

## MIT Open Access Articles

*Measurement of the  $t\bar{t}$  production cross section in  $pp$  collisions at  $\sqrt{s} = 8$  TeV in dilepton final states containing one  $\tau$  lepton*

The MIT Faculty has made this article openly available. **Please share** how this access benefits you. Your story matters.

**Citation:** V. Khachatryan et al., "Measurement of the  $t\bar{t}$  Production Cross Section in  $Pp$  Collisions at  $\sqrt{s} = 8$  TeV in Dilepton Final States Containing One  $\tau$  Lepton." *Physics Letters B* 739 (December 2014): 23–43.

**As Published:** <http://dx.doi.org/10.1016/j.physletb.2014.10.032>

**Publisher:** Elsevier

**Persistent URL:** <http://hdl.handle.net/1721.1/92582>

**Version:** Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

**Terms of use:** Creative Commons Attribution





# Measurement of the $t\bar{t}$ production cross section in pp collisions at $\sqrt{s} = 8$ TeV in dilepton final states containing one $\tau$ lepton



CMS Collaboration\*

CERN, Switzerland

## ARTICLE INFO

### Article history:

Received 24 July 2014

Received in revised form 9 October 2014

Accepted 10 October 2014

Available online 16 October 2014

Editor: M. Doser

### Keywords:

CMS

Physics

Top quark

Tau

## ABSTRACT

The top-quark pair production cross section is measured in final states with one electron or muon and one hadronically decaying  $\tau$  lepton from the process  $t\bar{t} \rightarrow (\ell\nu_\ell)(\tau\nu_\tau)b\bar{b}$ , where  $\ell = e, \mu$ . The data sample corresponds to an integrated luminosity of  $19.6 \text{ fb}^{-1}$  collected with the CMS detector in proton–proton collisions at  $\sqrt{s} = 8$  TeV. The measured cross section  $\sigma_{t\bar{t}} = 257 \pm 3 \text{ (stat)} \pm 24 \text{ (syst)} \pm 7 \text{ (lumi)} \text{ pb}$ , assuming a top-quark mass of 172.5 GeV, is consistent with the standard model prediction.

© 2014 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/3.0/>). Funded by SCOAP<sup>3</sup>.

## 1. Introduction

Top quarks at the CERN LHC are mostly produced in pairs with the subsequent decays  $t\bar{t} \rightarrow W^+bW^-\bar{b}$ . The decay modes of the two W bosons determine the event signature. The dilepton decay channel corresponds to the case in which both W bosons decay into leptons, where the term lepton usually refers to electrons or muons, as studied in Refs. [1,2]. In this letter we measure the production cross section of top-quark pairs by considering dilepton decays where one W boson promptly decays into  $\ell\nu_\ell$ , with  $\ell = e$  or  $\mu$ , and the other decays into  $\tau\nu_\tau$ ,  $t\bar{t} \rightarrow (\ell\nu_\ell)(\tau\nu_\tau)b\bar{b}$ . The expected fraction of these events is 4/81 of all  $t\bar{t}$  decays. The  $\tau$  lepton is identified by means of its hadronic decay products, with a branching fraction  $\mathcal{B}(\tau \rightarrow \text{hadrons} + \nu_\tau) \simeq 65\%$ , to produce a narrow jet with a small number of charged hadrons, denoted as  $\tau_h$ . The cross section is measured by counting the number of  $\ell\tau_h + X$  events consistent with originating from  $t\bar{t}$  production, after subtracting the contributions from other processes, and correcting for the efficiency of the event selection. A similar method was used in pp collisions at a centre-of-mass energy of  $\sqrt{s} = 7$  TeV [3]. This “ $\tau$  dilepton” channel is of particular interest because it is a natural background process to the search for a charged Higgs boson [4,5] with a mass smaller than that of the top quark. In this case, the production chain  $t\bar{t} \rightarrow H^+bW^-\bar{b}$ , with  $H^+ \rightarrow \tau^+\nu_\tau$  (or the

corresponding charge-conjugate particles) could give rise to differences with respect to the standard model (SM) prediction of the number of  $t\bar{t}$  events with a  $\tau$  lepton [6]. The present measurement is based on data collected by the CMS experiment in pp collisions at  $\sqrt{s} = 8$  TeV corresponding to an integrated luminosity of  $19.6 \text{ fb}^{-1}$ . The relative accuracy of this measurement improves over previous results [7–11], thanks to the inclusion of additional data and improved analysis techniques.

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

## 2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter and 13 m in length, providing a magnetic field of 3.8 T. Within the superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass/scintillator hadron calorimeter, each composed of a barrel and two endcap sections. The calorimetry provides high-resolution energy and direction measurements of electrons and hadronic jets. Muons are identified using gas-ionisation detectors embedded in the steel flux-return

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

yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. The CMS experiment uses a right-handed coordinate system, with the origin at the nominal interaction point, the  $x$  axis pointing to the centre of the LHC ring, the  $y$  axis pointing up (perpendicular to the LHC plane), and the  $z$  axis along the anticlockwise-beam direction. The polar angle  $\theta$  is measured from the positive  $z$  axis and the azimuthal angle  $\varphi$  is measured in the  $x$ - $y$  plane. Charged particle trajectories are measured covering  $0 < \varphi \leq 2\pi$  in azimuth and  $|\eta| < 2.5$ , where the pseudorapidity  $\eta$  is defined as  $\eta = -\ln[\tan(\theta/2)]$ . The detector is nearly hermetic, allowing for energy balance measurements 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 analyses. A more detailed description of the CMS detector can be found elsewhere [12].

### 3. Data and simulation samples

Events are selected online by a trigger requiring a single isolated electron (muon) with transverse momentum  $p_T > 27$  (24) GeV and  $|\eta| < 2.5$  (2.1).

This measurement makes use of simulated samples of  $t\bar{t}$  events as well as other processes that mimic the  $\ell\tau_h$  decay signature. These samples are used to optimise the event selection, to calculate the acceptance for  $t\bar{t}$  events, and to estimate some of the backgrounds in the analysis.

The signal acceptance and  $t\bar{t}$  dilepton background are evaluated using a version of MADGRAPH which includes the effects of spin correlations [13,14]. The number of expected  $t\bar{t}$  events is estimated with the next-to-next-to-leading-order (NNLO) SM cross section of  $251.7_{-8.6}^{+6.3}$  (scale)  $\pm 6.5$  (PDF) pb [15–19] for a top-quark mass of 172.5 GeV, where the first uncertainty is due to renormalisation and factorisation scales, and the second is due to the choice of parton distribution functions (PDFs). The generated events are subsequently processed with PYTHIA 6.426 [20] which performs the hadronisation of partons. Soft radiation is matched to the contributions from direct emissions accounted for in the matrix-element calculations using the  $k_T$ -MLM approach [21]. The  $\tau$  lepton decays are simulated using TAUOLA 27.121.5 [22], which accounts for the  $\tau$ -lepton polarisation.

The samples containing  $W + \text{jet}$  and  $Z + \text{jet}$  events are simulated using the MADGRAPH 5.1.3.30 event generator [23]. The electroweak production of single top quarks is considered as a background process and is simulated with POWHEG 1.0, r1380 [24–28]. The diboson production processes  $WW$ ,  $WZ$ , and  $ZZ$  are generated with PYTHIA 6.424. In each case, the PYTHIA parameters for the underlying event are set according to the  $ZZ^*$  tune [29], which uses the CTEQ6L PDFs [30].

Simulated events are processed using the full CMS detector simulation based on GEANT4 [31,32], followed by a detailed trigger emulation and event reconstruction. For both signal and background events, additional  $pp$  interactions (pileup) in the same or nearby bunch crossings are simulated with PYTHIA and superimposed on the hard collision, using a pileup multiplicity distribution that reflects the luminosity profile of the analysed data.

### 4. Event selection

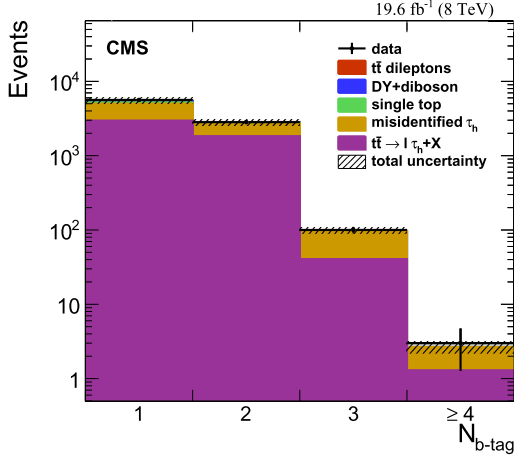
Events are reconstructed with the particle-flow (PF) algorithm [33,34], which combines information from all sub-detectors to identify and reconstruct individual electrons, muons, photons, charged and neutral hadrons. The primary collision vertex is chosen as the reconstructed vertex with the largest  $\sum p_T^2$  of the

associated tracks. Electrons are identified with a multivariate discriminant combining several quantities describing the track quality, the shape of the energy deposits in the electromagnetic calorimeter, and the compatibility of the measurements from the tracker and the electromagnetic calorimeter [35], and are reconstructed with an average efficiency of approximately 95%. Muons are identified with additional requirements on the quality of the track reconstruction and on the number of measurements in the tracker and the muon systems [36], and are reconstructed with an average efficiency of approximately 96%. Charged and neutral particles provide the input to the anti- $k_T$  jet clustering algorithm with a distance parameter of 0.5 [37]. The jet momentum is determined from the vector sum of particle momenta in the jet. After jet energies are corrected for additional pileup contributions and for detector effects, they are found in simulations to be within 5–10% of the actual jet momentum [38]. The missing transverse energy  $E_T^{\text{miss}}$  is calculated as the magnitude of the vector sum of momenta from all reconstructed particles in the plane transverse to the beam.

In addition, higher-level observables such as  $b$ -tagging discriminators and lepton isolation variables are used. The lepton relative isolation is defined as the transverse energy contributions deposited by charged hadrons ( $E_{T,\text{ch}}$ ), neutral hadrons ( $E_{T,\text{nh}}$ ), and photons ( $E_{T,\text{ph}}$ ) in a cone of radius  $R = \sqrt{(\Delta\varphi)^2 + (\Delta\eta)^2} = 0.4$  centred on the lepton candidate track, relative to the lepton's transverse momentum ( $p_T$ ),  $I_{\text{rel}} = (E_{T,\text{ch}} + E_{T,\text{nh}} + E_{T,\text{ph}})/p_T$ . An electron (muon) candidate is considered to be non-isolated and is rejected if  $I_{\text{rel}} > 0.1$  ( $> 0.12$ ).

