Measurement of the $t\bar{t}$ production cross section in pp collisions at $\sqrt{s}=7$ TeV in dilepton final states containing a $\tau$

Abstract: The top quark pair production cross section is measured in dilepton events with one electron or muon, and one hadronically decaying lepton from the decay \( t\bar{t} \rightarrow (\ell\nu\ell\nu)bb \), \((\ell=e,\mu)\). The data sample corresponds to an integrated luminosity of 2.0 fb\(^{-1}\) for the electron channel and 2.2 fb\(^{-1}\) for the muon channel, collected by the CMS detector at the LHC. This is the first measurement of the $t\bar{t}$ cross section explicitly including leptons in proton-proton collisions at $\sqrt{s}=7$ TeV. The measured value $\sigma_{t\bar{t}} = 143\pm14$ (stat) $\pm 22$ (syst) $\pm 3$ (lumi) pb is consistent with the standard model predictions.

DOI: [https://doi.org/10.1103/PhysRevD.85.112007](https://doi.org/10.1103/PhysRevD.85.112007)
Measurement of the $t\bar{t}$ production cross section in pp collisions at $\sqrt{s}=7$ TeV in dilepton final states containing a $\tau$

The CMS Collaboration

Abstract

The top quark pair production cross section is measured in dilepton events with one electron or muon, and one hadronically decaying $\tau$ lepton from the decay $t\bar{t} \rightarrow (\ell\nu\ell)(\tau_h\nu\tau)bb, (\ell = e, \mu)$. The data sample corresponds to an integrated luminosity of $2.0\text{ fb}^{-1}$ for the electron channel and $2.2\text{ fb}^{-1}$ for the muon channel, collected by the CMS detector at the LHC. This is the first measurement of the $t\bar{t}$ cross section explicitly including $\tau$ leptons in proton-proton collisions at $\sqrt{s} = 7$ TeV. The measured value $\sigma_{t\bar{t}} = 143 \pm 14\text{ (stat.)} \pm 22\text{ (syst.)} \pm 3\text{ (lumi.)} \text{ pb}$ is consistent with the standard model predictions.

Submitted to Physical Review D

*See Appendix A for the list of collaboration members*
1 Introduction

Top quarks at the Large Hadron Collider (LHC) are mostly produced in pairs with subsequent decay $t \rightarrow W^+bW^-\bar{b}$. The decay modes of the two W bosons determine the observed event signature. The dilepton decay channel denotes the case where both W bosons from the decaying top quark pair decay leptonically. In this Letter, top quark decays in the “tau dilepton” channel are studied, where one W boson decays into $e\nu$ or $\mu\nu$ and the other into the hadronically decaying $\tau$ lepton and $\nu$, in the final state $t \rightarrow (\ell\nu_{\ell})(\tau_{\ell}\nu_{\tau})b\bar{b}$, where $\ell = e, \mu$. The expected fraction of events in the dilepton channel with at least one $\tau$ lepton in the final state is approximately 6% (5/81) of all $t\bar{t}$ decays, i.e. higher than the fraction of the light dilepton channels ($ee, \mu\mu, e\mu$) which is equal to 4/81 of all $t\bar{t}$ decays. The tau dilepton channel is of particular interest because the existence of a charged Higgs boson [1, 2] with a mass smaller than the top quark mass could give rise to anomalous $\tau$ lepton production, which could be directly observable in this decay channel. Furthermore, in the final state studied, the $t \rightarrow (\tau\nu_{\tau})b$ decay exclusively involves third generation leptons and quarks. Understanding the $\tau$ yield in top quark decays is important to increase the acceptance for $t\bar{t}$ events and to search for new physics processes.

This is the first measurement of the $t\bar{t}$ production cross section at the LHC that explicitly includes $\tau$ leptons, improving over the results obtained at the Tevatron which are limited by the small number of candidate events found [3-5]. Experimentally, the $\tau$ lepton is identified by its decay products, either hadrons ($\tau_h$) or leptons ($\tau_\ell$), with the corresponding branching fractions $Br(\tau_h \rightarrow \text{hadrons}+\nu_{\tau}) \simeq 65\%$ and $Br(\tau_\ell \rightarrow \ell\nu_{\tau}, \ell = e, \mu) \simeq 35\%$. In the first case, a narrow jet with a distinct signature is produced; in the case of leptonic decays, the distinction from prompt electron or muon production is experimentally difficult, consequently only hadronic $\tau$ decays are studied here. The cross section is measured by counting the number of $e\tau_h + X$ and $\mu\tau_h + X$ events consistent with originating from $t\bar{t}$, subtracting the contributions from other processes, and correcting for the efficiency of the event selection. The measurement is based on data collected by the Compact Muon Solenoid (CMS) experiment in 2011. The integrated luminosity of the data samples are 1.99 fb$^{-1}$ and 2.22 fb$^{-1}$ for the $e\tau_h$ and $\mu\tau_h$ final states, respectively.

The CMS detector is briefly summarized in Section 2, details of the simulated samples are given in Section 3, a brief description of the event reconstruction and event selection is provided in Section 4, followed by the description of the background determination and systematic uncertainties in Sections 5 and 6, respectively. The measurement of the cross section is discussed in Section 7 and the results are summarized in Section 8.

2 The CMS detector

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. Inside the solenoid, various particle detection systems are employed. Charged particle trajectories are measured by the silicon pixel and strip tracker, covering $0 < \varphi < 2\pi$ in azimuth and $|\eta| < 2.5$, where the pseudorapidity $\eta$ is defined as $\eta = -\ln|\tan(\theta/2)|$, with $\theta$ being the polar angle of the trajectory of the particle with respect to the counterclockwise beam direction. A crystal electromagnetic calorimeter and a brass/scintillator hadron calorimeter surround the tracking volume; in this analysis the calorimetry provides high-resolution energy and direction measurements of electrons and hadronic jets. Muon detection systems are located outside of the solenoid and embedded in the steel return yoke. The detector is nearly hermetic, allowing for energy balance measure-
ments in the plane transverse to the beam directions. A two-level trigger system selects the most interesting proton-proton collision events for use in physics analysis. A more detailed description of the CMS detector can be found elsewhere [6].

3 Event simulation

The analysis makes use of simulated samples of $t\bar{t}$ events as well as other processes that result in $\tau$s in the final state. These samples are used to design the event selection, to calculate the acceptance to $t\bar{t}$ events, and to estimate some of the backgrounds in the analysis.

Signal $t\bar{t}$ events are simulated with the MADGRAPH event generator (v. 4.4.12) [7] with matrix elements corresponding to up to three additional partons, for a top quark mass of $172.5 \text{ GeV}/c^2$. The number of expected $t\bar{t}$ events is estimated with the next-to-next-leading order (NNLO) expected standard model (SM) value of $165^{+16}_{-13}(\text{scale})^{+7}_{-7}(\text{PDF})$ pb [8, 9], where the first uncertainty is due to renormalization and factorization scales, and the second is due to the parton distribution function (PDF) uncertainty. This cross section is used for illustrative purposes to normalize the $t\bar{t} e\nu$ and $\mu\tau$ expectations discussed in Section 4. The generated events are subsequently processed with PYTHIA (v. 6.422) [10] to provide the showering of the partons, and to perform the matching of the soft radiation with the contributions from direct emissions accounted for in the matrix-element calculations. The $Z2$ tune [11] is used with the CTEQ6L PDFs [12]. The $\tau$ decays are simulated with TAUOLA (v. 27.121.5) [13] which correctly accounts for the $\tau$ lepton polarization in describing the decay kinematics. The CMS detector response is simulated with GEANT4 (v. 9.3 Rev01) [14].

The background samples used in the measurement of the cross section are simulated with MADGRAPH and PYTHIA. The $W$-jet samples include only the leptonic decays of the $W$ boson, and are normalized to the inclusive next-to-next-leading-order (NNLO) cross section of $31.3 \pm 1.6$ nb, calculated with the FEWZ (Fully Exclusive W and Z boson) production program [15]. Drell–Yan (DY) pair production of charged leptons in the final state is generated with MADGRAPH for dilepton invariant masses above $50 \text{ GeV}/c^2$, and is normalized to a cross section of $3.04^{+0.13}_{-0.12}$ nb, computed with FEWZ. The DY events with masses between 10 and $50 \text{ GeV}/c^2$ are generated with MADGRAPH with a cross section (with a k-factor to correct for NLO) of $12.4$ nb.

