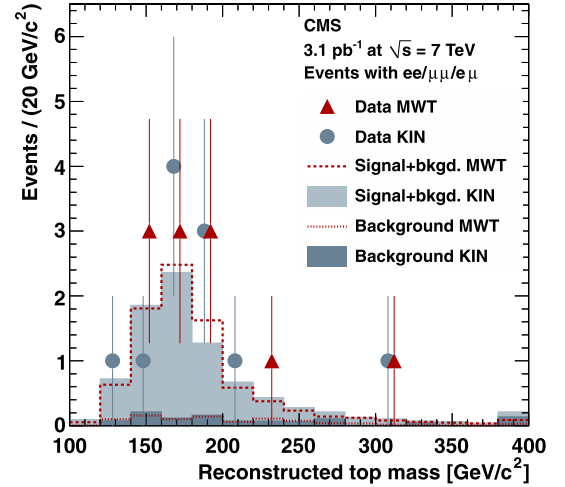


Fig. 2. Distribution of the top-quark mass using two different reconstruction methods [35,36], compared with the expected yields from simulated signal-plus-background and background-only hypotheses. The points in each bin for the two methods are slightly offset in reconstructed mass to allow coincident points to be visible. The last bin contains the overflow.

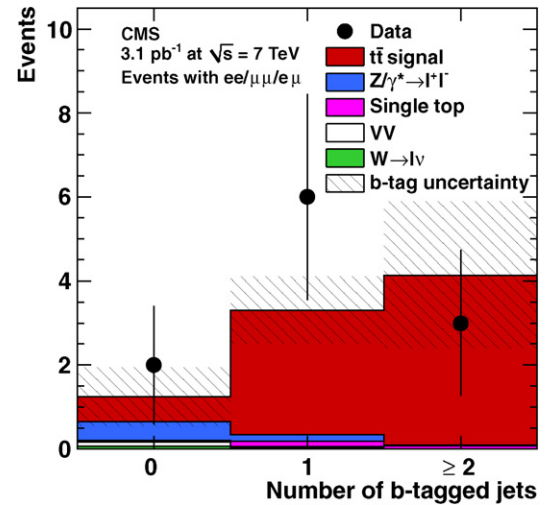


Fig. 3. Number of b-tagged jets in events passing all dilepton selection criteria for all three dilepton modes combined, compared to signal and background directly from simulations. The hatched bands reflect the expected uncertainties on the b-tag efficiency for signal events.

a b quark if there are at least two tracks satisfying a minimum impact parameter significance requirement. The efficiency of this algorithm for a b-quark jet in dilepton $t\bar{t}$ signal events is about 80% with a 10% false positive rate, as estimated in simulated QCD multijet events with no b quarks. This algorithm is applied to events passing all the selection criteria. The multiplicity of jets satisfying these b-tagging criteria in events passing the full dilepton event selection is shown in Fig. 3. Although not used directly in the cross section extraction, the b-tag multiplicity provides additional support for the hypothesis that the selected data are consistent with dilepton $t\bar{t}$ production.

The top-quark pair production cross section is determined from the ratio of the number of observed events in the data after background subtraction with the product of the total signal acceptance, the branching fractions, and the integrated luminosity. The impact of systematic uncertainty is included on each piece, as described below.

Various sources of systematic uncertainty related to the event selection have been evaluated. The systematic uncertainty assigned to the dilepton selection efficiency is 4.4%, obtained from a comparison of Z events in data and simulation, together with half of the difference between the efficiencies obtained in simulated Z and $t\bar{t}$ events. The effect of multiple pp interactions in a single beam crossing – an effect that is present in the data but not in these simulated samples – is included in this uncertainty. The systematic uncertainty due to the reconstruction of jets and missing transverse energy is estimated by varying the jet energy scale by $\pm 5\%$, simultaneously with a $\pm 5\%$ variation in the hadronic part of the missing transverse energy, resulting in a value of 3.7%. Uncertainties on the simulation of the signal selection efficiency include the amount of QCD radiation, hadron and tau decay modeling, and the W leptonic branching fraction; these sources combined give a systematic uncertainty of 2.8%. Other sources of systematic uncertainty pertaining to the signal, including uncertainties in the parton distribution functions inside the colliding protons, the effect of uncertainty on the world-average top-quark mass measurement [38], and the effect of additional minimum bias interactions in the signal selection, are neglected because they were found to have a relatively small impact. The overall systematic uncertainty on the total $t\bar{t}$ cross section from the above sources is 6.4%.

The background contributions from single-top, diboson, and Drell–Yan $Z/\gamma^* \rightarrow \tau^+\tau^-$ processes shown in Table 1 are obtained from simulation and found to be small compared to the total event yield. Each of these backgrounds is assigned a 50% systematic uncertainty. The contributions from Drell–Yan e^+e^- and $\mu^+\mu^-$ processes and events with non-W/Z isolated leptons are estimated from data with absolute systematic uncertainties of 0.5 and 0.3 events, respectively. The contribution to the systematic uncertainty on the cross section from the uncertainties on the background estimates is 11%.