The hadronic products of the  $\tau$ -lepton decay are reconstructed using a jet as the initial seed, and are then classified as having one or three charged hadrons with the “hadron-plus-strips” algorithm [39,40]. In the “hadron-plus-strips” algorithm, calorimeter energy deposits clustered along strips in the  $\varphi$  direction are used for neutral pion identification. Then, the decay modes, four-momenta, and isolation quantities of the  $\tau_h$  are determined, and the following categories are considered: single hadron, hadron plus a strip, hadron plus two strips, and three hadrons. These categories together encompass approximately 95% of hadronic  $\tau$ -lepton decays. The sum of the charged hadron charges provides the  $\tau_h$  charge. The  $\tau_h$ -jet momentum is required to match the direction of the original jet within a maximum distance  $R = 0.1$ . Isolation criteria require that there be no additional charged hadrons with  $p_T > 1.0$  GeV or photons with transverse energy  $E_T > 1.5$  GeV within a cone of size  $R = 0.5$  around the direction of the  $\tau_h$  jet. Electrons and muons misidentified as  $\tau_h$  are suppressed using algorithms that combine information from the tracker, calorimeters, and muon detectors [12]. The  $\tau_h$  identification efficiency is defined as the ratio of the number of selected  $\tau_h$  candidates divided by the number of hadronic  $\tau$ -lepton decays in  $t\bar{t}$  events; the ratio depends on  $p_T$  and  $\eta$  of the  $\tau_h$ , and is on average 50% for  $p_T^{\tau_h} > 20$  GeV, with a probability of approximately 1% for generic jets to be misidentified as a  $\tau_h$  jet.

The combined secondary vertex (CSV) algorithm [41] is used to identify jets originating from the hadronisation of  $b$  quarks. The algorithm combines the information about track impact parameters and secondary vertices within jets into a likelihood discriminant to provide separation between  $b$  jets and jets originating from light quarks, gluons, or charm quarks. The output of this CSV discriminant has values between zero and one; a jet with a CSV value above a certain threshold is referred to as being “ $b$  tagged”. We choose a working point where the  $b$ -tagging efficiency is approximately 60%, as measured in a data sample of events enriched with jets from semileptonic  $b$ -hadron decays. The misidentification rate of light-flavour jets is estimated from inclusive jet studies and is measured to be about 0.1% for jets with  $p_T > 30$  GeV.



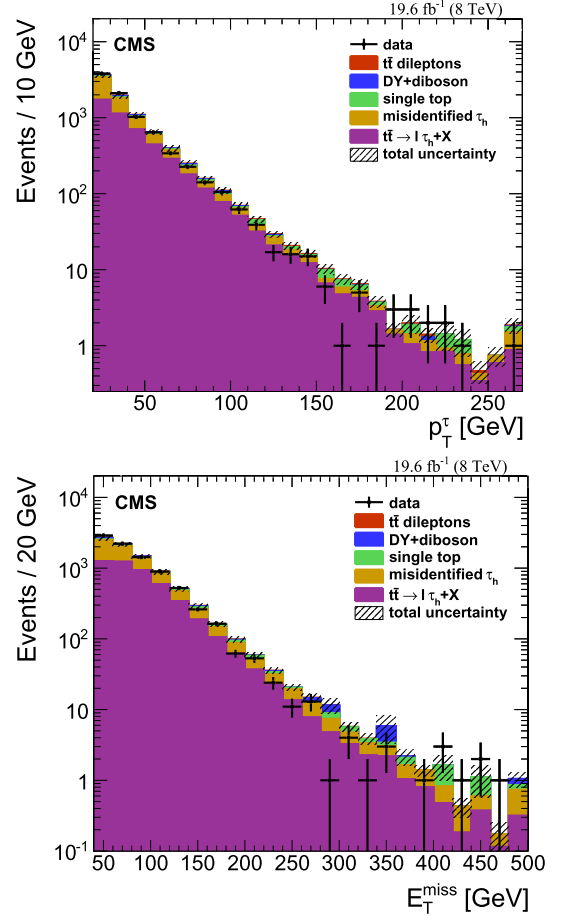
**Fig. 1.** The b-tagged jet multiplicity after the full event selection. The simulated contributions are normalised to the SM predicted values. The hatched area shows the total uncertainty.

Events are preselected by requiring exactly one isolated electron (muon) with transverse momentum  $p_T > 35$  (30) GeV and  $|\eta| < 2.5$  (2.1), at least two jets with  $p_T > 30$  GeV, and one additional jet with  $p_T > 20$  GeV. The selected jets must be within  $|\eta| < 2.4$ . The electron or muon is required to be separated from any jet in the  $(\eta, \varphi)$  plane by a distance  $R > 0.4$ . Events with any additional loosely isolated,  $I_{\text{rel}} < 0.2$ , electron (muon) of  $p_T > 15$  (10) GeV are rejected. Further event selection requirements include  $E_T^{\text{miss}} > 40$  GeV and only one  $\tau_h$  with  $p_T > 20$  GeV and  $|\eta| < 2.4$ . The  $\tau_h$  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 hadronisation (b-tagged).

**Fig. 1** shows, for the sum of the  $e\tau_h$  and  $\mu\tau_h$  final states, a comparison between data and simulation of the number of b-tagged jets in each event  $N_{b\text{-tag}}$  after all the selection criteria have been applied. The distributions of the  $\tau_h$   $p_T$  and  $E_T^{\text{miss}}$  after the final event selection are shown in the top and bottom panels of **Fig. 2**, respectively. The distributions show agreement between the observed numbers of events and the expected numbers of signal and background events obtained from the simulated distributions normalised to the integrated luminosity of the selected data sample.

Following the final selection, additional kinematic features of the  $t\bar{t}$  events are studied to evaluate the agreement between the observed data and the predicted sum of signal and background. For each event, two invariant mass combinations are reconstructed by pairing the  $\tau_h$  with the two candidate b-jets: (1) in events with two or more b-tagged jets, the two combinations are based on the two b-tagged jets with the highest value of the discriminator; (2) in events with one b-tagged jet, this is used for the first combination, while the non-b-tagged jet with the highest  $p_T$  is used to form the second combination. For the two combinations, the invariant mass with the lowest value is shown in **Fig. 3** (top), for the  $e\tau_h$  and  $\mu\tau_h$  channels combined.

For each event, the top-quark mass  $m_{\text{top}}$  is reconstructed using the KINb algorithm [42,43]. Due to the multiple neutrinos in the event, the reconstruction of  $m_{\text{top}}$  leads to an underconstrained system. The KINb algorithm applies constraints on the W boson mass, the mass difference between the top and anti-top quark, and the longitudinal momentum of the  $t\bar{t}$  system. For each event, solutions to the kinematic equations are evaluated, varying the jet momenta and the direction of  $E_T^{\text{miss}}$  within their resolutions. For each set of variations and each lepton–jet combination, the kinematic equations allow up to four solutions; the one with the lowest  $t\bar{t}$  invariant mass is accepted if the mass difference between the two



**Fig. 2.** Distribution of the  $\tau_h$   $p_T$  (top) and  $E_T^{\text{miss}}$  (bottom) after the full event selection, for the  $e\tau_h$  and  $\mu\tau_h$  channels combined. The simulated contributions are normalised to the SM predicted values. The hatched area shows the total uncertainty. The last bins include the overflow events.

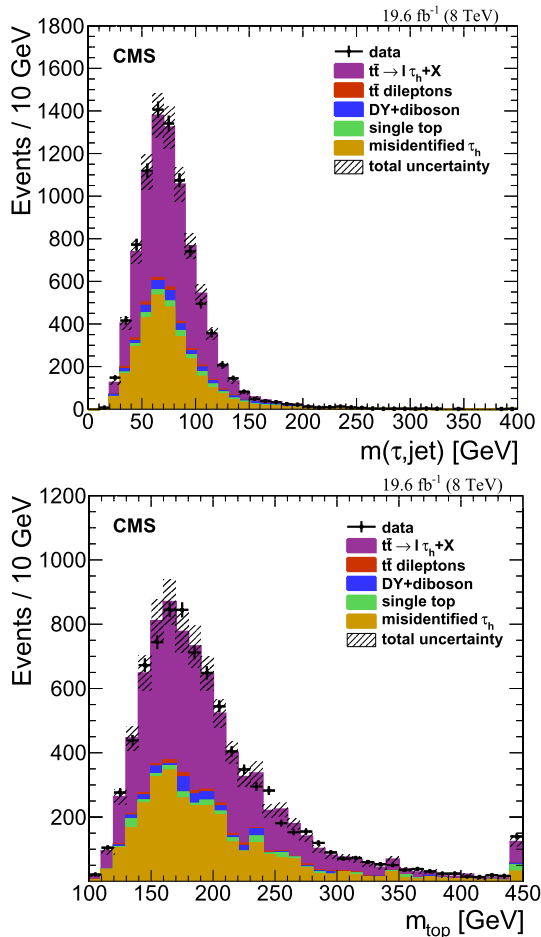
top quarks is less than 3 GeV. For each event, the accepted solutions corresponding to the two possible lepton–jet combinations are counted and the combination with the largest number of solutions is chosen and  $m_{\text{top}}$  is obtained by fitting the peak of this distribution. The events in which solutions are found are shown in **Fig. 3** (bottom). Data are in agreement with the expected sum of signal and background events.

## 5. Background estimate

The main background (misidentified  $\tau_h$ ) comes from events with one lepton (electron or muon), significant  $E_T^{\text{miss}}$ , and three or more jets, where one jet is misidentified as a  $\tau_h$  jet [6]. The dominant source is  $t\bar{t}$  lepton + jet events. The misidentified  $\tau_h$  background accounts also for events with W bosons produced in association with jets, either genuine W + jet or single-top-quark production, and for QCD multijet events. In order to estimate this background from data, the misidentification probability  $w(\text{jet} \rightarrow \tau_h)$  is parameterised as a function of the jet  $p_T$ ,  $\eta$ , and width ( $R_{\text{jet}}$ ). The quantity  $R_{\text{jet}}$  is defined as  $\sqrt{\sigma_\eta^2 + \sigma_\varphi^2}$ , where  $\sigma_\eta$  ( $\sigma_\varphi$ ) expresses the extent in  $\eta$  ( $\varphi$ ) of the jet cluster [38].

The probability  $w(\text{jet} \rightarrow \tau_h)$  is evaluated from two control samples:

- $w_{W+\text{jets}}$ : from a W + jet event sample, selected by requiring one isolated muon with  $p_T > 20$  GeV and  $|\eta| < 2.1$ , and at least one jet with  $p_T > 20$  GeV and  $|\eta| < 2.4$ ;



**Fig. 3.** (Top) Minimum invariant mass reconstructed by pairing the  $\tau_h$  with either a b-tagged jet or with the highest  $p_T$  non-b-tagged jet, as described in the text. (Bottom) Distribution of the reconstructed top-quark mass  $m_{\text{top}}$  for the  $\ell\tau_h$  candidate events after the full event selection. Data (points) are compared with the sum of signal and background yields, for the  $e\tau_h$  and  $\mu\tau_h$  channels combined. The simulated contributions are normalised to the SM predicted values. The hatched area shows the total uncertainty. The last bins include the overflow events.

- $w_{\text{QCD}}$ : from a QCD multijet sample, triggered by one jet with  $p_T > 40$  GeV, selected by requiring events to have at least two jets with  $p_T > 20$  GeV and  $|\eta| < 2.4$ , where the triggering jet is removed from the misidentification rate calculation to avoid a trigger bias.

Both probabilities are evaluated in simulated events as well as in data, with good agreement found between the results from simulation and data [39].

The number of events containing misidentified  $\tau_h$  candidates is then determined as

$$N^{\text{misid}} = \sum_i^M \sum_j^m w_i^j(\text{jet} \rightarrow \tau) - N^{\text{other}}, \quad (1)$$

where  $j$  is the jet index of event  $i$ , and  $m$  is the number of jets in each event and  $M$  is the total number of events. The quantity  $N^{\text{other}}$  is the expected  $\simeq 20\%$  contamination from signal and other processes to the misidentified background as estimated from simulated samples. The value of  $N^{\text{other}}$  is evaluated by applying the procedure described above to simulated events of  $Z/\gamma^* \rightarrow \tau\tau$ , single-top-quark production, diboson production, and the  $t\bar{t}$  processes included in the misidentified  $\tau_h$  background estimation.