The electroweak production of single top quarks is considered as a background process, and is simulated with POWHEG [16]. The $t$-channel single top quark NLO cross section is $\sigma_{t-\text{ch.}} = 64.6^{+3.2}_{-3.3}$ pb from MCFM [17–20]. The single top quark associated production ($tW$) cross section amounts to $\sigma_{tW} = 15.7 \pm 1.2$ pb [21]. The $s$-channel single top quark next-to-next-leading-log (NNLL) cross section is determined as $\sigma_{s-\text{ch.}} = 4.6 \pm 0.06$ pb [22]. Finally, the production of $WW$, $WZ$, and $ZZ$ pairs, with inclusive cross sections of $43.0 \pm 1.5$ pb, $18.8 \pm 0.7$ pb, and $7.4 \pm 0.2$ pb, respectively (all calculated at the NLO with MCFM), are simulated with PYTHIA.

4 Event selection

The signal topology is defined by the presence of two b jets from the top quark decays, one $W$ boson decaying leptonically into $e\nu$ or $\mu\nu$, and a second $W$ boson decaying into $\tau\nu$. In the event, all objects are reconstructed with a particle-flow (PF) algorithm [23]. The PF algorithm combines the information from all sub-detectors to identify and reconstruct all types of particles produced in the collision, namely charged hadrons, photons, neutral hadrons, muons, and electrons. The resulting list of particles is used to construct a variety of higher-level objects.
and observables such as jets, missing transverse energy ($E_T^{\text{miss}}$), leptons (including $\tau$s), photons, b-tagging discriminators, and isolation variables. The missing transverse energy $E_T^{\text{miss}}$ is computed as the absolute value of the vectorial sum of the transverse momenta of all reconstructed particles in the event.

Electron or muon candidates are required to be isolated relative to other activity in the event. The relative isolation is based on PF objects and defined as $I_{\text{rel}} = (E_{\text{ch}} + E_{\text{nh}} + E_{\text{ph}})/p_T$ < 0.5, where $E_{\text{ch}}$ is the transverse energy deposited by charged hadrons in a cone of radius $\Delta R = 0.3$ around the electron or muon track, and $E_{\text{nh}}$ and $E_{\text{ph}}$ are the respective transverse energies of the neutral hadrons and photons. The electron (muon) candidate is considered to be non-isolated and is rejected if $I_{\text{rel}} > 0.1$ (> 0.2). Jets are reconstructed with the anti-$k_T$ [24] [25] jet algorithm with a distance parameter $R = 0.5$.

Hadronic $\tau$ decays are reconstructed with the Hadron Plus Strips (HPS) algorithm [26]. The identification process starts with the clustering of all PF particles into jets with the anti-$k_T$ algorithm with a distance parameter $R = 0.5$. For each jet, a charged hadron is combined with other nearby charged hadrons or photons to identify the decay modes. The identification of $\pi^0$ mesons is enhanced by clustering electrons and photons in “strips” along the bending plane to take into account possible broadening of calorimeter signatures by early showering photons. Then, strips and charged hadrons are combined to reconstruct the following combinations: single hadron, hadron plus a strip, hadron plus two strips and three hadrons. To reduce the contamination from quark and gluon jets, the $\tau_h$ candidate isolation is calculated in a cone of $\Delta R = 0.5$ around the reconstructed $\tau$-momentum direction. It is required that there be no charged hadrons with $p_T > 1.0 \text{ GeV/c}$ and no photons with $E_T > 1.5 \text{ GeV}$ in the isolation cone, other than the $\tau$ decay particles. Additional requirements are applied to discriminate genuine $\tau$ leptons from prompt electrons and muons. The $\tau$ charge is taken as the sum of the charge of the charged hadrons (prongs) in the signal cone. The $\tau$ reconstruction efficiency of this algorithm is estimated to be approximately 37% (i.e. “medium” working point in Ref. [26]) for $p_T^{\tau_h} > 20 \text{ GeV/c}$, and it is measured in a sample enriched in $Z \rightarrow \tau\tau \rightarrow \mu\tau_h$ events with a “tag-and-probe” technique [27]. The “medium” working point corresponds to a probability of approximately 0.5% for generic hadronic jets to be misidentified as $\tau_h$.

For the $e\tau_h$ final state, events are triggered by the combined electron plus two jets plus $H_T^{\text{miss}}$ trigger ($e + \text{dijet} + H_T^{\text{miss}}$), where $H_T^{\text{miss}}$ is the absolute value of the vectorial sum of all jet momenta in the plane transverse to the beams. The thresholds for the electron and for $H_T^{\text{miss}}$ are respectively $p_T > 17–27 \text{ GeV/c}$ and $H_T^{\text{miss}} > 15–20 \text{ GeV}$ depending on the data-taking period, and the $p_T$ thresholds for the two jets are $30 \text{ GeV/c}$ and $25 \text{ GeV/c}$. The trigger efficiency is estimated from a suite of triggers with lower thresholds assuming the factorization $\epsilon_{\text{trig}} = \epsilon_e \times \epsilon_{\text{jets}} \times \epsilon_{\text{MHT}}$, where $\epsilon_e$ is the electron efficiency, $\epsilon_{\text{jets}}$ is the efficiency for selecting two jets, and $\epsilon_{\text{MHT}}$ is the efficiency for $H_T^{\text{miss}}$. The data-to-simulation scale factor for the electron trigger efficiency is $0.99 \pm 0.01$. The efficiencies $\epsilon_{\text{MHT}} = 1.00^{+0.00}_{-0.01}$ and $\epsilon_{\text{jets}}$, which is parameterized as a function of jet $p_T$, are estimated from data. In the $\mu\tau_h$ final state, data are collected with a trigger requiring at least one isolated muon with threshold of $p_T > 17(24) \text{ GeV/c}$, for the earlier (later) part of the data sample; the data-to-simulation scale factor for the trigger efficiency is $0.99 \pm 0.01$.

Events are selected by requiring one isolated electron (muon) with transverse momentum $p_T > 35(30) \text{ GeV/c}$ and $|\eta| < 2.5(2.1)$, at least two jets with $p_T > 35(30) \text{ GeV/c}$ and $|\eta| < 2.4$, missing transverse energy $E_T^{\text{miss}} > 45(40) \text{ GeV}$ and one hadronically decaying $\tau$ lepton ($\tau$ jet) with $p_T > 20 \text{ GeV/c}$ and $|\eta| < 2.4$. Electrons or muons are required to be separated from any jet in the $(\eta, \phi)$ plane by a distance $\Delta R > 0.3$. Events with any additional loosely isolated ($I_{\text{rel}} < 0.2$)
electron (muon) of $p_T > 15 \ (10) \ GeV/c$ are rejected.

The $\tau$ jet and the lepton are required to have electric charges of opposite sign (OS). At least one of the jets is required to be identified as originating from $b$ quark hadronization ($b$ tagged). The $b$-tagging algorithm used (“TCHEL” in Ref. [28]) is based on sorting tracks according to their impact parameter significance ($S_{IP}$); the $S_{IP}$ value of the second track is used as the discriminator. The $b$-tagging efficiency of this algorithm is $76 \pm 1\%$, measured in a sample of events enriched with jets from semileptonic $b$-hadron decays. The misidentification rate of light-flavor jets is obtained from inclusive jet studies and is measured to be $13 \pm 3\%$ for jets in the $p_T$ range relevant to this analysis. After the final event selection, a fraction of approximately $12\%$ of the generated $t\bar{t}$ tau dilepton events within the geometric and kinematic fiducial region are selected.