The total systematic uncertainty on the measured cross section, dominated by the uncertainty on the estimated background yield, is 24 pb. An additional systematic effect of 21 pb, due to a 11% relative uncertainty on the integrated luminosity measurement [5], is quoted separately.

Taking into account the data yield, the background estimation, the branching fraction, the signal acceptance, the integrated luminosity, and all associated statistical and systematic uncertainties, the top-quark pair production cross section is measured to be

$$\sigma(pp \rightarrow t\bar{t} + X) = 194 \pm 72(\text{stat.}) \pm 24(\text{syst.}) \pm 21(\text{lumi.}) \text{ pb.}$$

An alternative analysis, exploiting jets constructed only from silicon tracker information [39] and without missing transverse energy requirements in the event selection, yields a similar cross section. The quoted measurement can be compared with the calculated NLO theoretical cross section of 158^{+23}_{-24} pb for a top-quark mass of 172.5 GeV/ c^2 [19,20].

In conclusion, the first measurement at the LHC of the cross section for $t\bar{t}$ production has been completed. This measurement, made with an integrated luminosity of $3.1 \pm 0.3 \text{ pb}^{-1}$, is only the beginning of a rich top-quark physics program to be conducted at the CMS experiment.

Acknowledgements

We wish to congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC machine. We thank the technical and administrative staff at CERN and other CMS institutes, and acknowledge support from: FMSR (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP

(Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); Academy of Sciences and NICPB (Estonia); Academy of Finland, ME, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); PAEC (Pakistan); SCSR (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MST and MAE (Russia); MSTP (Serbia); MICINN and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); TUBITAK and TAEK (Turkey); STFC (United Kingdom); DOE and NSF (USA).

Open access

This article is published Open Access at sciencedirect.com. It is distributed under the terms of the Creative Commons Attribution License 3.0, which permits unrestricted use, distribution, and reproduction in any medium, provided the original authors and source are credited.

References

- [1] F. Abe, et al., Phys. Rev. Lett. 74 (1995) 2626, doi:10.1103/PhysRevLett.74.2626, arXiv:hep-ex/9503002.
- [2] S. Abachi, et al., Phys. Rev. Lett. 74 (1995) 2632, doi:10.1103/PhysRevLett.74.2632, arXiv:hep-ex/9503003.
- [3] J.R. Incandela, A. Quadt, W. Wagner, D. Wicke, Prog. Part. Nucl. Phys. 63 (2009) 239, doi:10.1016/j.ppnp.2009.08.001, arXiv:0904.2499.
- [4] L. Evans, P. Bryant (Eds.), LHC Machine, JINST 3 (2008) S08001, doi:10.1088/1748-0221/3/08/S08001.
- [5] CMS Collaboration, Measurement of CMS luminosity, CMS Physics Analysis Summary CMS-PAS-EWK-10-004, <http://cdsweb.cern.ch/record/1279145>.
- [6] R. Adolph, et al., JINST 0803 (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [7] K. Nakamura, J. Phys. G 37 (2010) 075021, doi:10.1088/0954-3899/37/7A/075021.
- [8] T. Aaltonen, et al., Phys. Rev. D 82 (2010) 052002, doi:10.1103/PhysRevD.82.052002, arXiv:1002.2919.
- [9] V.M. Abazov, et al., Phys. Lett. B 679 (2009) 177, doi:10.1016/j.physletb.2009.07.032, arXiv:0901.2137.
- [10] CMS Collaboration, CMS tracking performance results from early LHC operation, CMS Physics Analysis Summary CMS-PAS-TRK-10-001, arXiv:1007.1988, <http://cdsweb.cern.ch/record/1277738>.
- [11] CMS Collaboration, Performance of muon identification in pp collisions at $\sqrt{s} = 7$ TeV, CMS Physics Analysis Summary CMS-PAS-MUO-10-002, <http://cdsweb.cern.ch/record/1279140>.
- [12] CMS Collaboration, Electron reconstruction and identification at $\sqrt{s} = 7$ TeV, CMS Physics Analysis Summary CMS-PAS-EGM-10-004, <http://cdsweb.cern.ch/record/1299116>.
- [13] CMS Collaboration, CMS MET performance in events containing electroweak bosons from pp collisions at $\sqrt{s} = 7$ TeV, CMS Physics Analysis Summary CMS-PAS-JME-10-005, <http://cdsweb.cern.ch/record/1294501>.
- [14] M. Cacciari, G.P. Salam, G. Soyez, JHEP 0804 (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
- [15] CMS Collaboration, Jet performance in pp collisions at $\sqrt{s} = 7$ TeV, CMS Physics Analysis Summary CMS-PAS-JME-10-003, <http://cdsweb.cern.ch/record/1279362>.
- [16] F. Maltoni, T. Stelzer, JHEP 0302 (2003) 027, arXiv:hep-ph/0208156.
- [17] T. Sjöstrand, S. Mrenna, P. Skands, JHEP 0605 (2006) 026, arXiv:hep-ph/0603175.
- [18] J. Allison, et al., IEEE Trans. Nucl. Sci. 53 (2006) 270, doi:10.1109/TNS.2006.869826.
- [19] J.M. Campbell, R.K. Ellis, MCFM for the Tevatron and the LHC, arXiv:1007.3492, 2010.
- [20] R. Kleiss, W.J. Stirling, Z. Phys. C 40 (1988) 419, doi:10.1007/BF01548856.
- [21] P. Nason, S. Dawson, R.K. Ellis, Nucl. Phys. B 303 (1988) 607, doi:10.1016/0550-3213(88)90422-1.
- [22] W. Beenakker, H. Kuijf, W.L. van Neerven, J. Smith, Phys. Rev. D 40 (1989) 54, doi:10.1103/PhysRevD.40.54.
- [23] N. Kidonakis, Next-to-next-to-leading soft-gluon corrections for the top quark cross section and transverse momentum distribution, arXiv:1009.4935, 2010.
- [24] N. Kidonakis, R. Vogt, Phys. Rev. D 78 (2008) 074005, doi:10.1103/PhysRevD.78.074005, arXiv:0805.3844.