Jets in QCD multijet events originate mainly from gluons, while in  $W + \text{jet}$  events they are predominantly from quarks. The quark

**Table 1**

List of systematic uncertainties in the cross section measurement, and their combination. Lepton reconstruction uncertainties are uncorrelated, while all other uncertainties are assumed 100% correlated.

Source	Uncertainty [%]		
	$e\tau_h$	$\mu\tau_h$	Combined
<i>Experimental uncertainties:</i>			
$\tau_h$ jet identification	6.0	6.0	6.0
$\tau_h$ misidentification background	4.3	4.3	4.3
$\tau_h$ energy scale	2.4	2.5	2.5
b-jet tagging, jet misidentification	1.6	1.6	1.6
jet energy scale, jet energy resolution, $E_T^{\text{miss}}$	1.9	1.9	1.9
lepton reconstruction	0.8	0.6	0.5
other backgrounds	0.6	0.7	0.7
luminosity	2.6	2.6	2.6
<i>Theoretical uncertainties:</i>			
matrix element-parton shower matching	1.7	1.3	1.5
factorisation/renormalisation scale	2.9	2.9	2.9
generator	1.5	1.5	1.5
hadronisation	1.7	1.7	1.7
top-quark $p_T$ modelling	0.7	0.5	0.6
parton distribution functions	0.8	0.7	0.7
total systematic uncertainty	9.6	9.5	9.5

and gluon composition in the misidentified  $\tau_h$  events lies between these two control samples. As  $w_{\text{QCD}} < w_{W+\text{jets}}$ , the actual  $N^{\text{misid}}$  value is under- (over-) estimated by applying the  $w_{\text{QCD}}$  ( $w_{W+\text{jets}}$ ) probability. We determine from data the rate for the misidentification of a jet to be identified as a  $\tau_h$ , and from simulation the quark/gluon composition in the  $W + \text{jet}$  and multijet samples. From these quantities we derive the following combination:

$$\langle N^{\text{misid}} \rangle = SF_{W+\text{jet}} \times N_{W+\text{jet}}^{\text{misid}} + SF_{\text{QCD}} \times N_{\text{QCD}}^{\text{misid}}, \quad (2)$$

where the misidentification rates, extracted from the data control samples discussed above, are combined with the scale factors  $SFs$  determined from the set of equations describing the quark/gluon composition of the samples:  $SF_{\text{QCD}} = 0.83$  and  $SF_{W+\text{jet}} = 0.17$ . The corresponding systematic uncertainty is obtained from Eq. (2) by weighting the relative deviations of  $N_{W+\text{jet}}^{\text{misid}}$  and  $N_{\text{QCD}}^{\text{misid}}$  from  $\langle N^{\text{misid}} \rangle$  with the related scale factors. This results in an uncertainty of 7% for both  $e\tau_h$  and  $\mu\tau_h$  channels.

The efficiency of the OS requirement  $\varepsilon_{\text{OS}}$  is determined from simulated lepton + jet  $t\bar{t}$  events and is applied in order to obtain the misidentified  $\tau_h$  background after the final event selection  $N_{\text{OS}}^{\text{misid}}$ , where  $N_{\text{OS}}^{\text{misid}} = \varepsilon_{\text{OS}} \cdot N^{\text{misid}}$ . We find values of  $\varepsilon_{\text{OS}} = 0.729 \pm 0.002$  (stat)  $\pm 0.004$  (syst) for the  $e\tau_h$  selection,  $\varepsilon_{\text{OS}} = 0.731 \pm 0.002$  (stat)  $\pm 0.003$  (syst) for the  $\mu\tau_h$  selection, where all sources of systematic uncertainty are accounted for in the modelling of the simulated  $t\bar{t}$  lepton + jet events.

## 6. Systematic uncertainties

Several sources of systematic uncertainty are considered and listed in Table 1. They are related both to the signal reconstruction efficiency, background determination, and luminosity measurement (Experimental uncertainties) and to the theoretical assumptions on the  $t\bar{t}$  production (Theoretical uncertainties). In Table 1 and in what follows, relative values refer to the cross section uncertainty unless explicitly stated otherwise.

### 6.1. Experimental uncertainties

Regarding the  $\tau_h$  reconstruction, the uncertainty associated with the identification efficiency amounts to 6%, while the contribution relative to the  $\tau_h$  jet energy scale is 2.4% (2.5%) for the  $e\tau_h$  ( $\mu\tau_h$ ) channel, as estimated by varying the  $p_T$  of the  $\tau_h$  jet

by 3% [39,40]. The uncertainty in the  $\tau_h$  identification efficiency includes the uncertainty in charge determination which is estimated to be smaller than 1%. The uncertainty related to the misidentified  $\tau_h$  background process, discussed in Section 5, is obtained by propagating the 7% uncertainty on  $\langle N^{\text{misid}} \rangle$  to the cross section determination and results in 4.3% for both channels. It also includes the uncertainty in the OS efficiency determination.

The reconstruction of a light flavour jet as a b quark is defined as mistagging. The uncertainty due to b (mis)tagging is estimated to reflect the data-to-simulation scale factors and corresponding uncertainties for b-tagging and mistagging efficiencies [41]. When propagated to the cross section measurement, they amount to 1.6% for both  $e\tau_h$  and  $\mu\tau_h$  channels.

The jet energy scale (JES) uncertainty is estimated [38] by varying the jet energy within the  $p_T$ - and  $\eta$ -dependent JES uncertainties per jet, and taking into account the uncertainty due to pileup and parton flavour. The jet energy resolution (JER) is estimated by smearing the jet energy in simulation within the  $\eta$ -dependent JER uncertainties per jet. The JES and JER uncertainties are propagated in order to estimate the uncertainty of the  $E_T^{\text{miss}}$  scale. In addition, modelling of the  $E_T^{\text{miss}}$  component, which is not clustered in jets, is also considered. The resulting uncertainty from propagating these effects to the cross section measurement is 1.9% for both the  $e\tau_h$  and  $\mu\tau_h$  channels.

Uncertainties due to trigger, lepton identification, isolation, and lepton energy scale are calculated from independent samples with a “tag-and-probe” method [35,36], and yield 0.8% (0.6%) for the  $e\tau_h$  ( $\mu\tau_h$ ) channel.

An overall 0.6% (0.7%) uncertainty for the  $e\tau_h$  ( $\mu\tau_h$ ) channel is due to other minor backgrounds, accounting for the uncertainties related to the theoretical cross sections, JES, and b-tagging in these simulated samples, and the  $\ell \rightarrow \tau_h$  ( $\ell = e, \mu$ ) misidentification in the  $Z/\gamma^* \rightarrow \ell^+\ell^-$  and  $t\bar{t}$  dilepton processes.

Finally, the integrated luminosity is known with 2.6% accuracy [44].

## 6.2. Theoretical uncertainties

The theoretical uncertainty due to the matrix element (ME) and parton shower (PS) matching is estimated by varying up and down by a factor of two the threshold between jet production at the ME level and via PS, and it results in 1.7% (1.3%) for the  $e\tau_h$  ( $\mu\tau_h$ ) channel.

The modelling uncertainty in the signal acceptance due to the factorisation and renormalisation scale choices is estimated by varying them simultaneously up and down by a factor of two from the nominal value equal to the  $Q^2$  in the event, with an uncertainty of 2.9% found for both channels.

The uncertainty due to the choice of the generator is estimated as the relative difference between the acceptances evaluated with MADGRAPH and POWHEG [24–26,45] after the full event selection and results in 1.5%. In a similar way, the uncertainty in the hadronisation scheme is evaluated from the relative differences between the acceptances from POWHEG + PYTHIA and POWHEG + HERWIG samples, estimated prior to the b-tagging or  $\tau_h$  jet requirement, resulting in a 1.7% uncertainty.

We consider the uncertainty related to the top-quark  $p_T$  scale modelling by varying the top-quark  $p_T$  spectrum and evaluating the change in the signal acceptance, resulting in 0.6%, and the uncertainty related to the PDF variations following the PDF4LHC prescriptions [17], resulting in 0.7%.

## 7. Cross section measurement

The number of expected signal and background events as well as the number of observed events after all selections are

**Table 2**

Number of expected events for signal (assuming  $m_{\text{top}} = 172.5$  GeV) and backgrounds. The background from misidentified  $\tau_h$  is estimated from data, while the other backgrounds are estimated from simulation. Statistical and systematic uncertainties are shown.

Source	$e\tau_h$	$\mu\tau_h$
misidentified $\tau_h$	$1341 \pm 3 \pm 94$	$1653 \pm 3 \pm 116$
$t\bar{t} \rightarrow (\ell\nu_\ell)(\ell\nu_\ell)b\bar{b}$	$55 \pm 1 \pm 3$	$68 \pm 2 \pm 4$
$Z/\gamma^* \rightarrow ee, \mu\mu$	$11 \pm 5 \pm 5$	$12 \pm 5 \pm 5$
$Z/\gamma^* \rightarrow \tau\tau$	$85 \pm 14 \pm 8$	$166 \pm 20 \pm 18$
single top quark	$104 \pm 7 \pm 9$	$133 \pm 8 \pm 10$
dibosons	$15 \pm 1 \pm 1$	$19 \pm 1 \pm 1$
total expected background	$1611 \pm 17 \pm 95$	$2051 \pm 22 \pm 118$
expected signal yield	$2134 \pm 9 \pm 170$	$2632 \pm 11 \pm 212$
data	3779	4767

summarised in Table 2. The statistical and systematic uncertainties are also shown. The  $t\bar{t}$  production cross section measured from  $\tau$  dilepton events is  $\sigma_{t\bar{t}} = (N - B)/(L \cdot A_{\text{tot}})$ , where  $N$  is the number of observed candidate events,  $B$  is the estimate of the background and  $L$  is the integrated luminosity. The total acceptance  $A_{\text{tot}}$  is the product of the branching fractions, geometrical and kinematic acceptance, trigger, lepton identification, and the overall reconstruction efficiency. It is evaluated with respect to the inclusive  $t\bar{t}$  sample. After the OS requirement and assuming a top-quark mass  $m_{\text{top}} = 172.5$  GeV, we obtain:

$$A_{\text{tot}}(e\tau_h) = 0.04333 \pm 0.00017 \text{ (stat)} \pm 0.00300 \text{ (syst)}\%;$$

$$A_{\text{tot}}(\mu\tau_h) = 0.05370 \pm 0.00021 \text{ (stat)} \pm 0.00376 \text{ (syst)}\%.$$

The statistical uncertainties are due to the limited number of simulated events and the systematic uncertainties are estimated by accounting for all sources listed in Table 1. The statistical and systematic uncertainties listed in Table 2 are propagated to the final cross section measurements:

$$\sigma_{t\bar{t}}(e\tau_h) = 255 \pm 4 \text{ (stat)} \pm 24 \text{ (syst)} \pm 7 \text{ (lumi)} \text{ pb};$$

$$\sigma_{t\bar{t}}(\mu\tau_h) = 258 \pm 4 \text{ (stat)} \pm 24 \text{ (syst)} \pm 7 \text{ (lumi)} \text{ pb}.$$

The BLUE method [46] is used to combine the cross section measurements in the  $e\tau_h$  and  $\mu\tau_h$  channels, yielding weights of 0.47 and 0.53, respectively. Lepton reconstruction uncertainties are uncorrelated, while all other uncertainties are assumed 100% correlated. With this method we obtain a combined result of  $\sigma_{t\bar{t}} = 257 \pm 3 \text{ (stat)} \pm 24 \text{ (syst)} \pm 7 \text{ (lumi)} \text{ pb}$ , in agreement with the NNLO expectation of  $251.7_{-8.6}^{+6.3}$  (scales)  $\pm 6.5$  (PDF) pb. Following the most recent conventions for the treatment of PDF and scale uncertainties the same calculation yields  $252.9_{-8.6}^{+6.4}$  (scale)  $\pm 11.7$  (PDF +  $\alpha_S$ ) pb [15–19]. The dependence on the top-quark mass has been studied for the range 160–185 GeV and is well described by a linear variation. If we adjust our result to the current world average value of 173.3 GeV [47], we obtain a cross section that is lower by 3.1 pb.