The $b$-tagged jet multiplicity for the $e\tau_h$ and $\mu\tau_h$ final states is shown in Fig. 1 for the events in the pre-selected sample, i.e. one isolated electron (muon), missing transverse energy above $45 \ (40) \ GeV$, and at least three jets, two jets with $p_T > 35 \ (30) \ GeV/c$ and one jet with $p_T > 20 \ GeV/c$. The observed numbers of events are consistent with the expected numbers of signal and background events obtained from the simulation. The distributions of the $E_{miss}^T$ and of

Figure 1: The $b$-tagged jet multiplicity for pre-selected events with one electron (left) or muon (right). Distributions obtained from data (points) are compared with simulation. The simulated contributions are normalized to the SM predicted values. The hatched area shows the total systematic uncertainty.

the transverse momentum of the $\tau$ lepton after the final event selection are shown in Fig. 2 and in Fig. 3, respectively, for both the $e\tau_h$ and $\mu\tau_h$ final states. The distributions show good agreement between the observed numbers of events and the expected numbers of signal and background events obtained from the simulation. The top quark mass is reconstructed with the KINb [29] algorithm (Fig. 4), treating the additional neutrino in the $\tau$ decay as a contribution to the $E_{miss}^T$. Numerical solutions for the kinematic reconstruction of $t\bar{t}$ decays with two charged leptons in the final state are found for each event. The jet transverse momentum, the $E_{miss}^T$ direction, and the longitudinal momentum of the $t\bar{t}$ system are varied independently within their measured resolutions to scan the kinematic phase space compatible with the $t\bar{t}$ system. Solutions with the lowest invariant mass of the $t\bar{t}$ system are accepted if the difference between the two top quark masses is less than
Figure 2: $E_T^{\text{miss}}$ distribution after the full event selection for the $e\tau_h$ (left) and $\mu\tau_h$ (right) final states. Distributions obtained from data (points) are compared with simulation. The last bin includes the overflow. The simulated contributions are normalized to the SM predicted values. The hatched area shows the total systematic uncertainty.

Figure 3: The $\tau_p T$ distribution after the full event selection for the $e\tau_h$ (left) and $\mu\tau_h$ (right) final states. Distributions obtained from data (points) are compared with simulation. The simulated contributions are normalized to the SM predicted values. The hatched area shows the total systematic uncertainty.
3 GeV/c². The reconstructed top quark mass in Fig. 4 shows that the kinematic properties of the selected events are statistically compatible with predictions based on a top quark mass of 172.5 GeV/c², indicating the consistency of the selected sample in data with the sum of top quark pair production plus the background.

![Figure 4: Reconstructed top quark mass m_{top} distribution for the \( \tau \) dilepton candidate events after the full event selection, in the e\( \tau \)h (left) and \( \mu \tau \)h (right) final states. Distributions obtained from data (points) are compared with simulation. The hatched area shows the total systematic uncertainty.](image)

5 Background estimate

The background comes from two categories of events, the “misreconstructed \( \tau \)” background \( (N_{\text{misid}}) \) which is estimated from data, and the “other” background \( (N_{\text{other}}) \) which is estimated from simulation.

The main background (misreconstructed \( \tau \)) comes from events with one lepton (electron or muon), \( E_T^{\text{miss}} \) requirement and three or more jets, where one jet is misidentified as a \( \tau \) jet. The dominant contribution to this background is from events where one W boson is produced in association with jets, and from \( t\bar{t} \rightarrow W^+bW^−b \rightarrow \ellνbq̄q\bar{q} \) events. In order to estimate this background from data, the probability that a jet is misidentified as a \( \tau \) jet \( w_{\text{jet}}(\rightarrow \tau_h) \) as a function of the jet \( p_T, \eta \), and jet width \( R_{\text{jet}} \) is determined, then applied to every jet in the preselected sample with one b-tagged jet. The quantity \( R_{\text{jet}} \) is defined as \( \sqrt{\sigma_{\eta\eta}^2 + \sigma_{\phi\phi}^2} \), where \( \sigma_{\eta\eta} \) \( (\sigma_{\phi\phi}) \) expresses the extent in \( \eta \) \( (\phi) \) of the jet cluster. Thus the expected number of background is obtained as:

\[
N_{\text{misid}} = \sum_i^N \sum_j^n w_i^j(\text{jet} \rightarrow \tau) - N_{\text{other}},
\]

where \( j \) is the jet index of the event \( i \). The quantity \( N_{\text{other}} \) is the small \((\approx 18\%)\) contamination of other contributions to the misidentified \( \tau \) background, which is estimated from simulation. This is mostly due to the presence of genuine \( \tau \) jets in the \( W+ \geq 3 \) jet sample. In order to
estimate this contribution, the same procedure described above is applied to simulated events of $Z/\gamma^* \rightarrow \tau\tau$, single top quark production, diboson production, and the part of the SM $t\bar{t}$ background not included in the misidentified $\tau$ background estimate.

In order to estimate the misidentification probability, the hadronic multijet events are selected from a sample triggered by at least one jet with $p_T > 30\text{ GeV}/c$ and $|\eta| < 2.4$. The triggering jet is removed from the misidentification rate calculation in order to avoid a trigger bias. The $W+ \geq 1$ jet events are selected by requiring only one isolated muon with $p_T > 20\text{ GeV}/c$ and $|\eta| < 2.1$, and at least one jet with $p_T > 20\text{ GeV}/c$ and $|\eta| < 2.4$. The probability $w_{\text{jet} \rightarrow \tau_{h}}$ is evaluated from all jets in a sample enriched in QCD multijet events ($w_{\text{QCD}}$), and all jets in another sample enriched in $W+\geq 1$ jet events ($w_{W+\text{jets}}$). The probability that a jet is misidentified as a $\tau$ jet as a function of jet $p_T$, $\eta$ and $R_{\text{jet}}$ is compared between simulated events (Z2 tune [11]) and data, and a good agreement is found.

Jets in QCD multijet events are mainly gluon jets ($\simeq 75\%$ obtained from simulation), while the jets in $W+ \geq 1$ jet events are predominantly quark jets ($\simeq 64\%$ obtained from simulation), where $w_{\text{QCD}} < w_{W+\text{jets}}$. Since the quark and gluon jet composition in $\ell + E_T^{\text{miss}} + \geq 3$ jet events lies between two categories of events, QCD multijet and $W+ \geq 1$ jet events, the $N_{\text{misid}}$ value is under- (over-) estimated by applying the $w_{\text{QCD}}$ ($w_{W+\text{jets}}$) probability. Thus, the $N_{\text{misid}}$ and its systematic uncertainty are estimated as in the following:

$$N_{\text{misid}} = \sum_i \sum_j w_{W+\text{jets},i} + \sum_i \sum_j w_{\text{QCD},i}$$

$$\Delta N_{\text{misid}} = \frac{1}{2} \sum_i \sum_j w_{W+\text{jets},i} - \sum_i \sum_j w_{\text{QCD},i}$$

The contribution of $N_{\text{other}}$ described earlier is subtracted from Eq.(2). Finally, the efficiency $\epsilon_{\text{OS}}$ of the OS requirement obtained from simulated events is applied to obtain the misidentified $\tau$ background $N_{\text{OS misid}} = \epsilon_{\text{OS}} \times N_{\text{misid}}$. The estimated efficiencies for the $e\tau_h$ and $\mu\tau_h$ final states are $\epsilon_{\text{OS}} = 0.72 \pm 0.09\text{(stat.)} \pm 0.02\text{(syst.)}$ and $\epsilon_{\text{OS}} = 0.69 \pm 0.07\text{(stat.)} \pm 0.03\text{(syst.)}$, respectively, where the statistical uncertainty comes from the limited number of simulated events, and the systematic uncertainty is taken as half of the difference of the efficiency estimated from $W+\text{jets}$ and lepton+jet $t\bar{t}$ simulated events.

Other backgrounds in this analysis are $Z/\gamma^* \rightarrow \tau\tau$, single top quark production, diboson production, and the part of the SM $t\bar{t}$ background not included in the misidentified $\tau$ background, and are estimated from simulation. Events from $Z \rightarrow ee, \mu\mu$ are also taken into account because they contain misidentified $\tau$ jets, where the misidentified $\tau$ lepton can originate from an electron or muon misidentified as a $\tau$ jet. The statistical uncertainties are due to the limited number of simulated events.