- [25] M. Cacciari, S. Frixione, M.L. Mangano, P. Nason, G. Ridolfi, JHEP 0809 (2008) 127, doi:[10.1088/1126-6708/2008/09/127](https://doi.org/10.1088/1126-6708/2008/09/127), arXiv:0804.2800.
- [26] S. Moch, P. Uwer, Phys. Rev. D 78 (2008) 034003, doi:[10.1103/PhysRevD.78.034003](https://doi.org/10.1103/PhysRevD.78.034003), arXiv:0804.1476.
- [27] U. Langenfeld, S. Moch, P. Uwer, New results for $t\bar{t}$ production at hadron colliders, arXiv:0907.2527, 2009.
- [28] U. Langenfeld, S. Moch, P. Uwer, Phys. Rev. D 80 (2009) 054009, doi:[10.1103/PhysRevD.80.054009](https://doi.org/10.1103/PhysRevD.80.054009), arXiv:0906.5273.
- [29] V. Ahrens, A. Ferroglia, M. Neubert, B.D. Pecjak, L.L. Yang, JHEP 1009 (2010) 097, doi:[10.1007/JHEP09\(2010\)097](https://doi.org/10.1007/JHEP09(2010)097), arXiv:1003.5827.
- [30] A.D. Martin, W.J. Stirling, R.S. Thorne, G. Watt, Eur. Phys. J. C 64 (2009) 653, doi:[10.1140/epjc/s10052-009-1164-2](https://doi.org/10.1140/epjc/s10052-009-1164-2), arXiv:0905.3531.
- [31] H.-L. Lai, et al., Uncertainty induced by QCD coupling in the CTEQ-TEA global analysis of parton distributions, arXiv:1004.4624, 2010.
- [32] F. Demartin, S. Forte, E. Mariani, J. Rojo, A. Vicini, Phys. Rev. D 82 (2010) 014002, doi:[10.1103/PhysRevD.82.014002](https://doi.org/10.1103/PhysRevD.82.014002), arXiv:1004.0962.
- [33] J.M. Campbell, F. Tramontano, Nucl. Phys. B 726 (2005) 109, doi:[10.1016/j.nuclphysb.2005.08.015](https://doi.org/10.1016/j.nuclphysb.2005.08.015), arXiv:hep-ph/0506289.
- [34] K. Melnikov, F. Petriello, Phys. Rev. D 74 (2006) 114017, doi:[10.1103/PhysRevD.74.114017](https://doi.org/10.1103/PhysRevD.74.114017), arXiv:hep-ph/0609070.
- [35] A. Abulencia, et al., Phys. Rev. D 73 (2006) 112006, doi:[10.1103/PhysRevD.73.112006](https://doi.org/10.1103/PhysRevD.73.112006), arXiv:hep-ex/0602008.
- [36] V.M. Abazov, et al., Phys. Rev. D 80 (2009) 092006, doi:[10.1103/PhysRevD.80.092006](https://doi.org/10.1103/PhysRevD.80.092006), arXiv:0904.3195.
- [37] CMS Collaboration, Commissioning of b-jet identification with pp collisions at $\sqrt{s} = 7$ TeV, CMS Physics Analysis Summary CMS-PAS-BTV-10-001, <http://cdsweb.cern.ch/record/1279144>.
- [38] Tevatron Electroweak Working Group, Combination of CDF and D0 results on the mass of the top quark, arXiv:1007.3178, 2010.
- [39] CMS Collaboration, Commissioning of Trackjets in pp collisions at $\sqrt{s} = 7$ TeV, CMS Physics Analysis Summary CMS-PAS-JME-10-006, <http://cdsweb.cern.ch/record/1275133>.