## 8. Summary

A measurement of the  $t\bar{t}$  production cross section in the channel  $t\bar{t} \rightarrow (\ell\nu_\ell)(\tau\nu_\tau)b\bar{b}$  is presented, where  $\ell$  is an electron or a muon, and the  $\tau$  lepton is reconstructed through its hadronic decays. The data sample corresponds to an integrated luminosity of  $19.6 \text{ fb}^{-1}$  collected in proton–proton collisions at  $\sqrt{s} = 8$  TeV. Events are selected by requiring the presence of one isolated electron or muon, two or more jets (at least one of which is b-tagged), significant missing transverse energy, and one  $\tau$ . The

largest background contribution is estimated from data and consists of  $t\bar{t}$  events with one W boson decaying into jets, where one jet is misidentified as a  $\tau$ . The measured cross section is  $\sigma_{t\bar{t}} = 257 \pm 3$  (stat)  $\pm 24$  (syst)  $\pm 7$  (lumi) pb for a top-quark mass of 172.5 GeV. This measurement improves over previous results in this decay channel, and it is in good agreement with the standard model expectation and other measurements of the  $t\bar{t}$  cross section at the same centre-of-mass energy.

## Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MOST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); MoER, ERC IUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS and RFBR (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPcenter, IPST, STAR and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie programme and the European Research Council and EPLANET (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt-Stiftung; 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 Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS programme of Foundation For Polish Science, cofinanced from European Union, Regional Development Fund; the Compagnia di San Paolo (Torino); the Consorzio per la Fisica (Trieste); MIUR project 20108T4XTM (Italy); the Thalís and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; and the National Priorities Research Program by Qatar National Research Fund.

## References

- [1] ATLAS Collaboration, Measurement of the  $t\bar{t}$  production cross-section using  $e\mu$  events with  $b$ -tagged jets in  $pp$  collisions at  $\sqrt{s} = 7$  and 8 TeV with the ATLAS detector, arXiv:1406.5375, 2014.
- [2] CMS Collaboration, Measurement of the  $t\bar{t}$  production cross section in the dilepton channel in  $pp$  collisions at  $\sqrt{s} = 8$  TeV, J. High Energy Phys. 02 (2014) 024, [http://dx.doi.org/10.1007/JHEP02\(2014\)024](http://dx.doi.org/10.1007/JHEP02(2014)024), arXiv:1312.7582.
- [3] CMS Collaboration, Measurement of the top quark pair production cross section in  $pp$  collisions at  $\sqrt{s} = 7$  TeV in dilepton final states containing a  $\tau$ , Phys. Rev. D 85 (2012) 112007, <http://dx.doi.org/10.1103/PhysRevD.85.112007>, arXiv:1203.6810.
- [4] J.F. Gunion, H.E. Haber, G.L. Kane, S. Dawson, The Higgs Hunter's Guide, Frontiers in Physics, Addison-Wesley, 1990.
- [5] A. Djouadi, The anatomy of electro-weak symmetry breaking, Tome II: the Higgs bosons in the minimal supersymmetric model, Phys. Rep. 459 (2008) 1, <http://dx.doi.org/10.1016/j.physrep.2007.10.005>, arXiv:hep-ph/0503173.
- [6] CMS Collaboration, Search for a light charged Higgs boson in top quark decays in  $pp$  collisions at  $\sqrt{s} = 7$  TeV, J. High Energy Phys. 07 (2012) 143, [http://dx.doi.org/10.1007/JHEP07\(2012\)143](http://dx.doi.org/10.1007/JHEP07(2012)143), arXiv:1205.5736.
- [7] F. Abe, et al., 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, <http://dx.doi.org/10.1103/PhysRevLett.79.3585>, arXiv:hep-ex/9704007.
- [8] A. Abulencia, et al., CDF Collaboration, A search for  $t \rightarrow \tau\nu q$  in  $t\bar{t}$  production, Phys. Lett. B 639 (2006) 172, <http://dx.doi.org/10.1016/j.physletb.2006.06.030>, arXiv:hep-ex/0510063.
- [9] V.M. Abazov, et al., 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, <http://dx.doi.org/10.1016/j.physletb.2009.07.032>, arXiv:0901.2137.
- [10] T.A. Aaltonen, et al., CDF Collaboration, Study of top quark production and decays involving a tau lepton at CDF and limits on a charged Higgs boson contribution, Phys. Rev. D 89 (2014) 091101, <http://dx.doi.org/10.1103/PhysRevD.89.091101>, arXiv:1402.6728.
- [11] ATLAS Collaboration, Measurement of the top quark pair cross section with ATLAS in  $pp$  collisions at  $\sqrt{s} = 7$  TeV using final states with an electron or a muon and a hadronically decaying  $\tau$  lepton, Phys. Lett. B 717 (2012) 89, <http://dx.doi.org/10.1016/j.physletb.2012.09.032>, arXiv:1205.2067.
- [12] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. 3 (2008) S08004, <http://dx.doi.org/10.1088/1748-0221/3/08/S08004>.
- [13] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, T. Stelzer, MadGraph 5: going beyond, J. High Energy Phys. 06 (2011) 128, [http://dx.doi.org/10.1007/JHEP06\(2011\)128](http://dx.doi.org/10.1007/JHEP06(2011)128), arXiv:1106.0522.
- [14] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. Shao, T. Stelzer, P. Torielli, M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, J. High Energy Phys. 07 (2014) 079, [http://dx.doi.org/10.1007/JHEP07\(2014\)079](http://dx.doi.org/10.1007/JHEP07(2014)079), arXiv:1405.0301.
- [15] M. Czakon, P. Fiedler, A. Mitov, The total top quark pair production cross section at hadron colliders through  $O(\alpha_s^3)$ , Phys. Rev. Lett. 110 (2013) 252004, <http://dx.doi.org/10.1103/PhysRevLett.110.252004>, arXiv:1303.6254.
- [16] M. Czakon, A. Mitov, Top++: a program for the calculation of the top pair cross-section at hadron colliders, Comput. Phys. Commun. 185 (2014) 2930, <http://dx.doi.org/10.1016/j.cpc.2014.06.021>, arXiv:1112.5675.
- [17] M. Botje, J. Butterworth, A. Cooper-Sarkar, A. de Roeck, J. Feltesse, S. Forte, A. Glazov, J. Huston, R. McNulty, T. Sjöstrand, R.S. Thorne, The PDF4LHC working group interim recommendations, arXiv:1101.0538, 2011.
- [18] J. Gao, M. Guzzi, J. Huston, H.-L. Lai, Z. Li, P. Nadolsky, J. Pumplin, D. Stump, C.-P. Yuan, CT10 next-to-next-to-leading order global analysis of QCD, Phys. Rev. D 89 (2014) 033009, <http://dx.doi.org/10.1103/PhysRevD.89.033009>, arXiv:1302.6246.
- [19] R.D. Ball, V. Bertone, S. Carrazza, C.S. Deans, L. Del Debbio, S. Forte, A. Guffanti, N.P. Hartland, J.I. Latorre, J. Rojo, M. Ubiali, NNPDF Collaboration, Parton distributions with LHC data, Nucl. Phys. B 867 (2013) 244, <http://dx.doi.org/10.1016/j.nuclphysb.2012.10.003>, arXiv:1207.1303.
- [20] T. Sjöstrand, S. Mrenna, P.Z. Skands, PYTHIA 6.4 physics and manual, J. High Energy Phys. 05 (2006) 026, <http://dx.doi.org/10.1088/1126-6708/2006/05/026>, arXiv:hep-ph/0603175.
- [21] J. Alwall, S. Höche, F. Krauss, N. Lavesson, L. Lönnblad, F. Maltoni, M.L. Mangano, M. Moretti, C.G. Papadopoulos, F. Piccinini, S. Schumann, M. Treccani, J. Winter, M. Worek, Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions, Eur. Phys. J. C 53 (2008) 473, <http://dx.doi.org/10.1140/epjc/s10052-007-0490-5>, arXiv:0706.2569.
- [22] P. Golonka, B. Kersevan, T. Pierzchala, E. Richter-Was, M. Worek, The tauola-photos-F environment for the TAUOLA and PHOTOS packages, release II, Comput. Phys. Commun. 174 (2006) 818, <http://dx.doi.org/10.1016/j.cpc.2005.12.018>, arXiv:hep-ph/0312240.
- [23] P. Artoisenet, R. Frederix, O. Mattelaer, R. Rietkerk, Automatic spin-entangled decays of heavy resonances in Monte Carlo simulations, J. High Energy Phys. 03 (2013) 015, [http://dx.doi.org/10.1007/JHEP03\(2013\)015](http://dx.doi.org/10.1007/JHEP03(2013)015), arXiv:1212.3460.
- [24] P. Nason, A New method for combining NLO QCD with shower Monte Carlo algorithms, J. High Energy Phys. 11 (2004) 040, <http://dx.doi.org/10.1088/1126-6708/2004/11/040>, arXiv:hep-ph/0409146.
- [25] S. Frixione, P. Nason, C. Oleari, Matching NLO QCD computations with parton shower simulations: the POWHEG method, J. High Energy Phys. 11 (2007) 070, <http://dx.doi.org/10.1088/1126-6708/2007/11/070>, arXiv:0709.2092.
- [26] S. Alioli, P. Nason, C. Oleari, E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX, J. High Energy Phys. 06 (2010) 043, [http://dx.doi.org/10.1007/JHEP06\(2010\)043](http://dx.doi.org/10.1007/JHEP06(2010)043), arXiv:1002.2581.
- [27] S. Alioli, P. Nason, C. Oleari, E. Re, NLO single-top production matched with shower in POWHEG: s- and t-channel contributions, J. High Energy Phys. 09 (2009) 111, <http://dx.doi.org/10.1088/1126-6708/2009/09/111>, arXiv:0907.4076; Erratum: [http://dx.doi.org/10.1007/JHEP02\(2010\)011](http://dx.doi.org/10.1007/JHEP02(2010)011).