### 6 Systematic uncertainties

Different sources of systematic uncertainties on the measurement of the cross section due to signal selection efficiencies and backgrounds are considered, as shown in Table [1]. The main sources of systematic uncertainties are due to $\tau$ identification, b-tagging and mistagging efficiencies, jet energy scale (JES), jet energy resolution (JER), $E_T^{\text{miss}}$ scale, and to the estimate of the
misreconstructed $\tau$ background (from data). The systematic uncertainties for the determination of the misidentified $\tau$ background are discussed in detail in Section 5.

The uncertainty on the $\tau$ jet identification includes contributions from $\tau$ identification efficiency and $\ell \rightarrow \tau_h$ ($\ell = e, \mu$) misidentification. The uncertainty on $\tau$ identification efficiency is estimated to be 6\% (from an updated measurement with respect to [26]), and it includes the uncertainty on charge determination which is estimated to be smaller than 1\%. The uncertainty on the $\ell \rightarrow \tau_h$ misidentification rate is estimated as the difference of $\tau$ misidentification rate measured in data and in simulated events, and is taken to be 15\% [26]. These uncertainties are applied to the simulated $Z \rightarrow ee, \mu\mu$, and $t\bar{t}$ dilepton background events.

The uncertainties related to b-tagging and mistagging efficiencies are estimated from a variety of control samples enriched in b quarks, and the data-to-simulation scale factors amount to $0.95 \pm 0.06$ and $1.11 \pm 0.11$, respectively [28].

The uncertainties on JES, JER, and $E_T^{\text{miss}}$ scale are estimated according to the prescription described in Ref. [30]. These uncertainties also take into account the uncertainty due to the JES dependence on the parton flavor. The uncertainty on JES is evaluated as a function of jet $p_T$ and jet $\eta$. The JES and JER uncertainties are propagated in order to estimate the uncertainty of the $E_T^{\text{miss}}$ scale. An additional 10\% uncertainty on the contribution to $E_T^{\text{miss}}$ coming from the energy of particles that are not clustered into jets is also taken into account.

The theoretical uncertainty on the signal acceptance is estimated to be 4\% [29]. It accounts for variations in the renormalization and factorization scales (2\%), $\tau$ lepton and hadron decay modelling (2\%), top quark mass (1.6\%), leptonic branching fractions of the W boson (1.7\%), and jet and $E_T^{\text{miss}}$ modelling (1\%). Uncertainties on the PDFs are found to be negligible.

The uncertainty on the integrated luminosity is estimated to be 2.2\% [31]. The number of interactions per bunch crossing in the data (pile-up) is estimated from the measured luminosity in each bunch crossing times an average total inelastic cross section (with an uncertainty of 6.5\%). The estimated number of interactions has a total uncertainty of approximately 8\%, which corresponds to an overall uncertainty of the pile-up distribution. The mean of pile-up in the data sample is about 5–6 interactions, with the uncertainty estimated conservatively by shifting the overall mean up or down by 0.6 interactions.

The lepton trigger, identification, and isolation efficiencies are measured with the “tag-and-probe” method in events containing a lepton pair of invariant mass between 76 and 106 GeV/$c^2$. Within the precision of the present measurement, the scale factors between efficiencies measured in data and in simulation are estimated to be equal to one. The combined uncertainty on the electron (muon) trigger, identification and isolation efficiencies is 3% (2\%).

Theoretical uncertainties on the cross sections of single top quark, diboson, and DY processes are estimated as in Ref. [32]. The uncertainties include the scale and PDF uncertainties on theoretical cross sections.

### 7 Cross section measurement

The number of events expected from the backgrounds, the number of signal events from $t\bar{t}$, and the number of observed events after all selection cuts are summarized in Table 2. The statistical and systematic uncertainties are also shown.

The $t\bar{t}$ production cross section measured from tau dilepton events is:
Table 1: List of systematic uncertainties (in %) on the cross section measurement. The Best Linear Unbiased Estimation method [33] is used to combine the cross section measurements in the $e\tau_h$ and $\mu\tau_h$ channels, with the corresponding weights. Systematic uncertainties common to the two channels are assumed to be 100% correlated.

| Source                                      | Uncertainty [%] | Combination [%] |
|---------------------------------------------|-----------------|-----------------|
| $\tau$ misidentification background        | 12.6            | 9.8             |
| $\tau$ jet identification                   | 6.4             | 6.3             |
| b-jet tagging, misidentification            | 5.3             | 5.3             |
| jet energy scale, jet energy resolution, $E_T^{\text{miss}}$ | 5.1             | 6.2             |
| theoretical uncertainty on signal efficiency| 4.0             | 4.0             |
| pile-up modelling                           | 2.3             | 2.3             |
| electron selection                          | 3.1             | 0               |
| muon selection                              | 0               | 2.0             |
| cross section of MC backgrounds             | 1.6             | 1.4             |
| luminosity                                  | 2.2             | 2.2             |
| weight                                      | 0.38            | 0.62            |
| $\chi^2/N_{\text{dof}} = 2.381/1$          |                 | (p-value = 0.198) |

Table 2: Number of expected events for signal and backgrounds. The background from “misidentified $\tau$” is estimated from data, while the other backgrounds are estimated from simulation. Statistical and systematic uncertainties are shown.

| Source                                      | $N_{\text{events}}$ (± stat. ± syst.) |
|---------------------------------------------|----------------------------------------|
| $t\bar{t} \rightarrow WbWb \rightarrow \ell\nu b \tau\nu b$ | $99.9 \pm 3.0 \pm 10.1$ | $162.0 \pm 4.0 \pm 16.7$ |
| misidentified $\tau$                        | $54.3 \pm 6.4 \pm 8.1$ | $88.5 \pm 8.9 \pm 10.8$ |
| $Z/\gamma^* \rightarrow \tau\tau$          | $16.6 \pm 3.3 \pm 2.9$ | $25.8 \pm 4.3 \pm 6.1$ |
| $t\bar{t} \rightarrow WbWb \rightarrow \ell\nu b \ell\nu b$ | $9.0 \pm 0.9 \pm 1.7$ | $13.3 \pm 1.2 \pm 2.5$ |
| $Z/\gamma^* \rightarrow ee, \mu\mu$       | $4.8 \pm 1.8 \pm 1.3$ | $0.7 \pm 0.7 \pm 0.7$ |
| Single top                                  | $7.9 \pm 0.4 \pm 1.1$ | $13.5 \pm 0.5 \pm 1.9$ |
| VV                                          | $1.3 \pm 0.1 \pm 0.2$ | $2.0 \pm 0.2 \pm 0.3$ |
| Total expected                              | $193.9 \pm 4.9 \pm 18.0$ | $306.1 \pm 6.1 \pm 27.9$ |
| Data                                        | 176           | 288             |
\begin{equation}
\sigma_{tt} = \frac{N - B}{L \cdot A_{\text{tot}}},
\end{equation}

where \(N\) is the number of observed candidate events, \(B\) is the estimate of the background, \(L\) is the integrated luminosity. The total acceptance \(A_{\text{tot}}\) is the product of all branching fractions, geometrical and kinematical acceptance, efficiencies for trigger, lepton identification and the overall reconstruction efficiency, and it is evaluated with respect to the inclusive \(t\bar{t}\) sample. After the OS requirement:

\begin{align*}
A_{\text{tot}}(e\tau_h) &= [0.0304 \pm 0.0009 (\text{stat.}) \pm 0.0031 (\text{syst.})]\%; \\
A_{\text{tot}}(\mu\tau_h) &= [0.0443 \pm 0.0011 (\text{stat.}) \pm 0.0047 (\text{syst.})]\%.
\end{align*}

The statistical uncertainties are due to the limited number of simulated events and the systematic uncertainties are estimated by varying all sources of systematics in Table 1 affecting the signal (i.e., all uncertainties except for the luminosity and for the background). All systematic and statistical uncertainties in Table 2 are propagated from Eq. (4) to the final cross section measurement. The measured \(t\bar{t}\) cross section is:

\begin{align*}
\sigma_{tt}(e\tau_h) &= 136 \pm 23 (\text{stat.}) \pm 3 (\text{lumi.}) \text{ pb}; \\
\sigma_{tt}(\mu\tau_h) &= 147 \pm 18 (\text{stat.}) \pm 3 (\text{lumi.}) \text{ pb}.
\end{align*}

The Best Linear Unbiased Estimation method [33] is used to combine the cross section measurements in the \(e\tau_h\) and \(\mu\tau_h\) channels with the associated uncertainties and correlation factors. Systematic uncertainties common to the two channels are assumed to be 100\% correlated. The combined result is

\begin{equation}
\sigma_{tt} = 143 \pm 14 (\text{stat.}) \pm 3 (\text{lumi.}) \text{ pb},
\end{equation}

in agreement with the measured values in the dilepton [29] and lepton+jet [32, 34] final states, and with the SM expectations in the approximate NNLO calculation of 163^{+7}_{-5} (\text{scale}) \pm 9 (\text{PDF}) \text{ pb} [35].