CMS Collaboration

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

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan, M. Friedl, R. Frühwirth, V.M. Ghete, J. Hammer¹, S. Häsnel, C. Hartl, 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, A. Taurok, F. Teischinger, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz

Institut für Hochenergiephysik der OeAW, Wien, Austria

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

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

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

Universiteit Antwerpen, Antwerpen, Belgium

V. Adler, S. Beauceron, S. Blyweert, J. D'Hondt, O. Devroede, A. Kalogeropoulos, J. Maes, M. Maes, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

Vrije Universiteit Brussel, Brussel, 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, J. Wickens

Université Libre de Bruxelles, Bruxelles, Belgium

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

Ghent University, Ghent, Belgium

S. Basegmez, G. Bruno, J. Caudron, J. De Favereau De Jeneret, C. Delaere, P. Demin, D. Favart, A. Giammanco, G. Grégoire, J. Hollar, V. Lemaitre, J. Liao, O. Militaru, S. Ovyn, D. Pagano, A. Pin, K. Piotrkowski, L. Quertenmont, N. Schul

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

N. Beliy, T. Caebergs, E. Daubie

Université de Mons, Mons, Belgium

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

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

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

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

F.A. Dias, M.A.F. Dias, T.R. Fernandez Perez Tomei, E.M. Gregores², F. Marinho, S.F. Novaes, Sandra S. Padula

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

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

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

M. Dyulendarova, R. Hadjiiska, V. Kozhuharov, L. Litov, E. Marinova, M. Mateev, 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, J. Wang, J. Wang, X. Wang, Z. Wang, M. Yang, J. Zang, Z. Zhang

Institute of High Energy Physics, Beijing, China

Y. Ban, S. Guo, Z. Hu, W. Li, Y. Mao, S.J. Qian, H. Teng, B. Zhu

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

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

Universidad de Los Andes, Bogota, Colombia

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

Technical University of Split, Split, Croatia

Z. Antunovic, M. Dzelalija

University of Split, Split, Croatia

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

Institute Rudjer Boskovic, Zagreb, Croatia

A. Attikis, R. Fereos, M. Galanti, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

University of Cyprus, Nicosia, Cyprus

A. Abdel-basit⁴, Y. Assran⁵, M.A. Mahmoud⁶

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

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

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

V. Azzolini, P. Eerola

Department of Physics, University of Helsinki, Helsinki, Finland

S. Czellar, J. Härkönen, A. Heikkinen, V. Karimäki, R. Kinnunen, J. Klem, 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

Helsinki Institute of Physics, Helsinki, Finland

K. Banzuzi, A. Korpela, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

D. Sillou

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

M. Besancon, 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, M. Titov, P. Verrecchia

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

S. Baffioni, L. Bianchini, M. Bluj⁷, C. Broutin, P. Busson, C. Charlot, L. Dobrzynski, R. Granier de Cassagnac, M. Haguenaue, P. Miné, C. Mironov, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Thiebaux, B. Wyslouch⁸, A. Zabi

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

J.-L. Agram⁹, J. Andrea, A. Besson, 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

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 Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

C. Baty, 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, H. Xiao

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

V. Roinishvili

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

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, I. Physikalisches Institut, Aachen, Germany

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

RWTH Aachen University, III. Physikalisches Institut A, 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

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

M. Aldaya Martin, W. Behrenhoff, U. Behrens, M. Bergholz¹⁰, K. Borras, A. Cakir, A. Campbell, E. Castro, D. Dammann, G. Eckerlin, D. Eckstein, A. Flossdorf, G. Flucke, A. Geiser, I. Glushkov, J. Hauk, H. Jung, M. Kasemann, I. Katkov, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, 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, A. Parenti, A. Raspereza, A. Raval, R. Schmidt¹⁰, T. Schoerner-Sadenius, N. Sen, M. Stein, J. Tomaszewska, D. Volyanskyy, R. Walsh, C. Wissing

Deutsches Elektronen-Synchrotron, Hamburg, Germany

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

University of Hamburg, Hamburg, Germany

J. Bauer, V. Buege, T. Chwalek, D. Daeuwel, 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, T. Kuhr, D. Martschei, S. Mueller, Th. Müller, M.B. Neuland, M. Niegel, O. Oberst, A. Oehler, J. Ott, T. Peiffer, D. Piparo, G. Quast, K. Rabbertz, F. Ratnikov, M. Renz, A. Sabellek, C. Saout, A. Scheurer, P. Schieferdecker, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, J. Wagner-Kuhr, M. Zeise, V. Zhukov¹¹, E.B. Ziebarth