- [28] E. Re, Single-top Wt-channel production matched with parton showers using the POWHEG method, Eur. Phys. J. C 71 (2011) 1547, <http://dx.doi.org/10.1140/epjc/s10052-011-1547-z>, arXiv:1009.2450.
- [29] CMS Collaboration, Measurement of the underlying event activity at the LHC with  $\sqrt{s} = 7$  TeV and comparison with  $\sqrt{s} = 0.9$  TeV, J. High Energy Phys. 11 (2011) 109, [http://dx.doi.org/10.1007/JHEP09\(2011\)109](http://dx.doi.org/10.1007/JHEP09(2011)109), arXiv:1107.0330.
- [30] P.M. Nadolsky, H.-L. Lai, Q.-H. Cao, J. Huston, J. Pumplin, D. Stump, W.-K. Tung, C.-P. Yuan, Implications of CTEQ global analysis for collider observables, Phys. Rev. D 78 (2008) 013004, <http://dx.doi.org/10.1103/PhysRevD.78.013004>, arXiv:0802.0007.
- [31] S. Agostinelli, et al., GEANT4 Collaboration, GEANT4—a simulation toolkit, Nucl. Instrum. Methods A 506 (2003) 250, [http://dx.doi.org/10.1016/S0168-9002\(03\)01368-8](http://dx.doi.org/10.1016/S0168-9002(03)01368-8).
- [32] J. Allison, et al., GEANT4 developments and applications, IEEE Trans. Nucl. Sci. 53 (2006) 270, <http://dx.doi.org/10.1109/TNS.2006.869826>.
- [33] CMS Collaboration, Particle flow event reconstruction in CMS and performance for jets, taus, and  $E_T^{\text{miss}}$ , CMS Physics Analysis Summary CMS-PAS-PFT-09-001, 2009, <http://cdsweb.cern.ch/record/1194487>.
- [34] CMS Collaboration, Commissioning of the particle flow event reconstruction with the first LHC collisions recorded in the CMS detector, CMS Physics Analysis Summary CMS-PAS-PFT-10-001, 2010, <http://cdsweb.cern.ch/record/1247373>.
- [35] CMS Collaboration, Electron reconstruction and identification at  $\sqrt{s} = 7$  TeV, CMS Physics Analysis Summary CMS-PAS-EGM-10-004, 2010, <http://cdsweb.cern.ch/record/1299116>.
- [36] CMS Collaboration, Performance of CMS muon reconstruction in pp collision events at  $\sqrt{s} = 7$  TeV, J. Instrum. 7 (2012) P10002, <http://dx.doi.org/10.1088/1748-0221/7/10/P10002>, arXiv:1206.4071.
- [37] M. Cacciari, G.P. Salam, G. Soyez, The anti- $k_t$  jet clustering algorithm, J. High Energy Phys. 04 (2008) 063, <http://dx.doi.org/10.1088/1126-6708/2008/04/063>, arXiv:0802.1189.
- [38] CMS Collaboration, Determination of jet energy calibration and transverse momentum resolution in CMS, J. Instrum. 6 (2011) P11002, <http://dx.doi.org/10.1088/1748-0221/6/11/P11002>, arXiv:1107.4277.
- [39] CMS Collaboration, Performance of tau lepton reconstruction and identification in CMS, J. Instrum. 7 (2012) P01001, <http://dx.doi.org/10.1088/1748-0221/7/01/P01001>, arXiv:1109.6034.
- [40] CMS Collaboration, Evidence for the 125 GeV Higgs boson decaying to a pair of  $\tau$  leptons, J. High Energy Phys. 05 (2014) 104, [http://dx.doi.org/10.1007/JHEP05\(2014\)104](http://dx.doi.org/10.1007/JHEP05(2014)104), arXiv:1401.5041.
- [41] CMS Collaboration, Identification of b-quark jets with the CMS experiment, J. Instrum. 8 (2013) P04013, <http://dx.doi.org/10.1088/1748-0221/8/04/P04013>, arXiv:1211.4462.
- [42] CMS Collaboration, Measurement of the top-quark mass in  $t\bar{t}$  events with dilepton final states in pp collisions at  $\sqrt{s} = 7$  TeV, Eur. Phys. J. C 72 (2012) 2202, <http://dx.doi.org/10.1140/epjc/s10052-012-2202-z>, arXiv:1209.2393.
- [43] CMS Collaboration, Measurement of the  $t\bar{t}$  production cross section and the top quark mass in the dilepton channel in pp collisions at  $\sqrt{s} = 7$  TeV, J. High Energy Phys. 07 (2011) 049, [http://dx.doi.org/10.1007/JHEP07\(2011\)049](http://dx.doi.org/10.1007/JHEP07(2011)049), arXiv:1105.5661.
- [44] CMS Collaboration, CMS luminosity based on pixel cluster counting – Summer 2013 update, CMS Physics Analysis Summary CMS-PAS-LUM-13-001, 2013, <http://cds.cern.ch/record/1598864?ln=en>.
- [45] S. Alioli, S.-O. Moch, P. Uwer, Hadronic top-quark pair-production with one jet and parton showering, J. High Energy Phys. 01 (2012) 137, [http://dx.doi.org/10.1007/JHEP01\(2012\)137](http://dx.doi.org/10.1007/JHEP01(2012)137), arXiv:1110.5251.
- [46] L. Lyons, D. Gibaut, P. Clifford, How to combine correlated estimates of a single physical quantity, Nucl. Instrum. Methods A 270 (1988) 110, [http://dx.doi.org/10.1016/0168-9002\(88\)90018-6](http://dx.doi.org/10.1016/0168-9002(88)90018-6).
- [47] ATLAS Collaboration, CDF Collaboration, CMS Collaboration, D0 Collaboration, First combination of Tevatron and LHC measurements of the top quark mass, arXiv:1403.4427, 2014.

## CMS Collaboration

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

*Yerevan Physics Institute, Yerevan, Armenia*

W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan<sup>1</sup>, M. Friedl, R. Frühwirth<sup>1</sup>, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler<sup>1</sup>, W. Kiesenhofer, V. Knünz, M. Krammer<sup>1</sup>, I. Krätschmer, D. Liko, I. Mikulec, D. Rabady<sup>2</sup>, B. Rahbaran, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz<sup>1</sup>

*Institut für Hochenergiephysik der OeAW, Wien, Austria*

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

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

S. Alderweireldt, M. Bansal, S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, S. Luyckx, S. Ochesanu, B. Roland, R. Rougny, M. Van De Klundert, H. Van Haeveermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

*Universiteit Antwerpen, Antwerpen, Belgium*

F. Blekman, S. Blyweert, J. D'Hondt, N. Daci, N. Heracleous, J. Keaveney, S. Lowette, M. Maes, A. Olbrechts, Q. Python, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

*Vrije Universiteit Brussel, Brussel, Belgium*

C. Caillol, B. Clerbaux, G. De Lentdecker, D. Dobur, L. Favart, A.P.R. Gay, A. Grebenyuk, A. Léonard, A. Mohammadi, L. Perniè<sup>2</sup>, T. Reis, T. Seva, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang

*Université Libre de Bruxelles, Bruxelles, Belgium*

V. Adler, K. Beernaert, L. Benucci, A. Cimmino, S. Costantini, S. Crucy, S. Dildick, A. Fagot, G. Garcia, J. Mccartin, A.A. Ocampo Rios, D. Ryckbosch, S. Salva Diblen, M. Sigamani, N. Strobbe, F. Thyssen, M. Tytgat, E. Yazgan, N. Zaganidis

*Ghent University, Ghent, Belgium*



S. Basegmez, C. Beluffi<sup>3</sup>, G. Bruno, R. Castello, A. Caudron, L. Ceard, G.G. Da Silveira, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco<sup>4</sup>, J. Hollar, P. Jez, M. Komm, V. Lemaître, C. Nuttens, D. Pagano, L. Perrini, A. Pin, K. Piotrkowski, A. Popov<sup>5</sup>, L. Quertenmont, M. Selvaggi, M. Vidal Marono, J.M. Vizan Garcia

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

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

*Université de Mons, Mons, Belgium*

W.L. Aldá Júnior, G.A. Alves, L. Brito, M. Correa Martins Junior, T. Dos Reis Martins, C. Mora Herrera, M.E. Pol

*Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*

W. Carvalho, J. Chinellato<sup>6</sup>, A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, J. Santaolalla, A. Santoro, A. Sznajder, E.J. Tonelli Manganote<sup>6</sup>, A. Vilela Pereira

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

C.A. Bernardes<sup>b</sup>, S. Dogra<sup>a</sup>, T.R. Fernandez Perez Tomei<sup>a</sup>, E.M. Gregores<sup>b</sup>, P.G. Mercadante<sup>b</sup>, S.F. Novaes<sup>a</sup>, Sandra S. Padula<sup>a</sup>

<sup>a</sup> *Universidade Estadual Paulista, São Paulo, Brazil*

<sup>b</sup> *Universidade Federal do ABC, São Paulo, Brazil*

A. Aleksandrov, V. Genchev<sup>2</sup>, P. Iaydjiev, A. Marinov, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, M. Vutova

*Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria*

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

*University of Sofia, Sofia, Bulgaria*

J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, R. Du, C.H. Jiang, S. Liang, R. Plestina<sup>7</sup>, J. Tao, X. Wang, Z. Wang

*Institute of High Energy Physics, Beijing, China*

C. Asawatangtrakuldee, Y. Ban, Y. Guo, Q. Li, W. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, L. Zhang, W. Zou

*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*

C. Avila, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

*Universidad de Los Andes, Bogota, Colombia*

N. Godinovic, D. Lelas, D. Polic, I. Puljak

*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia*

Z. Antunovic, M. Kovac

*University of Split, Faculty of Science, Split, Croatia*

V. Brigljevic, K. Kadija, J. Luetic, D. Mekterovic, L. Sudic

*Institute Rudjer Boskovic, Zagreb, Croatia*

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

*University of Cyprus, Nicosia, Cyprus*

M. Bodlak, M. Finger, M. Finger Jr.<sup>8</sup>

*Charles University, Prague, Czech Republic*

Y. Assran<sup>9</sup>, A. Ellithi Kamel<sup>10</sup>, M.A. Mahmoud<sup>11</sup>, A. Radi<sup>12,13</sup>

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

M. Kadastik, M. Murumaa, M. Raidal, A. Tiko

*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*

P. Eerola, G. Fedi, M. Voutilainen

*Department of Physics, University of Helsinki, Helsinki, Finland*

J. Härkönen, 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, L. Wendland

*Helsinki Institute of Physics, Helsinki, Finland*

T. Tuuva

*Lappeenranta University of Technology, Lappeenranta, Finland*

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, C. Favaro, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M. Titov

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

S. Baffioni, F. Beaudette, P. Busson, C. Charlot, T. Dahms, M. Dalchenko, L. Dobrzynski, N. Filipovic, A. Florent, R. Granier de Cassagnac, L. Mastrolorenzo, P. Miné, C. Mironov, I.N. Naranjo, M. Nguyen, C. Ochando, P. Paganini, S. Regnard, R. Salerno, J.B. Sauvan, Y. Sirois, C. Veelken, Y. Yilmaz, A. Zabi

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

J.-L. Agram<sup>14</sup>, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte<sup>14</sup>, J.-C. Fontaine<sup>14</sup>, D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, P. Van Hove