8 Summary

We present the first measurement of the \(t\bar{t}\) production cross section in the tau dilepton channel \(t\bar{t} \rightarrow (\ell \nu_{\ell})(\tau_h \nu_{\tau})b\bar{b}, (\ell = e, \mu)\) with data samples corresponding to an integrated luminosity of 2.0–2.2 fb\(^{-1}\) collected in proton-proton collisions at \(\sqrt{s} = 7\) TeV. Events are selected by requiring the presence of one electron or muon, two or more jets (at least one jet is b tagged), missing transverse energy, and one hadronically decaying \(\tau\) lepton. The largest background contributions come from events where one W boson is produced in association with jets, and from \(t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow \ell\nu_b q\bar{q}'\bar{b}\) events, where one jet is misidentified as the \(\tau\), and from \(Z \rightarrow \tau\tau\) events. The measured cross section is \(\sigma_{tt} = 143 \pm 14 (\text{stat.}) \pm 3 (\text{lumi.}) \text{ pb}\), in agreement with SM expectations.
Acknowledgments

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); MoER, SF0690030s09 and ERDF (Estonia); Academy of Finland, MEC, 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); MSI (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MON, RosAtom, RAS and RFBR (Russia); MSTD (Serbia); MICINN and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); TUBITAK and TAEK (Turkey); STFC (United Kingdom); DOE and NSF (USA). Individuals have received support from the Marie-Curie programme and the European Research Council (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l’Industrie et dans l’Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Council of Science and Industrial Research, India; and the HOMING PLUS programme of Foundation for Polish Science, cofinanced from European Union, Regional Development Fund.

References

[1] J. F. Gunion, H. E. Haber, G. L. Kane et al., “The Higgs Hunter’s Guide”. Frontiers in Physics. Addison-Wesley, 1990.

[2] A. Djouadi, “The anatomy of electro-weak symmetry breaking Tome II: The Higgs bosons in the minimal supersymmetric model”, Phys. Rept. 459 (2008) 1, arXiv:hep-ph/0503173, doi:10.1016/j.physrep.2007.10.005

[3] CDF Collaboration, “The $\mu\tau$ and $e\tau$ decays of top quark pairs produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV”, Phys. Rev. Lett. 79 (1997) 3585, arXiv:hep-ex/9704007, doi:10.1103/PhysRevLett.79.3585

[4] CDF Collaboration, “A search for $t \rightarrow \tau q\bar{q}$ in $t\bar{t}$ production”, Phys. Lett. B 639 (2006) 172, arXiv:hep-ex/0510063, doi:10.1016/j.physletb.2006.06.030

[5] D0 Collaboration, “Measurement of the $t\bar{t}$ production cross section and top quark mass extraction using dilepton events in $p\bar{p}$ collisions”, Phys. Lett. B 679 (2009) 177, arXiv:0901.2137, doi:10.1016/j.physletb.2009.07.032

[6] CMS Collaboration, “The CMS experiment at the CERN LHC”, JINST 3 (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

[7] J. Alwall et al., “MadGraph/MadEvent v4: The New Web Generation”, JHEP 09 (2007) 028, arXiv:0706.2334, doi:10.1088/1126-6708/2007/09/028

[8] S. Moch and P. Uwer, “Heavy-quark pair production at two loops in QCD”, Nucl. Phys. Proc. Suppl. 183 (2008) 75, arXiv:0807.2794, doi:10.1016/j.nuclphysbps.2008.09.085
[9] U. Langenfeld, S. Moch, and P. Uwer, “New results for $t\bar{t}$ production at hadron colliders”, (2009). [arXiv:0907.2527]

[10] T. Sjöstrand, S. Mrenna, and P. Z. Skands, “PYTHIA 6.4 Physics and Manual”, JHEP 05 (2006) 026, [arXiv:hep-ph/0603175 doi:10.1088/1126-6708/2006/05/026]

[11] R. Field, “Early LHC Underlying Event Data - Findings and Surprises”, in Proceedings of the Hadron Collider Physics Symposium. 2010, [arXiv:1010.3558]

[12] P. M. Nadolsky, H.-L. Lai, Q.-H. Cao et al., “Implications of CTEQ global analysis for collider observables”, Phys. Rev. D 78 (2008) 013004, [arXiv:0802.0007, doi:10.1103/PhysRevD.78.013004]

[13] N. Davidson, G. Nanava, T. Przedzinski et al., “Universal Interface of TAUOLA Technical and Physics Documentation”, (2010). [arXiv:1002.0543]

[14] J. Allison et al., “Geant4 developments and applications”, IEEE Trans. Nucl. Sci. 53 (2006) 270. doi:10.1109/TNS.2006.869826

[15] K. Melnikov and F. Petriello, “Electroweak gauge boson production at hadron colliders through $O(\alpha_s^2)$”, Phys. Rev. D 74 (2006) 114017, [arXiv:hep-ph/0609070]

[16] S. Frixione, P. Nason, and C. Oleari, “Matching NLO QCD computations with parton shower simulations: the POWHEG method”, JHEP 11 (2007) 070, [arXiv:0709.2092, doi:10.1088/1126-6708/2007/11/070]

[17] J. M. Campbell and R. K. Ellis, “MCFM for the Tevatron and the LHC”, Nucl. Phys. Proc. Suppl. 205-206 (2010) 10, [arXiv:1007.3492, doi:10.1016/j.nuclphysbps.2010.08.011]

[18] J. M. Campbell, R. Frederix, F. Maltoni et al., “Next-to-Leading-Order Predictions for t-Channel Single-Top Production at Hadron Colliders”, Phys. Rev. Lett. 102 (2009) 182003, [arXiv:0903.0005 doi:10.1103/PhysRevLett.102.182003]

[19] J. M. Campbell and F. Tramontano, “Next-to-leading order corrections to $W t$ production and decay”, Nucl. Phys. B 726 (2005) 109, [arXiv:hep-ph/0506289, doi:10.1016/j.nuclphysb.2005.08.015]

[20] J. M. Campbell, R. K. Ellis, and F. Tramontano, “Single top production and decay at next-to-leading order”, Phys. Rev. D 70 (2004) 094012, [arXiv:hep-ph/0408158, doi:10.1103/PhysRevD.70.094012]

[21] N. Kidonakis, “Two-loop soft anomalous dimensions for single top quark associated production with a $W^-$ or $H^-$”, Phys. Rev. D 82 (2010) 054018, [arXiv:1005.4451, doi:10.1103/PhysRevD.82.054018]

[22] N. Kidonakis, “Next-to-next-to-leading logarithm resummation for s-channel single top quark production”, Phys. Rev. D 81 (2010) 054028, [arXiv:1001.5034, doi:10.1103/PhysRevD.81.054028]

[23] CMS Collaboration, “Particle–Flow Event Reconstruction in CMS and Performance for Jets, Taus, and $E_{\text{T}}^{\text{miss}}$”, CMS Physics Analysis Summary CMS-PAS-PFT-09-001, (2009).
[24] M. Cacciari, G. P. Salam, and G. Soyez, “The anti-$k_T$ jet clustering algorithm”, JHEP 04 (2008) 063, arXiv:0802.1189 doi:10.1088/1126-6708/2008/04/063

[25] M. Cacciari and G. P. Salam, “Dispelling the $N^3$ myth for the $k_T$ jet-finder”, Phys. Lett. B 641 (2006) 57, arXiv:hep-ph/0512210 doi:10.1016/j.physletb.2006.08.037

[26] CMS Collaboration, “Performance of tau lepton reconstruction and identification in CMS”, JINST 7 (2012) P01001. doi:10.1088/1748-0221/7/01/P01001

[27] CMS Collaboration, “Measurement of the inclusive W and Z production cross sections in pp collisions at $\sqrt{s} = 7$ TeV”, JHEP 1110 (2011) 132, arXiv:1107.4789 doi:10.1007/JHEP10(2011)132

[28] CMS Collaboration, “Performance of b-jet identification in CMS”, CMS Physics Analysis Summary CMS-PAS-BTV-11-001, (2011).