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

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

Institute of Nuclear Physics “Demokritos”, Aghia Paraskevi, Greece

L. Gouskos, T. Mertzimekis, A. Panagiotou¹

University of Athens, Athens, Greece

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

University of Ioánnina, Ioánnina, Greece

A. Aranyi, G. Bencze, L. Boldizsar, G. Debreczeni, C. Hajdu¹, D. Horvath¹², A. Kapusi, K. Krajczar¹³, A. Laszlo, F. Sikler, G. Vesztergombi¹³

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

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

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

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

University of Debrecen, Debrecen, Hungary

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

Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India

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

Bhabha Atomic Research Centre, 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 – EHEP, Mumbai, India

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

Tata Institute of Fundamental Research – HEER, Mumbai, India

H. Arfaei, H. Bakhshiansohi, S.M. Etesami, A. Fahim, M. Hashemi, A. Jafari, M. Khakzad, A. Mohammadi, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh, M. Zeinali

Institute for Studies in Theoretical Physics & Mathematics (IPM), Tehran, Iran

M. Abbrescia^{a,b}, L. Barbone^{a,b}, C. Calabria^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, N. De Filippis^{a,c}, M. De Palma^{a,b}, A. Dimitrov^a, F. Fedele^a, L. Fiore^a, G. Iaselli^{a,c}, L. Lusito^{a,b,1}, 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. Tupputi^{a,b}, 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, S. Braibant-Giacomelli^{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, P. Giacomelli^a, M. Giunta^a, C. Grandi^a, S. Marcellini^a, M. Meneghelli^{a,b}, A. Montanari^a, F.L. Navarria^{a,b}, F. Odorici^a, A. Perrotta^a, 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,1}, S. Costa^{a,b}, A. Tricomi^{a,b}, C. Tuve^a

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

^a INFN Sezione di Firenze, Firenze, Italy

^b Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, S. Colafranceschi¹⁶, 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}, G.B. Cerati^{a,b}, F. De Guio^{a,b,1}, L. Di Matteo^{a,b}, A. Ghezzi^{a,b,1}, P. Govoni^{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}

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

^b Università di Milano-Bicocca, Milano, Italy

S. Buontempo^a, C.A. Carrillo Montoya^a, A. Cimmino^{a,b}, A. De Cosa^{a,b,1}, M. De Gruttola^{a,b}, F. Fabozzi^{a,17}, A.O.M. Iorio^a, L. Lista^a, M. Merola^{a,b}, P. Noli^{a,b}, P. Paolucci^a

^a INFN Sezione di Napoli, Napoli, Italy

^b Università di Napoli "Federico II", Napoli, 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. Gasparini^{a,b}, U. Gasparini^{a,b}, P. Giubilato^{a,b}, A. Gresele^{a,c}, S. Lacaprara^{a,18}, I. Lazzizzera^{a,c}, M. Margoni^{a,b}, M. Mazzucato^a, A.T. Meneguzzo^{a,b}, M. Nespolo^a, L. Perrozzi^{a,1}, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, M. Tosi^{a,b}, A. Triossi^a, S. Vanini^{a,b}, P. Zotto^{a,b}, G. Zumerle^{a,b}

^a INFN Sezione di Padova, Padova, Italy

^b Università di Padova, Padova, Italy

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

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

^a INFN Sezione di Pavia, Pavia, Italy

^b Università di Pavia, Pavia, 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}, A. Santocchia^{a,b}, L. Servoli^a, S. Taroni^{a,b}, M. Valdata^{a,b}, R. Volpe^{a,b,1}

^a INFN Sezione di Perugia, Perugia, Italy

^b Università di Perugia, Perugia, 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, A. Messineo^{a,b}, F. Palla^a, F. Palmonari^a, S. Sarkar^{a,c}, 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

^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}, E. Di Marco^{a,b}, M. Diemoz^a, D. Franci^{a,b}, M. Grassi^a, E. Longo^{a,b}, G. Organtini^{a,b}, A. Palma^{a,b}, F. Pandolfi^{a,b,1}, R. Paramatti^a, S. Rahatlou^{a,b,1}

^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, 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,1}, 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,1}

^a INFN Sezione di Torino, Torino, Italy

^b Università di Torino, Torino, Italy

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

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

^a INFN Sezione di Trieste, Trieste, Italy

^b Università di Trieste, Trieste, Italy

S.G. Heo

Kangwon National University, Chunchon, Republic of Korea

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

Kyungpook National University, Daegu, Republic of Korea

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

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

S. Choi, B. Hong, 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

Korea University, Seoul, Republic of Korea

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

University of Seoul, Seoul, Republic of Korea

Y. Choi, Y.K. Choi, J. Goh, J. Lee, S. Lee, H. Seo, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

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

Vilnius University, Vilnius, Lithuania

H. Castilla Valdez, E. De La Cruz Burelo, R. Lopez-Fernandez, A. Sánchez Hernández, L.M. Villaseñor-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