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

S. Gadrat

*Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France*

S. Beauceron, N. Beaupere, G. Boudoul<sup>2</sup>, E. Bouvier, S. Brochet, C.A. Carrillo Montoya, J. Chasserat, R. Chierici, D. Contardo<sup>2</sup>, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, J.D. Ruiz Alvarez, D. Sabes, L. Sgandurra, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret, H. Xiao

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

Z. Tsamalaidze<sup>8</sup>

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

C. Autermann, S. Beranek, M. Bontenackels, M. Edelhoff, L. Feld, O. Hindrichs, K. Klein, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, H. Weber, B. Wittmer, V. Zhukov<sup>5</sup>

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

M. Ata, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, S. Knutzen, P. Kreuzer, M. Merschmeyer, A. Meyer, P. Millet, M. Olschewski, K. Padeken, P. Papacz, H. Reithler, S.A. Schmitz, L. Sonnenschein, D. Teyssier, S. Thüer, M. Weber

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

V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, A. Heister, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, J. Lingemann<sup>2</sup>, A. Nowack, I.M. Nugent, L. Perchalla, O. Pooth, A. Stahl

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

I. Asin, N. Bartosik, J. Behr, W. Behrenhoff, U. Behrens, A.J. Bell, M. Bergholz<sup>15</sup>, A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, S. Choudhury, F. Costanza, C. Diez Pardos, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, T. Eichhorn, G. Flucke, J. Garay Garcia, A. Geiser, P. Gunnellini, J. Hauk, G. Hellwig, M. Hempel, D. Horton, H. Jung, A. Kalogeropoulos, M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, D. Krücker, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann<sup>15</sup>, B. Lutz, R. Mankel, I. Marfin, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, A. Nayak, O. Novgorodova, F. Nowak, E. Ntomari, H. Perrey, D. Pitzl, R. Placakyte, A. Raspereza, P.M. Ribeiro Cipriano, E. Ron, M.Ö. Sahin, J. Salfeld-Nebgen, P. Saxena, R. Schmidt<sup>15</sup>, T. Schoerner-Sadenius, M. Schröder, C. Seitz, S. Spannagel, A.D.R. Vargas Trevino, R. Walsh, C. Wissing

*Deutsches Elektronen-Synchrotron, Hamburg, Germany*

M. Aldaya Martin, V. Blobel, M. Centis Vignali, A.r. Draeger, J. Erfle, E. Garutti, K. Goebel, M. Görner, J. Haller, M. Hoffmann, R.S. Höing, H. Kirschenmann, R. Klanner, R. Kogler, J. Lange, T. Lapsien, T. Lenz, I. Marchesini, J. Ott, T. Peiffer, N. Pietsch, J. Poehlsen, T. Poehlsen, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, D. Troendle, E. Usai, L. Vanelderren

*University of Hamburg, Hamburg, Germany*

C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, F. Frensch, M. Giffels, F. Hartmann<sup>2</sup>, T. Hauth<sup>2</sup>, U. Husemann, I. Katkov<sup>5</sup>, A. Kornmayer<sup>2</sup>, E. Kuznetsova, P. Lobelle Pardo, M.U. Mozer, Th. Müller, A. Nürnberg, G. Quast, K. Rabbertz, F. Ratnikov, S. Röcker, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, R. Wolf

*Institut für Experimentelle Kernphysik, Karlsruhe, Germany*

G. Anagnostou, G. Daskalakis, T. Gerasis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, A. Markou, C. Markou, A. Psallidas, I. Topsis-Giotis

*Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece*

A. Panagiotou, N. Saoulidou, E. Stiliaris

*University of Athens, Athens, Greece*

X. Aslanoglou, I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, E. Paradas

*University of Ioánnina, Ioánnina, Greece*

G. Bencze, C. Hajdu, P. Hidas, D. Horvath<sup>16</sup>, F. Sikler, V. Veszpremi, G. Vesztergombi<sup>17</sup>, A.J. Zsigmond

*Wigner Research Centre for Physics, Budapest, Hungary*

N. Beni, S. Czellar, J. Karacsi<sup>18</sup>, J. Molnar, J. Palinkas, Z. Szillasi

*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*

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

*University of Debrecen, Debrecen, Hungary*

S.K. Swain

National Institute of Science Education and Research, Bhubaneswar, India

S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, U. Bhawandeep, A.K. Kalsi, M. Kaur, M. Mittal, N. Nishu, J.B. Singh

Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India

S. Banerjee, S. Bhattacharya, K. Chatterjee, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, A. Modak, S. Mukherjee, D. Roy, S. Sarkar, M. Sharan

Saha Institute of Nuclear Physics, Kolkata, India

A. Abdulsalam, D. Dutta, S. Kailas, V. Kumar, A.K. Mohanty<sup>2</sup>, L.M. Pant, P. Shukla, A. Topkar

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Banerjee, S. Bhowmik<sup>19</sup>, R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu<sup>20</sup>, G. Kole, S. Kumar, M. Maity<sup>19</sup>, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage<sup>21</sup>

Tata Institute of Fundamental Research, Mumbai, India

H. Bakhshiansohi, H. Behnamian, S.M. Etesami<sup>22</sup>, A. Fahim<sup>23</sup>, R. Goldouzian, A. Jafari, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, B. Safarzadeh<sup>24</sup>, M. Zeinali

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

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia<sup>a,b</sup>, L. Barbone<sup>a,b</sup>, C. Calabria<sup>a,b</sup>, S.S. Chhibra<sup>a,b</sup>, A. Colaleo<sup>a</sup>, D. Creanza<sup>a,c</sup>, N. De Filippis<sup>a,c</sup>, M. De Palma<sup>a,b</sup>, L. Fiore<sup>a</sup>, G. Iaselli<sup>a,c</sup>, G. Maggi<sup>a,c</sup>, M. Maggi<sup>a</sup>, S. My<sup>a,c</sup>, S. Nuzzo<sup>a,b</sup>, A. Pompili<sup>a,b</sup>, G. Pugliese<sup>a,c</sup>, R. Radogna<sup>a,b,2</sup>, G. Selvaggi<sup>a,b</sup>, L. Silvestris<sup>a,2</sup>, G. Singh<sup>a,b</sup>, R. Venditti<sup>a,b</sup>, P. Verwilligen<sup>a</sup>, G. Zito<sup>a</sup>

<sup>a</sup> INFN Sezione di Bari, Bari, Italy

<sup>b</sup> Università di Bari, Bari, Italy

<sup>c</sup> Politecnico di Bari, Bari, Italy

G. Abbiendi<sup>a</sup>, A.C. Benvenuti<sup>a</sup>, D. Bonacorsi<sup>a,b</sup>, S. Braibant-Giacomelli<sup>a,b</sup>, L. Brigliadori<sup>a,b</sup>, R. Campanini<sup>a,b</sup>, P. Capiluppi<sup>a,b</sup>, A. Castro<sup>a,b</sup>, F.R. Cavallo<sup>a</sup>, G. Codispoti<sup>a,b</sup>, M. Cuffiani<sup>a,b</sup>, G.M. Dallavalle<sup>a</sup>, F. Fabbri<sup>a</sup>, A. Fanfani<sup>a,b</sup>, D. Fasanella<sup>a,b</sup>, P. Giacomelli<sup>a</sup>, C. Grandi<sup>a</sup>, L. Guiducci<sup>a,b</sup>, S. Marcellini<sup>a</sup>, G. Masetti<sup>a,2</sup>, A. Montanari<sup>a</sup>, F.L. Navarria<sup>a,b</sup>, A. Perrotta<sup>a</sup>, F. Primavera<sup>a,b</sup>, A.M. Rossi<sup>a,b</sup>, T. Rovelli<sup>a,b</sup>, G.P. Siroli<sup>a,b</sup>, N. Tosi<sup>a,b</sup>, R. Travaglini<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Bologna, Bologna, Italy

<sup>b</sup> Università di Bologna, Bologna, Italy

S. Albergo<sup>a,b</sup>, G. Cappello<sup>a</sup>, M. Chiorboli<sup>a,b</sup>, S. Costa<sup>a,b</sup>, F. Giordano<sup>a,2</sup>, R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b</sup>, C. Tuve<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Catania, Catania, Italy

<sup>b</sup> Università di Catania, Catania, Italy

<sup>c</sup> CSFNSM, Catania, Italy

G. Barbagli <sup>a</sup>, V. Ciulli <sup>a,b</sup>, C. Civinini <sup>a</sup>, R. D'Alessandro <sup>a,b</sup>, E. Focardi <sup>a,b</sup>, E. Gallo <sup>a</sup>, S. Gonzi <sup>a,b</sup>, V. Gori <sup>a,b,2</sup>, P. Lenzi <sup>a,b</sup>, M. Meschini <sup>a</sup>, S. Paoletti <sup>a</sup>, G. Sguazzoni <sup>a</sup>, A. Tropiano <sup>a,b</sup>

<sup>a</sup> INFN Sezione di Firenze, Firenze, Italy

<sup>b</sup> Università di Firenze, Firenze, Italy

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

INFN Laboratori Nazionali di Frascati, Frascati, Italy

F. Ferro <sup>a</sup>, M. Lo Vetere <sup>a,b</sup>, E. Robutti <sup>a</sup>, S. Tosi <sup>a,b</sup>

<sup>a</sup> INFN Sezione di Genova, Genova, Italy

<sup>b</sup> Università di Genova, Genova, Italy

M.E. Dinardo <sup>a,b</sup>, P. Dini <sup>a</sup>, S. Fiorendi <sup>a,b,2</sup>, S. Gennai <sup>a,2</sup>, R. Gerosa <sup>2</sup>, A. Ghezzi <sup>a,b</sup>, P. Govoni <sup>a,b</sup>, M.T. Lucchini <sup>a,b,2</sup>, S. Malvezzi <sup>a</sup>, R.A. Manzoni <sup>a,b</sup>, A. Martelli <sup>a,b</sup>, B. Marzocchi, D. Menasce <sup>a</sup>, L. Moroni <sup>a</sup>, M. Paganoni <sup>a,b</sup>, S. Ragazzi <sup>a,b</sup>, N. Redaelli <sup>a</sup>, T. Tabarelli de Fatis <sup>a,b</sup>

<sup>a</sup> INFN Sezione di Milano-Bicocca, Milano, Italy

<sup>b</sup> Università di Milano-Bicocca, Milano, Italy

S. Buontempo <sup>a</sup>, N. Cavallo <sup>a,c</sup>, S. Di Guida <sup>a,d,2</sup>, F. Fabozzi <sup>a,c</sup>, A.O.M. Iorio <sup>a,b</sup>, L. Lista <sup>a</sup>, S. Meola <sup>a,d,2</sup>, M. Merola <sup>a</sup>, P. Paolucci <sup>a,2</sup>