[29] CMS Collaboration, “Measurement of the $tt$ production cross section and the top quark mass in the dilepton channel in pp collisions at $\sqrt{s} = 7$ TeV”, JHEP 07 (2011) 049, arXiv:1105.5661 doi:10.1007/JHEP07(2011)049

[30] CMS Collaboration, “Determination of jet energy calibration and transverse momentum resolution in CMS”, JINST 6 (2011) P11002, arXiv:1107.4277 doi:10.1088/1748-0221/6/11/P11002

[31] CMS Collaboration, “Absolute calibration of the luminosity measurement at CMS: Winter 2012 update”, CMS Physics Analysis Summary PAS-SMP-12-008, (2012).

[32] CMS Collaboration, “Measurement of the $tt$ production cross section in pp collisions at $\sqrt{s} = 7$ TeV using the kinematic properties of events with leptons and jets”, Eur. Phys. J. C 71 (2011) 1721, arXiv:1106.0902 doi:10.1140/epjc/s10052-011-1721-3

[33] L. Lyons, D. Gibaut, and P. Clifford, “How to combine correlated estimates of a single physical quantity”, Nucl. Instrum. Meth. A 270 (1988) 110. doi:10.1016/0168-9002(88)90018-6

[34] CMS Collaboration, “Measurement of the $tt$ pair production cross section at $\sqrt{s} = 7$ TeV using b-quark jet identification techniques in lepton+jet events”, Phys. Rev. D 84 (2011) 092004, arXiv:1108.3773 doi:10.1103/PhysRevD.84.092004

[35] N. Kidonakis, “Next-to-next-to-leading soft-gluon corrections for the top quark cross section and transverse momentum distribution”, Phys. Rev. D 82 (2010) 114030, arXiv:1009.4935 doi:10.1103/PhysRevD.82.114030
A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
S. Chatrchyan, V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiedyophysik der OeAW, Wien, Austria
W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan, M. Friedl, R. Frühwirth, V.M. Ghete, J. Hammer, N. Hörmann, J. Hrubec, M. Jeitler, W. Kiesenhofer, M. Krammer, D. Liko, I. Mikulec, M. Pernicka, B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, F. Teischinger, P. Wagner, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz

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

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

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

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

Ghent University, Gent, 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, L. Vanelderen, P. Verwilligen, S. Walsh, E. Yazgan, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Basegmez, G. Bruno, L. Ceard, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco, J. Hollar, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, D. Pagano, A. Pin, K. Piotrzkowski, N. Schul

Université de Mons, Mons, Belgium
N. Beliy, T. Caebers, E. Daubie, G.H. Hammad

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, M. Correa Martins Junior, D. De Jesus Damiao, T. Martins, M.E. Pol, M.H.G. Souza

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, W. Carvalho, A. Custódio, E.M. Da Costa, C. De Oliveira Martins, S. Fonseca De Souza, D. Matos Figueiredo, L. Mundim, H. Nogima, V. Oguri, W.L. Prado Da Silva, A. Santoro, S.M. Silva Do Amaral, L. Soares Jorge, A. Sznajder

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

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
V. Genchev, P. Iaydjiev, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, M. Vutova
University of Sofia, Sofia, Bulgaria
A. Dimitrov, R. Hadjiiska, A. Karadzhinova, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China
J.G. Bian, G.M. Chen, H.S. Chen, C.H. Jiang, D. Liang, S. Liang, X. Meng, J. Tao, J. Wang, J. Wang, X. Wang, Z. Wang, H. Xiao, M. Xu, J. Zang, Z. Zhang

State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China
C. Asawatangtrakuldee, Y. Ban, S. Guo, Y. Guo, W. Li, S. Liu, Y. Mao, S.J. Qian, H. Teng, S. Wang, B. Zhu, W. Zou

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

Technical University of Split, Split, Croatia
N. Godinovic, D. Lelas, R. Plestina, D. Polic, I. Puljak

University of Split, Split, Croatia
Z. Antunovic, M. Dzelalija, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, S. Duric, K. Kadija, J. Luetic, S. Morovic

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

Charles University, Prague, Czech Republic
M. Finger, M. Finger Jr.

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran, S. Elgammal, A. Ellithi Kamel, S. Khalil, M.A. Mahmoud, A. Radi

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

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

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

Lappeenranta University of Technology, Lappeenranta, Finland
K. Banzuzi, A. Korpela, T. Tuuva

Laboratoire d’Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
D. Sillou

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
M. Besancon, S. Choudhury, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malec, L. Millischer, A. Nayak, J. Rander, A. Rosowsky, I. Shreyber, M. Titov
Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj11, C. Broutin, P. Busson, C. Charlot, N. Daci, T. Dahms, L. Dobrzynski, R. Granier de Cassagnac, M. Haguenauer, P. Miné, C. Mironov, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Širois, C. Veelken, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
J.-L. Agram12, J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte12, F. Drouhin12, C. Ferro, J.-C. Fontaine12, D. Gelé, U. Goerlach, P. Juillot, M. Karim12, A.-C. Le Bihan, P. Van Hove

Centre de Calcul de l’Institut National de Physique Nucleaire et de Physique des Particules (IN2P3), Villeurbanne, France
F. Fassi, D. Mercier

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
C. Baty, S. Beauceron, N. Beaupere, M. Bedjidian, O. Bondu, G. Boudoul, D. Boumediene, H. Brun, J. Chasserat, R. Chierici1, D. Contardo, P. Depasse, H. El Mamouni, A. Falkiewicz, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, T. Le Grand, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, S. Tosi, Y. Tschudi, P. Verdier, S. Viret

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze13

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
G. Anagnostou, S. Beranek, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, B. Wittmer, V. Zhukov14

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
M. Ata, J. Caudron, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, T. Klimkovich, D. Klingebiel, P. Kreuzer, D. Lanske1, J. Lingemann, C. Magass, M. Merschmeyer, A. Meyer, M. Olschewski, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier, M. Weber

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

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, J. Behr, W. Behrenhoff, U. Behrens, M. Bergholz15, A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, E. Castro, F. Costanza, D. Dammann, G. Eckerlin, D. Eckstein, G. Flucke, A. Geiser, I. Glushkov, S. Habib, J. Hauk, H. Jung1, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krückner, E. Kuznetsova, W. Lange, W. Lohmann15, B. Lutz, R. Mankel, I. Marfin, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, J. Olzem, H. Perrey, A. Petrukhin, D. Pitzl, A. Raspereza, P.M. Ribeiro Cipriano, C. Riedl, M. Rosin, J. Salfeld-Nebgen, R. Schmidt15, T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, R. Walsh, C. Wissing
University of Hamburg, Hamburg, Germany
C. Autermann, V. Blobel, S. Bobrovskyi, J. Draeger, H. Enderle, J. Erfle, U. Gebbert, M. Görner, T. Hermanns, R.S. Höing, K. Kaschube, G. Kaussen, H. Kirschmann, R. Klanner, J. Lange, B. Mura, F. Nowak, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, M. Seidel, H. Stadie, G. Steinbrück, J. Thomsen