P. Allfrey, D. Krofcheck, J. Tam

University of Auckland, Auckland, New Zealand

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

University of Canterbury, Christchurch, New Zealand

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

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

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

Institute of Experimental Physics, Warsaw, Poland

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

Soltan Institute for Nuclear Studies, Warsaw, Poland

N. Almeida, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, P. Martins, G. Mini, P. Musella, A. Nayak, L. Raposo, P.Q. Ribeiro, J. Seixas, P. Silva, D. Soares, J. Varela¹, H.K. Wöhri

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

I. Belotelov, P. Bunin, M. Finger, M. Finger Jr., I. Golutvin, A. Kamenev, V. Karjavin, G. Kozlov, A. Lanev, P. Moisenz, V. Palichik, V. Pereygin, S. Shmatov, V. Smirnov, A. Volodko, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

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

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

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

Institute for Nuclear Research, Moscow, Russia

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

Institute for Theoretical and Experimental Physics, Moscow, Russia

E. Boos, M. Dubinin¹⁹, L. Dudko, A. Ershov, A. Gribushin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, L. Sarycheva, V. Savrin, A. Snigirev

Moscow State University, Moscow, Russia

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

P.N. Lebedev Physical Institute, Moscow, 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

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

P. Adzic²⁰, M. Djordjevic, D. Krpic²⁰, 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. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, C. Diez Pardos, 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, 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

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

Universidad de Oviedo, Oviedo, Spain

I.J. Cabrillo, A. Calderon, M. Chamizo Llatas, S.H. Chuang, J. Duarte Campderros, M. Felcini²¹, M. Fernandez, G. Gomez, J. Gonzalez Sanchez, R. Gonzalez Suarez, C. Jorda, P. Lobelle Pardo, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, J. Piedra Gomez²², T. Rodrigo, 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, P. Baillon, A.H. Ball, D. Barney, F. Beaudette³, A.J. Bell²³, D. Benedetti, C. Bernet³, W. Bialas, P. Bloch, A. Bocci, S. Bolognesi, H. Breuker, G. Bruna, K. Bunkowski, T. Camporesi, E. Cano, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, R. Covarelli, B. Curé, D. D'Enterria, T. Dahms, A. De Roeck, A. Elliott-Peisert, W. Funk, A. Gaddi, S. Gennai, G. Georgiou, H. Gerwig, D. Gigi, K. Gill, D. Giordano, F. Glege, R. Gomez-Reino Garrido, M. Gouzevitch, S. Gowdy, L. Guiducci, M. Hansen, J. Harvey, J. Hegeman, B. Hegner, C. Henderson, H.F. Hoffmann, A. Honma, V. Innocente, P. Janot,

E. Karavakis, P. Lecoq, C. Leonidopoulos, C. Lourenço, A. Macpherson, T. Mäki, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, E. Nesvold¹, T. Orimoto, L. Orsini, E. Perez, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, G. Polese, A. Racz, G. Rolandi²⁴, T. Rommerskirchen, C. Rovelli²⁵, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, I. Segoni, A. Sharma, P. Siegrist, M. Simon, P. Sphicas²⁶, D. Spiga, M. Spiropulu¹⁹, F. Stöckli, M. Stoye, P. Tropea, A. Tsiros, A. Tsyganov, G.I. Veres¹³, P. Vichoudis, M. Voutilainen, 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. Sibille²⁷, A. Starodumov²⁸

Paul Scherrer Institut, Villigen, Switzerland

P. Bortignon, L. Caminada²⁹, Z. Chen, S. Cittolin, G. Dissertori, M. Dittmar, J. Eugster, K. Freudenreich, C. Grab, A. Hervé, W. Hintz, P. Lecomte, W. Lustermann, C. Marchica²⁹, P. Martinez Ruiz del Arbol, P. Meridiani, P. Milenovic³⁰, F. Moortgat, A. Nardulli, P. Nef, F. Nessi-Tedaldi, L. Pape, F. Pauss, T. Punz, A. Rizzi, F.J. Ronga, L. Sala, A.K. Sanchez, M.-C. Sawley, B. Stieger, L. Tauscher[†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny²¹, M. Weber, L. Wehrli, J. Weng

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

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

Universität Zürich, Zurich, Switzerland

Y.H. Chang, K.H. Chen, W.T. Chen, S. Dutta, A. Go, C.M. Kuo, S.W. Li, W. Lin, M.H. Liu, Z.k. Liu, Y.J. Lu, J.H. Wu, S.S. Yu

National Central University, Chung-Li, 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, J.T. Wei

National Taiwan University (NTU), Taipei, Taiwan

A. Adiguzel, M.N. Bakirci, S. Cerci³¹, Z. Demir, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gökbulut, Y. Güler, E. Gurpinar, I. Hos, E.E. Kangal, T. Karaman, A. Kayis Topaksu, A. Nart, G. Önengüt, K. Ozdemir, S. Ozturk, A. Polatöz, K. Sogut³², B. Tali, H. Topakli, D. Uzun, L.N. Vergili, M. Vergili, C. Zorbilmez