<sup>a</sup> INFN Sezione di Napoli, Napoli, Italy

<sup>b</sup> Università di Napoli 'Federico II', Napoli, Italy

<sup>c</sup> Università della Basilicata (Potenza), Napoli, Italy

<sup>d</sup> Università G. Marconi (Roma), Napoli, Italy

P. Azzi <sup>a</sup>, N. Bacchetta <sup>a</sup>, D. Bisello <sup>a,b</sup>, A. Branca <sup>a,b</sup>, R. Carlin <sup>a,b</sup>, P. Checchia <sup>a</sup>, M. Dall'Osso <sup>a,b</sup>, T. Dorigo <sup>a</sup>, M. Galanti <sup>a,b</sup>, F. Gasparini <sup>a,b</sup>, U. Gasparini <sup>a,b</sup>, P. Giubilato <sup>a,b</sup>, A. Gozzelino <sup>a</sup>, K. Kanishchev <sup>a,c</sup>, S. Lacaprara <sup>a</sup>, M. Margoni <sup>a,b</sup>, A.T. Meneguzzo <sup>a,b</sup>, M. Passaseo <sup>a</sup>, J. Pazzini <sup>a,b</sup>, N. Pozzobon <sup>a,b</sup>, P. Ronchese <sup>a,b</sup>, F. Simonetto <sup>a,b</sup>, E. Torassa <sup>a</sup>, M. Tosi <sup>a,b</sup>, P. Zotto <sup>a,b</sup>, A. Zucchetta <sup>a,b</sup>, G. Zumerle <sup>a,b</sup>

<sup>a</sup> INFN Sezione di Padova, Padova, Italy

<sup>b</sup> Università di Padova, Padova, Italy

<sup>c</sup> Università di Trento (Trento), Padova, Italy

M. Gabusi <sup>a,b</sup>, S.P. Ratti <sup>a,b</sup>, C. Riccardi <sup>a,b</sup>, P. Salvini <sup>a</sup>, P. Vitulo <sup>a,b</sup>

<sup>a</sup> INFN Sezione di Pavia, Pavia, Italy

<sup>b</sup> Università di Pavia, Pavia, Italy

M. Biasini <sup>a,b</sup>, G.M. Bilei <sup>a</sup>, D. Ciangottini <sup>a,b</sup>, L. Fanò <sup>a,b</sup>, P. Lariccia <sup>a,b</sup>, G. Mantovani <sup>a,b</sup>, M. Menichelli <sup>a</sup>, F. Romeo <sup>a,b</sup>, A. Saha <sup>a</sup>, A. Santocchia <sup>a,b</sup>, A. Spiezia <sup>a,b,2</sup>

<sup>a</sup> INFN Sezione di Perugia, Perugia, Italy

<sup>b</sup> Università di Perugia, Perugia, Italy

K. Androsof <sup>a,25</sup>, P. Azzurri <sup>a</sup>, G. Bagliesi <sup>a</sup>, J. Bernardini <sup>a</sup>, T. Boccali <sup>a</sup>, G. Broccolo <sup>a,c</sup>, R. Castaldi <sup>a</sup>, M.A. Ciocci <sup>a,25</sup>, R. Dell'Orso <sup>a</sup>, S. Donato <sup>a,c</sup>, F. Fiori <sup>a,c</sup>, L. Foà <sup>a,c</sup>, A. Giassi <sup>a</sup>, M.T. Grippo <sup>a,25</sup>, F. Ligabue <sup>a,c</sup>, T. Lomtadze <sup>a</sup>, L. Martini <sup>a,b</sup>, A. Messineo <sup>a,b</sup>, C.S. Moon <sup>a,26</sup>, F. Palla <sup>a,2</sup>, A. Rizzi <sup>a,b</sup>, A. Savoy-Navarro <sup>a,27</sup>, A.T. Serban <sup>a</sup>, P. Spagnolo <sup>a</sup>, P. Squillacioti <sup>a,25</sup>, R. Tenchini <sup>a</sup>, G. Tonelli <sup>a,b</sup>, A. Venturi <sup>a</sup>, P.G. Verdini <sup>a</sup>, C. Vernieri <sup>a,c,2</sup>

<sup>a</sup> INFN Sezione di Pisa, Pisa, Italy

<sup>b</sup> Università di Pisa, Pisa, Italy

<sup>c</sup> Scuola Normale Superiore di Pisa, Pisa, Italy

L. Barone <sup>a,b</sup>, F. Cavallari <sup>a</sup>, G. D'imperio <sup>a,b</sup>, D. Del Re <sup>a,b</sup>, M. Diemoz <sup>a</sup>, M. Grassi <sup>a,b</sup>, C. Jorda <sup>a</sup>, E. Longo <sup>a,b</sup>, F. Margaroli <sup>a,b</sup>, P. Meridiani <sup>a</sup>, F. Micheli <sup>a,b,2</sup>, S. Nourbakhsh <sup>a,b</sup>, G. Organtini <sup>a,b</sup>, R. Paramatti <sup>a</sup>, S. Rahatlou <sup>a,b</sup>, C. Rovelli <sup>a</sup>, F. Santanastasio <sup>a,b</sup>, L. Soffi <sup>a,b,2</sup>, P. Traczyk <sup>a,b</sup>

<sup>a</sup> INFN Sezione di Roma, Roma, Italy

<sup>b</sup> Università di Roma, Roma, Italy

N. Amapane <sup>a,b</sup>, R. Arcidiacono <sup>a,c</sup>, S. Argiro <sup>a,b,2</sup>, M. Arneodo <sup>a,c</sup>, R. Bellan <sup>a,b</sup>, C. Biino <sup>a</sup>, N. Cartiglia <sup>a</sup>, S. Casasso <sup>a,b,2</sup>, M. Costa <sup>a,b</sup>, A. Degano <sup>a,b</sup>, N. Demaria <sup>a</sup>, L. Finco <sup>a,b</sup>, C. Mariotti <sup>a</sup>, S. Maselli <sup>a</sup>, E. Migliore <sup>a,b</sup>, V. Monaco <sup>a,b</sup>, M. Musich <sup>a</sup>, M.M. Obertino <sup>a,c,2</sup>, G. Ortona <sup>a,b</sup>, L. Pacher <sup>a,b</sup>, N. Pastrone <sup>a</sup>, M. Pelliccioni <sup>a</sup>, G.L. Pinna Angioni <sup>a,b</sup>, A. Potenza <sup>a,b</sup>, A. Romero <sup>a,b</sup>, M. Ruspa <sup>a,c</sup>, R. Sacchi <sup>a,b</sup>, A. Solano <sup>a,b</sup>, A. Staiano <sup>a</sup>, U. Tamponi <sup>a</sup>

<sup>a</sup> INFN Sezione di Torino, Torino, Italy

<sup>b</sup> Università di Torino, Torino, Italy

<sup>c</sup> Università del Piemonte Orientale (Novara), Torino, Italy

S. Belforte <sup>a</sup>, V. Candelise <sup>a,b</sup>, M. Casarsa <sup>a</sup>, F. Cossutti <sup>a</sup>, G. Della Ricca <sup>a,b</sup>, B. Gobbo <sup>a</sup>, C. La Licata <sup>a,b</sup>, M. Marone <sup>a,b</sup>, D. Montanino <sup>a,b</sup>, A. Schizzi <sup>a,b,2</sup>, T. Umer <sup>a,b</sup>, A. Zanetti <sup>a</sup>

<sup>a</sup> INFN Sezione di Trieste, Trieste, Italy

<sup>b</sup> Università di Trieste, Trieste, Italy

T.J. Kim

Chonbuk National University, Chonju, Republic of Korea

S. Chang, A. Kropivnitskaya, S.K. Nam

Kangwon National University, Chunchon, Republic of Korea

D.H. Kim, G.N. Kim, M.S. Kim, D.J. Kong, S. Lee, Y.D. Oh, H. Park, A. Sakharov, D.C. Son

Kyungpook National University, Daegu, Republic of Korea

J.Y. Kim, S. Song

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

S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, Y. Kim, B. Lee, K.S. Lee, S.K. Park, Y. Roh

Korea University, Seoul, Republic of Korea

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

University of Seoul, Seoul, Republic of Korea

Y. Choi, Y.K. Choi, J. Goh, D. Kim, E. Kwon, J. Lee, H. Seo, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

A. Juodagalvis

Vilnius University, Vilnius, Lithuania

J.R. Komaragiri, M.A.B. Md Ali

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz <sup>28</sup>, R. Lopez-Fernandez, A. Sanchez-Hernandez

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

S. Carrillo Moreno, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

I. Pedraza, H.A. Salazar Ibarguen

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

E. Casimiro Linares, A. Morelos Pineda

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

**D. Krofcheck***University of Auckland, Auckland, New Zealand***P.H. Butler, S. Reucroft***University of Canterbury, Christchurch, New Zealand***A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, S. Khalid, W.A. Khan, T. Khurshid, M.A. Shah, M. Shoaib***National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan***H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, P. Zalewski***National Centre for Nuclear Research, Swierk, Poland***G. Brona, K. Bunkowski, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, W. Wolszczak***Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland***P. Bargassa, C. Beirão Da Cruz E Silva, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, F. Nguyen, J. Rodrigues Antunes, J. Seixas, J. Varela, P. Vischia***Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal***I. Golutvin, V. Karjavin, V. Konoplyanikov, V. Korenkov, G. Kozlov, A. Lanev, A. Malakhov, V. Matveev<sup>29</sup>, V.V. Mitsyn, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, E. Tikhonenko, A. Zarubin***Joint Institute for Nuclear Research, Dubna, Russia***V. Golovtsov, Y. Ivanov, V. Kim<sup>30</sup>, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev***Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia***Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin***Institute for Nuclear Research, Moscow, Russia***V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, A. Spiridonov, V. Stolin, E. Vlasov, A. Zhokin***Institute for Theoretical and Experimental Physics, Moscow, Russia***V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, G. Mesyats, S.V. Rusakov, A. Vinogradov***P.N. Lebedev Physical Institute, Moscow, Russia***A. Belyaev, E. Boos, M. Dubinin<sup>31</sup>, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, M. Perfilov, S. Petrushanko, V. Savrin***Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia***I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov***State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia***P. Adzic<sup>32</sup>, M. Ekmedzic, J. Milosevic, V. Rekovic***University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia*

J. Alcaraz Maestre, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, E. Navarro De Martino, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares

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

C. Albajar, J.F. de Trocóniz, M. Missiroli, D. Moran

*Universidad Autónoma de Madrid, Madrid, Spain*

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

*Universidad de Oviedo, Oviedo, Spain*

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, G. Gomez, A. Graziano, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, R. Vilar Cortabitarte

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

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, A. Benaglia, J. Bendavid, L. Benhabib, J.F. Benitez, C. Bernet<sup>7</sup>, G. Bianchi, P. Bloch, A. Bocci, A. Bonato, O. Bondu, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, S. Colafranceschi<sup>33</sup>, M. D'Alfonso, D. d'Enterria, A. Dabrowski, A. David, F. De Guio, A. De Roeck, S. De Visscher, M. Dobson, M. Dordevic, N. Dupont-Sagorin, A. Elliott-Peisert, J. Eugster, G. Franzoni, W. Funk, D. Gigi, K. Gill, D. Giordano, M. Girone, F. Glege, R. Guida, S. Gundacker, M. Guthoff, J. Hammer, M. Hansen, P. Harris, J. Hegeman, V. Innocente, P. Janot, K. Kousouris, K. Krajczar, P. Lecoq, C. Lourenço, N. Magini, L. Malgeri, M. Mannelli, J. Marrouche, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, P. Musella, L. Orsini, L. Pape, E. Perez, L. Perrozzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, M. Plagge, A. Racz, G. Rolandi<sup>34</sup>, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas<sup>35</sup>, D. Spiga, J. Steggemann, B. Stieger, M. Stoye, D. Treille, A. Tsirou, G.I. Veres<sup>17</sup>, J.R. Vlimant, N. Wardle, H.K. Wöhri, H. Wollny, W.D. Zeuner