Institut für Experimentelle Kernphysik, Karlsruhe, Germany
C. Barth, J. Berger, T. Chwalek, W. De Boer, A. Dierlamm, M. Feindt, M. Guthoff1, C. Hackstein, F. Hartmann, M. Heinrich, H. Held, K.H. Hoffmann, S. Honc, U. Husemann, I. Katkov14, J.R. Komaragiri, D. Martischi, S. Mueller, Th. Müller, M. Niegel, A. Nürnberg, O. Oberst, A. Oehler, J. Ott, T. Peiffer, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, S. Röcker, C. Saout, A. Scheurer, F.-P. Schilling, M. Schmanau, G. Schott, H.J.Simonis, F.M. Stober, D. Troendle, R. Ulrich, J. Wagner-Kuhrt, T. Weiler, M. Zeise, E.B. Ziebarth

Institute of Nuclear Physics “Demokritos”, Aghia Paraskevi, Greece
G. Daskalakis, T. Geralis, S. Kesisoglou, A. Kyriakidis, D. Loukas, I. Manolakos, A. Markou, C. Markou, C. Mavrommatis, E. Ntomari

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

University of Ioánnina, Ioánnina, Greece
I. Evangelou, C. Foudas1, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
G. Bencze, C. Hajdu1, P. Hidas, D. Horvath16, A. Kapusi, K. Krajcziar17, B. Radics, F. Sikler1, V. Veszpremi, G. Vesztergombi17

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

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

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

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

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

Bhabha Atomic Research Centre, Mumbai, India
A. Abdulsalam, R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, A.K. Mohanty1, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research - EHEP, Mumbai, India
T. Aziz, S. Ganguly, M. Guchait18, A. Gurtu19, M. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research - HECR, Mumbai, India
S. Banerjee, S. Dugad
INFINSezione di Pisa\textsuperscript{a}, Università di Pisa\textsuperscript{b}, Scuola Normale Superiore di Pisa\textsuperscript{c}, Pisa, Italy
P. Azzurri\textsuperscript{a}, A. Bagliesi\textsuperscript{a}, G. Broccolo\textsuperscript{a,c}, T. Boccali\textsuperscript{a}, G. Castaldi\textsuperscript{a}, R.T. D’Agnolo\textsuperscript{a,c}, R. Dell’Orso\textsuperscript{a}, F. Fiori\textsuperscript{a,b}, B. Foà\textsuperscript{a,c}, A. Giassi\textsuperscript{a}, A. Kraan\textsuperscript{a}, F. Ligabue\textsuperscript{a,c}, T. Lomtadze\textsuperscript{a}, L. Martini\textsuperscript{a,28}, A. Messineo\textsuperscript{a,b}, F. Palla\textsuperscript{a}, F. Palmonari\textsuperscript{a}, A. Rizzi\textsuperscript{a,b}, R. Trenchini\textsuperscript{a}, G. Tonelli\textsuperscript{a}, N. Amapane\textsuperscript{a,b}, R. Arcidiacono\textsuperscript{a,c}, S. Argiro\textsuperscript{a,b}, M. Arneodo\textsuperscript{a,c}, C. Biino\textsuperscript{a}, C. Botta\textsuperscript{a,b}, N. Cartiglia\textsuperscript{a}, R. Castello\textsuperscript{a,b}, M. Costa\textsuperscript{a,b}, N. Demaria\textsuperscript{a}, A. Graziano\textsuperscript{a,b}, C. Mariotti\textsuperscript{a,1}, S. Maselli\textsuperscript{a}, E. Migliore\textsuperscript{a,b}, V. Monaco\textsuperscript{a,b}, M. Musich\textsuperscript{a,1}, M.M. Obertino\textsuperscript{a,c}, N. Pastrone\textsuperscript{a}, M. Pelliccioni\textsuperscript{a}, A. Potenza\textsuperscript{a,b}, A. Romero\textsuperscript{a,b}, M. Ruspa\textsuperscript{a,c}, R. Sacchi\textsuperscript{a,b}, V. Sola\textsuperscript{a,b}, A. Staiano\textsuperscript{a}, A. Vilela Pereira\textsuperscript{a}

INFINSezione di Trieste\textsuperscript{a}, Università di Trieste\textsuperscript{b}, Trieste, Italy
S. Belforte\textsuperscript{a}, F. Cossutti\textsuperscript{a}, G. Della Ricca\textsuperscript{a,b}, B. Gobbo\textsuperscript{a}, M. Marone\textsuperscript{a,b,1}, D. Montanino\textsuperscript{a,b,1}, A. Penzo\textsuperscript{a}, A. Schizzi\textsuperscript{a,b}

Kangwon National University, Chunchon, Korea
S.G. Heo, T.Y. Kim, S.K. Nam

Kyungpook National University, Daegu, Korea
S. Chang, J. Chung, D.H. Kim, G.N. Kim, D.J. Kong, H. Park, S.R. Ro, D.C. Son

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
J.Y. Kim, Zero J. Kim, S. Song

Konkuk University, Seoul, Korea
H.Y. Jo

Korea University, Seoul, Korea
S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park, E. Seo

University of Seoul, Seoul, Korea
M. Choi, S. Kang, H. Kim, J.H. Kim, C. Park, I.C. Park, S. Park, G. Ryu

Sungkyunkwan University, Suwon, Korea
Y. Cho, Y. Choi, Y.K. Choi, J. Goh, M.S. Kim, B. Lee, J. Lee, S. Lee, H. Seo, I. Yu

Vilnius University, Vilnius, Lithuania
M.J. Bilinskas, I. Grigelionis, M. Janulis, A. Juodagalvis

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, R. Lopez-Fernandez, R. Magaña Villalba, J. Martínez-Ortega, A. Sánchez-Hernández, L.M. Villasenor-Cendejas

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, F. Vázquez Valencia
Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
H.A. Salazar Ibarguen

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
A.J. Bell, P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood

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

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

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

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
N. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, P. Musella, J. Pela1, J. Seixas, J. Varela, P. Vischia

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

Petersburg Nuclear Physics Institute, Gatchina (St Petersburg), Russia
S. Evstyukhin, V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

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

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, M. Erofeeva, V. Gavrilov, M. Kossov1, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, V. Bunichev, M. Dubinin1, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, S. Petrushanko, L. Sarycheva1, V. Savrin

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

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, V. Grishin1, V. Kachanov, D. Konstantinov, A. Korablev,
V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

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

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Aguilar-Benitez, J. Alcaraz Maestre, P. Arce, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, C. Diez Pardos, D. Domínguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. García-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, J. Puerta Pelayo, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, G. Codispoti, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain
J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J. Piedra Gomez, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini, M. Fernandez, G. Gomez, J. Gonzalez Sanchez, C. Jorda, P. Lobelle Pardo, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, M. Sobron Sanudo, I. Vila, R. Vilar Cortabiatarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, C. Bernet, G. Bianchi, P. Bloch, A. Bocci, A. Bonato, H. Breuker, K. Bunkowski, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, D. D’Enterría, 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. Güida, M. Hansen, P. Harris, C. Hartl, J. Harvey, B. Hegner, A. Hinzmann, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, K. Kousouris, P. Lecoq, P. Lenzi, C. Lourenço, T. Máki, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, E. Nesvold, M. Nguyen, T. Orimoto, L. Orsini, E. Palencia Cortezon, E. Perez, A. Petrelli, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, G. Polese, L. Quertenmont, A. Racz, W. Reece, J. Rodrigues Antunes, G. Rolandi, R. Rommerskirchen, C. Rovelli, M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas, D. Spiga, M. Spiropulu, M. Stoye, A. Tsirou, G.I. Veres, J.R. Vlimant, H.K. Wöhri, S.D. Worm, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kottlowski, U. Langenegger, F. Meier, D. Renker, T. Rohe, J. Sibille

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
L. Bäni, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, Z. Chen, A. Deisher, G. Dissertori, M. Dittmar, M. Dünser, J. Eugster, K. Freudenreich, C. Grab, P. Lecomte, W. Lustermann,
A.C. Marini, P. Martinez Ruiz del Arbol, N. Mohr, C. Nägeli, P. Nef, F. Nessi-Tedaldi, L. Pape, F. Pauss, M. Peruzzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, A. Starodumov, B. Stieger, M. Takahashi, L. Tauscher, A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H.A. Weber, L. Wehrli