Cukurova University, Adana, Turkey

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

Middle East Technical University, Physics Department, Ankara, Turkey

M. Deliomeroğlu, D. Demir³³, E. Gülmez, A. Halu, B. Isildak, M. Kaya³⁴, O. Kaya³⁴, M. Özbek, S. Ozkorucuklu³⁵, N. Sonmez³⁶

Bogazici University, Istanbul, Turkey

L. Levchuk

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

P. Bell, F. Bostock, J.J. Brooke, T.L. Cheng, D. Cussans, R. Frazier, J. Goldstein, M. Grimes, M. Hansen, G.P. Heath, H.F. Heath, B. Huckvale, J. Jackson, L. Kreczko, S. Metson, D.M. Newbold³⁷, K. Nirunpong, A. Poll, V.J. Smith, S. Ward

University of Bristol, Bristol, United Kingdom

L. Basso, K.W. Bell, A. Belyaev, 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

Rutherford Appleton Laboratory, Didcot, 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. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, G. Karapostoli, L. Lyons, A.-M. Magnan, J. Marrouche, R. Nandi, J. Nash, A. Nikitenko²⁸, A. Papageorgiou, M. Pesaresi, K. Petridis, M. Pioppi³⁸, D.M. Raymond, N. Rompotis, A. Rose, M.J. Ryan, C. Seez, P. Sharp, A. Sparrow, A. Tapper, S. Tourneur, M. Vazquez Acosta, T. Virdee¹, S. Wakefield, D. Wardrope, T. Whyntie

Imperial College, London, 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

Brunel University, Uxbridge, United Kingdom

K. Hatakeyama

Baylor University, Waco, USA

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

Boston University, Boston, USA

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

Brown University, Providence, USA

M.A. Borgia, R. Breedon, M. Calderon De La Barca Sanchez, D. Cebra, 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, T. Schwarz, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra, C. Veelken

University of California, Davis, 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, Los Angeles, USA

J. Babb, R. Clare, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng, S.C. Kao, F. Liu, H. Liu, A. Luthra, H. Nguyen, G. Pasztor³⁹, A. Satpathy, B.C. Shen[†], R. Stringer, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, Riverside, USA

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

University of California, San Diego, La Jolla, USA

D. Barge, R. Bellan, C. Campagnari, M. D'Alfonso, T. Danielson, 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, M. Witherell

University of California, Santa Barbara, USA

A. Bornheim, J. Bunn, Y. Chen, M. Gataullin, D. Kcira, V. Litvine, Y. Ma, A. Mott, H.B. Newman, C. Rogan, K. Shin, V. Timciuc, P. Traczyk, J. Veverka, R. Wilkinson, Y. Yang, R.Y. Zhu

California Institute of Technology, Pasadena, USA

B. Akgun, A. Calamba, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, S.Y. Jun, Y.F. Liu, M. Paulini, J. Russ, N. Terentyev, H. Vogel, I. Vorobiev

Carnegie Mellon University, Pittsburgh, USA

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

University of Colorado at Boulder, Boulder, USA

L. Agostino, J. Alexander, F. Blekman, A. Chatterjee, S. Das, N. Eggert, L.J. Fields, L.K. Gibbons, B. Heltsley, K. Henriksson, W. Hopkins, A. Khukhunaishvili, B. Kreis, V. Kuznetsov, Y. Liu, G. Nicolas Kaufman, J.R. Patterson, D. Puigh, D. Riley, A. Ryd, M. Saelim, X. Shi, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Vaughan, Y. Weng, L. Winstrom, P. Wittich

Cornell University, Ithaca, USA

A. Biselli, G. Cirino, D. Winn

Fairfield University, Fairfield, 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, M. Demarteau, D.P. Eartly, V.D. Elvira, I. Fisk, J. Freeman, Y. Gao, E. Gottschalk, D. Green, K. Gunthoti, O. Gutsche, A. Hahn, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, E. James, H. Jensen, M. Johnson, U. Joshi, R. Khatiwada, B. Kilminster, B. Klima, K. Kousouris, S. Kunori, S. Kwan, P. Limon, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, T. McCauley, T. Miao, K. Mishra, S. Mrenna, Y. Musienko⁴⁰, C. Newman-Holmes, V. O'Dell, S. Popescu, R. Pordes, O. Prokofyev, N. Saoulidou, E. Sexton-Kennedy, S. Sharma, A. Soha, 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

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, D. Bourilkov, M. Chen, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, S. Goldberg, B. Kim, S. Klimenko, J. Konigsberg, A. Korytov, K. Kotov, A. Kropivnitskaya, T. Kypreos, K. Matchev, G. Mitselmakher, L. Muniz, Y. Pakhotin, M. Petterson, C. Prescott, R. Remington, M. Schmitt, B. Scurlock, P. Sellers, N. Skhirtladze, M. Snowball, D. Wang, J. Yelton, M. Zakaria