Universität Zürich, Zurich, Switzerland
E. Aguilo, C. Amsler, V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, P. Otiougova, P. Robmann, H. Snoek, S. Tupputi, M. Verzetti

National Central University, Chung-Li, Taiwan
Y.H. Chang, K.H. Chen, A. Go, C.M. Kuo, S.W. Li, W. Lin, Z.K. Liu, Y.J. Lu, D. Mekterovic, A.P. Singh, R. Volpe, S.S. Yu

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

Cukurova University, Adana, Turkey
A. Adiguzel, M.N. Bakirci, C. Cerci, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, I. Hos, E.E. Kangal, G. Karapinar, A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk, A. Polatoz, K. Sogut, D. Sunar Cerci, B. Tali, H. Topakli, L.N. Vergili, M. Vergili

Middle East Technical University, Physics Department, Ankara, Turkey
I.V. Akin, T. Aliev, B. Bilin, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, M. Yalvac, E. Yildirim, M. Zeyrek

Bogazici University, Istanbul, Turkey
M. Deliomeroglu, E. Gülmez, B. Isildak, M. Kaya, O. Kaya, S. Ozkorucuklu, N. Sonmez

Istanbul Technical University, Istanbul, Turkey
K. Cankocak

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk

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

Rutherford Appleton Laboratory, Didcot, United Kingdom
L. Basso, K.W. Bell, A. Belyaev, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Jackson, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley

Imperial College, London, United Kingdom
R. Bainbridge, G. Ball, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, G. Karapostoli, L. Lyons, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko, A. Papageorgiou, M. Pesaresi, K. Petridis, M. Pioppi, D.M. Raymond, S. Rogerson, N. Rompotis, A. Rose, M.J. Ryan, C. Seez, P. Sharp, A. Sparrow, A. Tapper, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, T. Whyntie
Brunel University, Uxbridge, United Kingdom
M. Barrett, M. Chadwick, J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leggat, D. Leslie, W. Martin, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, USA
K. Hatakeyama, H. Liu, T. Scarborough

The University of Alabama, Tuscaloosa, USA
C. Henderson, P. Rumero

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

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

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

University of California, Los Angeles, Los Angeles, USA
V. Andreev, D. Cline, R. Cousins, J. Duris, S. Erhan, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, C. Plager, G. Rakness, P. Schlein, J. Tucker, V. Valuev, M. Weber

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

University of California, San Diego, La Jolla, USA
W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebougeois, J. Letts, I. Macneill, B. Mangano, J. Muelmenstaedt, S. Padhi, C. Palmer, G. Petrucciani, M. Pieri, R. Ranieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech, F. Würthwein, A. Yagil, J. Yoo

University of California, Santa Barbara, Santa Barbara, USA
D. Barge, R. Bellan, C. Campagnari, M. D’Alfonso, T. Danielson, K. Flowers, P. Geffert, J. Incandela, C. Justus, P. Kalavase, S.A. Koay, D. Kovalskyi, V. Krutelyov, S. Lowette, N. Mccoll, V. Pavlunin, F. Rebasso, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, C. West

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

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

University of Colorado at Boulder, Boulder, USA
J.P. Cumalat, B.R. Drell, C.J. Edelmaier, W.T. Ford, A. Gaz, B. Heyburn, E. Luiggi Lopez, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner
Cornell University, Ithaca, USA
L. Agostino, J. Alexander, A. Chatterjee, N. Eggert, L.K. Gibbons, B. Heltsley, W. Hopkins, A. Khukhunaishvili, B. Kreis, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Ryd, E. Salvati, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Vaughan, Y. Weng, L. Winstrom, P. Wittich

Fairfield University, Fairfield, USA
D. Winn

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

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

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

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

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

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, J. Callner, R. Cavanaugh, C. Dragoiu, O. Evdokimov, E.J. Garcia-Solis, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, F. Lacroix, M. Malek, C. O’Brien, C. Silburt, D. Strom, N. Varelas

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

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

The University of Kansas, Lawrence, USA
P. Baringer, A. Bean, G. Benelli, O. Grachov, R.P. Kenny Iii, M. Murray, D. Noonan, V. Radici, S. Sanders, R. Stringer, G. Tinti, J.S. Wood, V. Zhukova
Kansas State University, Manhattan, USA
A.F. Barfuss, T. Bolton, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze

Lawrence Livermore National Laboratory, Livermore, USA
J. Gronberg, D. Lange, D. Wright

University of Maryland, College Park, USA
A. Baden, M. Boutemeur, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, R.G. Kellogg, M. Kirn, T. Kolberg, Y. Lu, M. Marionneau, A.C. Mignerey, A. Peterman, K. Rossato, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, E. Twedt

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

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

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

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

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

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

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

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

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

Princeton University, Princeton, USA
N. Adam, E. Berry, P. Elmer, D. Gerbaudo, V. Halyo, P. Hebda, J. Hegeman, A. Hunt, E. Laird, D. Lopes Pegna, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, A. Raval, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski
University of Puerto Rico, Mayaguez, USA
J.G. Acosta, X.T. Huang, A. Lopez, H. Mendez, S. Oliveros, J.E. Ramirez Vargas, A. Zatserklyaniy

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

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

Rice University, Houston, USA
A. Adair, C. Boulahouache, V. Cuplov, K.M. Ecklund, F.J.M. Geurts, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

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

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

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

University of Tennessee, Knoxville, USA
G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

Texas A&M University, College Station, USA
R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon, V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, S. Sengupta, I. Suarez, A. Tatarinov, D. Toback

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

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

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

Wayne State University, Detroit, USA
S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, A. Sakharov
University of Wisconsin, Madison, USA
M. Anderson, M. Bachtis, D. Belknap, L. Borrello, D. Carlsmitht, 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, G.A. Pierro, I. Ross, A. Savin, W.H. Smith, J. Swanson

†: Deceased
1: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
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 Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
6: Also at Suez Canal University, Suez, Egypt
7: Also at Cairo University, Cairo, Egypt
8: Also at British University, Cairo, Egypt
9: Also at Fayoum University, El-Fayoum, Egypt
10: Now at Ain Shams University, Cairo, Egypt
11: Also at Soltan Institute for Nuclear Studies, Warsaw, Poland
12: Also at Université de Haute-Alsace, Mulhouse, France
13: Now at Joint Institute for Nuclear Research, Dubna, Russia
14: Also at Moscow State University, Moscow, Russia
15: Also at Brandenburg University of Technology, Cottbus, Germany
16: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
17: Also at Eötvös Loránd University, Budapest, Hungary
18: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
19: Now at King Abdulaziz University, Jeddah, Saudi Arabia
20: Also at University of Visva-Bharati, Santiniketan, India
21: Also at Sharif University of Technology, Tehran, Iran
22: Also at Isfahan University of Technology, Isfahan, Iran
23: Also at Shiraz University, Shiraz, 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 Faculty of Physics of University of Belgrade, Belgrade, Serbia
30: Also at University of Florida, Gainesville, USA
31: Also at University of California, Los Angeles, Los Angeles, USA
32: Also at Scuola Normale e Sezione dell’ INFN, Pisa, Italy
33: Also at INFN Sezione di Roma; Università di Roma “La Sapienza”, Roma, Italy
34: Also at University of Athens, Athens, Greece
35: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
36: Also at The University of Kansas, Lawrence, USA
37: Also at Paul Scherrer Institut, Villigen, Switzerland
38: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
39: Also at Gaziosmanpasa University, Tokat, Turkey
40: Also at Adiyaman University, Adiyaman, Turkey
41: Also at The University of Iowa, Iowa City, USA
42: Also at Mersin University, Mersin, Turkey
43: Also at Kafkas University, Kars, Turkey
44: Also at Suleyman Demirel University, Isparta, Turkey
45: Also at Ege University, Izmir, Turkey
46: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
47: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
48: Also at University of Sydney, Sydney, Australia
49: Also at Utah Valley University, Orem, USA
50: Also at Institute for Nuclear Research, Moscow, Russia
51: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
52: Also at Argonne National Laboratory, Argonne, USA
53: Also at Erzincan University, Erzincan, Turkey
54: Also at Kyungpook National University, Daegu, Korea