University of Florida, Gainesville, USA

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

Florida International University, Miami, USA

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

Florida State University, Tallahassee, USA

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

Florida Institute of Technology, Melbourne, USA

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

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

U. Akgun, E.A. Albayrak, B. Bilki, K. Cankocak⁴¹, 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. Wetzel, T. Yetkin, K. Yi

The University of Iowa, Iowa City, USA

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

Johns Hopkins University, Baltimore, USA

P. Baringer, A. Bean, G. Benelli, O. Grachov, M. Murray, D. Noonan, V. Radicci, S. Sanders, J.S. Wood, V. Zhukova

The University of Kansas, Lawrence, USA

D. Bandurin, T. Bolton, I. Chakaberia, A. Ivanov, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze, Z. Wan

Kansas State University, Manhattan, USA

J. Gronberg, D. Lange, D. Wright

Lawrence Livermore National Laboratory, Livermore, 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

University of Maryland, College Park, 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, J. Lopez, P.D. Luckey, T. Ma, S. Nahn, C. Paus, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephens, K. Sumorok, K. Sung, E.A. Wenger, S. Xie, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

Massachusetts Institute of Technology, Cambridge, USA

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

University of Minnesota, Minneapolis, USA

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

University of Mississippi, University, USA

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

University of Nebraska-Lincoln, Lincoln, USA

U. Baur, A. Godshalk, I. Iashvili, A. Kharchilava, A. Kumar, K. Smith, J. Zennamo

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, D. Baumgartel, O. Boeriu, M. Chasco, K. Kaadze, S. Reucroft, J. Swain, D. Wood, J. Zhang

Northeastern University, Boston, USA

A. Anastassov, A. Kubik, 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, 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, J. Warchol, M. Wayne, J. Ziegler

University of Notre Dame, Notre Dame, USA

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

The Ohio State University, Columbus, 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

Princeton University, Princeton, USA

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

Purdue University, West Lafayette, USA

P. Jindal, N. Parashar

Purdue University Calumet, Hammond, USA

C. Boulahouache, V. Cuplov, K.M. Ecklund, F.J.M. Geurts, J.H. Liu, J. Morales, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

Rice University, Houston, USA

B. Betchart, A. Bodek, Y.S. Chung, 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

University of Rochester, Rochester, USA

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

The Rockefeller University, New York, 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

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

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

Texas A&M University, College Station, USA

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

Texas Tech University, Lubbock, USA

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

Vanderbilt University, Nashville, USA

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

University of Virginia, Charlottesville, USA

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

Wayne State University, Detroit, USA

M. Anderson, M. Bachtis, J.N. Bellinger, D. Carlsmith, S. Dasu, J. Efron, L. Gray, A. Gregerson, K.S. Grogg, M. Grothe, R. Hall-Wilton¹, M. Herndon, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, J. Leonard, J. Liu, D. Lomidze, R. Loveless, A. Mohapatra, W. Parker, D. Reeder, I. Ross, A. Savin, W.H. Smith, J. Swanson, M. Weinberg

University of Wisconsin, Madison, USA

* Corresponding author.

E-mail address: Roberto.Tenchini@cern.ch (R. Tenchini).

† 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 Cairo University, Cairo, Egypt.

⁵ Also at Suez Canal University, Suez, 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 Facoltà Ingegneria, Università di Roma “La Sapienza”, Roma, Italy.

¹⁷ Also at Università della Basilicata, Potenza, Italy.

¹⁸ Also at Laboratori Nazionali di Legnaro dell’INFN, Legnaro, Italy.

¹⁹ Also at California Institute of Technology, Pasadena, USA.

²⁰ Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia.

²¹ Also at University of California, Los Angeles, Los Angeles, USA.

²² Also at University of Florida, Gainesville, USA.

²³ Also at Université de Genève, Geneva, Switzerland.

²⁴ Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy.

²⁵ Also at INFN Sezione di Roma; Università di Roma “La Sapienza”, Roma, Italy.

²⁶ Also at University of Athens, Athens, Greece.

²⁷ Also at The University of Kansas, Lawrence, USA.

²⁸ Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.

²⁹ Also at Paul Scherrer Institut, Villigen, Switzerland.

³⁰ Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.

³¹ Also at Adiyaman University, Adiyaman, Turkey.

³² Also at Mersin University, Mersin, Turkey.

³³ Also at Izmir Institute of Technology, Izmir, Turkey.

³⁴ Also at Kafkas University, Kars, Turkey.

³⁵ Also at Suleyman Demirel University, Isparta, Turkey.

³⁶ Also at Ege University, Izmir, Turkey.

³⁷ Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.

³⁸ Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy.

³⁹ Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.

⁴⁰ Also at Institute for Nuclear Research, Moscow, Russia.

⁴¹ Also at Istanbul Technical University, Istanbul, Turkey.