*CERN, European Organization for Nuclear Research, Geneva, Switzerland*

W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, D. Renker, T. Rohe

*Paul Scherrer Institut, Villigen, Switzerland*

F. Bachmair, L. Bäni, L. Bianchini, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, P. Eller, C. Grab, D. Hits, W. Lusterhmann, B. Mangano, A.C. Marini, P. Martinez Ruiz del Arbol, D. Meister, N. Mohr, C. Nägeli<sup>36</sup>, F. Nessi-Tedaldi, F. Pandolfi, F. Pauss, M. Peruzzi, M. Quittnat, L. Rebane, M. Rossini, A. Starodumov<sup>37</sup>, M. Takahashi, K. Theofilatos, R. Wallny, H.A. Weber

*Institute for Particle Physics, ETH Zurich, Zurich, Switzerland*

C. Amsler<sup>38</sup>, M.F. Canelli, V. Chiochia, A. De Cosa, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, B. Millan Mejias, J. Ngadiuba, P. Robmann, F.J. Ronga, S. Taroni, M. Verzetti, Y. Yang

*Universität Zürich, Zurich, Switzerland*

M. Cardaci, K.H. Chen, C. Ferro, C.M. Kuo, W. Lin, Y.J. Lu, R. Volpe, S.S. Yu

*National Central University, Chung-Li, Taiwan*



P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, U. Grundler, W.-S. Hou, K.Y. Kao, Y.J. Lei, Y.F. Liu, R.-S. Lu, D. Majumder, E. Petrakou, Y.M. Tzeng, R. Wilken

*National Taiwan University (NTU), Taipei, Taiwan*

B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

*Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand*

A. Adiguzel, M.N. Bakirci<sup>39</sup>, S. Cerci<sup>40</sup>, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, A. Kayis Topaksu, G. Onengut<sup>41</sup>, K. Ozdemir, S. Ozturk<sup>39</sup>, A. Polatoz, K. Sogut<sup>42</sup>, D. Sunar Cerci<sup>40</sup>, B. Tali<sup>40</sup>, H. Topakli<sup>39</sup>, M. Vergili

*Cukurova University, Adana, Turkey*

I.V. Akin, B. Bilin, S. Bilmis, H. Gamsizkan, G. Karapinar<sup>43</sup>, K. Ocalan, S. Sekmen, U.E. Surat, M. Yalvac, M. Zeyrek

*Middle East Technical University, Physics Department, Ankara, Turkey*

E. Gülmez, B. Isildak<sup>44</sup>, M. Kaya<sup>45</sup>, O. Kaya<sup>46</sup>

*Bogazici University, Istanbul, Turkey*

H. Bahtiyar<sup>47</sup>, E. Barlas, K. Cankocak, F.I. Vardarli, M. Yücel

*Istanbul Technical University, Istanbul, Turkey*

L. Levchuk, P. Sorokin

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

J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, Z. Meng, D.M. Newbold<sup>48</sup>, S. Paramesvaran, A. Poll, S. Senkin, V.J. Smith, T. Williams

*University of Bristol, Bristol, United Kingdom*

K.W. Bell, A. Belyaev<sup>49</sup>, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, W.J. Womersley, S.D. Worm

*Rutherford Appleton Laboratory, Didcot, United Kingdom*

M. Baber, R. Bainbridge, O. Buchmuller, D. Burton, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, G. Davies, M. Della Negra, P. Dunne, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, G. Hall, G. Iles, M. Jarvis, G. Karapostoli, M. Kenzie, R. Lane, R. Lucas<sup>48</sup>, L. Lyons, A.-M. Magnan, S. Malik, B. Mathias, J. Nash, A. Nikitenko<sup>37</sup>, J. Pela, M. Pesaresi, K. Petridis, D.M. Raymond, S. Rogerson, A. Rose, C. Seez, P. Sharp<sup>†</sup>, A. Tapper, M. Vazquez Acosta, T. Virdee

*Imperial College, London, United Kingdom*

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

*Brunel University, Uxbridge, United Kingdom*

J. Dittmann, K. Hatakeyama, A. Kasmi, H. Liu, T. Scarborough

*Baylor University, Waco, USA*

O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio

*The University of Alabama, Tuscaloosa, USA*

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

*Boston University, Boston, USA*

J. Alimena, E. Berry, S. Bhattacharya, G. Christopher, D. Cutts, Z. Demiragli, A. Ferapontov, A. Garabedian, U. Heintz, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, M. Segala, T. Sinthuprasith, T. Speer, J. Swanson

*Brown University, Providence, USA*

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, M. Gardner, W. Ko, R. Lander, T. Miceli, M. Mulhearn, D. Pellett, J. Pilot, F. Ricci-Tam, M. Searle, S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay

*University of California, Davis, Davis, USA*

R. Cousins, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, G. Rakness, E. Takasugi, V. Valuev, M. Weber

*University of California, Los Angeles, USA*

J. Babb, K. Burt, R. Clare, J. Ellison, J.W. Gary, G. Hanson, J. Heilman, M. Ivova Rikova, P. Jandir, E. Kennedy, F. Lacroix, H. Liu, O.R. Long, A. Luthra, M. Malberti, H. Nguyen, M. Olmedo Negrete, A. Shrinivas, S. Sumowidagdo, S. Wimpenny

*University of California, Riverside, Riverside, USA*

W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, R.T. D'Agnolo, D. Evans, A. Holzner, R. Kelley, D. Klein, M. Lebourgeois, J. Letts, I. Macneill, D. Olivito, S. Padhi, C. Palmer, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, C. Welke, F. Würthwein, A. Yagil, J. Yoo

*University of California, San Diego, La Jolla, USA*

D. Barge, J. Bradmiller-Feld, C. Campagnari, T. Danielson, A. Dishaw, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Incandela, C. Justus, N. Mccoll, J. Richman, D. Stuart, W. To, C. West

*University of California, Santa Barbara, Santa Barbara, USA*

A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, E. Di Marco, J. Duarte, A. Mott, H.B. Newman, C. Pena, C. Rogan, M. Spiropulu, V. Timciuc, R. Wilkinson, S. Xie, R.Y. Zhu

*California Institute of Technology, Pasadena, USA*

V. Azzolini, A. Calamba, B. Carlson, T. Ferguson, Y. Iiyama, M. Paulini, J. Russ, H. Vogel, I. Vorobiev

*Carnegie Mellon University, Pittsburgh, USA*

J.P. Cumalat, W.T. Ford, A. Gaz, E. Luiggi Lopez, U. Nauenberg, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner

*University of Colorado at Boulder, Boulder, USA*

J. Alexander, A. Chatterjee, J. Chu, S. Dittmer, N. Eggert, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Ryd, E. Salvati, L. Skinnari, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Tucker, Y. Weng, L. Winstrom, P. Wittich

*Cornell University, Ithaca, USA*

D. Winn

*Fairfield University, Fairfield, USA*

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, H.W.K. Cheung, F. Chlebana, S. Cihangir, V.D. Elvira, I. Fisk, J. Freeman, Y. Gao, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, D. Hare, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, K. Kaadze, B. Klima, B. Kreis, S. Kwan, J. Linacre, D. Lincoln, R. Lipton, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, V.I. Martinez Outschoorn, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko<sup>29</sup>, S. Nahn, C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, S. Sharma, A. Soha, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, A. Whitbeck, J. Whitmore, F. Yang

*Fermi National Accelerator Laboratory, Batavia, USA*

D. Acosta, P. Avery, D. Bourilkov, M. Carver, T. Cheng, D. Curry, S. Das, M. De Gruttola, G.P. Di Giovanni, R.D. Field, M. Fisher, I.K. Furic, J. Hugon, J. Konigsberg, A. Korytov, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic<sup>50</sup>, G. Mitselmakher, L. Muniz, A. Rinkevicius, L. Shchutska, M. Snowball, J. Yelton, M. Zakaria

*University of Florida, Gainesville, USA*

S. Hewamanage, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

*Florida International University, Miami, USA*

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

*Florida State University, Tallahassee, USA*

M.M. Baarmand, M. Hohlmann, H. Kalakhety, F. Yumiceva

*Florida Institute of Technology, Melbourne, USA*

M.R. Adams, L. Apanasevich, V.E. Bazterra, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, P. Kurt, D.H. Moon, C. O'Brien, C. Silkworth, P. Turner, N. Varelas

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

E.A. Albayrak<sup>47</sup>, B. Bilki<sup>51</sup>, W. Clarida, K. Dilsiz, F. Duru, M. Haytmyradov, J.-P. Merlo, H. Mermerkaya<sup>52</sup>, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok<sup>47</sup>, A. Penzo, R. Rahmat, S. Sen, P. Tan, E. Tiras, J. Wetzel, T. Yetkin<sup>53</sup>, K. Yi

*The University of Iowa, Iowa City, USA*

B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, A.V. Gritsan, P. Maksimovic, C. Martin, M. Swartz

*Johns Hopkins University, Baltimore, USA*

P. Baringer, A. Bean, G. Benelli, C. Bruner, J. Gray, R.P. Kenny III, M. Malek, M. Murray, D. Noonan, S. Sanders, J. Sekaric, R. Stringer, Q. Wang, J.S. Wood

*The University of Kansas, Lawrence, USA*

A.F. Barfuss, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, L.K. Saini, S. Shrestha, N. Skhirtladze, I. Svintradze

*Kansas State University, Manhattan, USA*

J. Gronberg, D. Lange, F. Rebassoo, D. Wright

*Lawrence Livermore National Laboratory, Livermore, USA*

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

*University of Maryland, College Park, USA*

A. Apyan, R. Barbieri, G. Bauer, W. Busza, I.A. Cali, M. Chan, L. Di Matteo, V. Dutta, G. Gomez Ceballos, M. Goncharov, D. Gulhan, M. Klute, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, T. Ma, C. Paus, D. Ralph, C. Roland, G. Roland, G.S.F. Stephans, F. Stöckli, K. Sumorok, D. Velicanu, J. Veverka, B. Wyslouch, M. Yang, M. Zanetti, V. Zhukova

*Massachusetts Institute of Technology, Cambridge, USA*

B. Dahmes, A. Gude, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, N. Pastika, R. Rusack, A. Singovsky, N. Tambe, J. Turkewitz

*University of Minnesota, Minneapolis, USA*

J.G. Acosta, S. Oliveros

*University of Mississippi, Oxford, USA*

E. Avdeeva, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, R. Gonzalez Suarez, J. Keller, D. Knowlton, I. Kravchenko, J. Lazo-Flores, S. Malik, F. Meier, G.R. Snow

*University of Nebraska-Lincoln, Lincoln, USA*

J. Dolen, A. Godshalk, I. Iashvili, A. Kharchilava, A. Kumar, S. Rappoccio

*State University of New York at Buffalo, Buffalo, USA*

G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, J. Haley, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, D. Trocino, R.J. Wang, D. Wood, J. Zhang

*Northeastern University, Boston, USA*

K.A. Hahn, A. Kubik, N. Mucia, N. Odell, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, K. Sung, M. Velasco, S. Won

*Northwestern University, Evanston, USA*

A. Brinkerhoff, K.M. Chan, A. Drozdetskiy, M. Hildreth, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, W. Luo, S. Lynch, N. Marinelli, T. Pearson, M. Planer, R. Ruchti, N. Valls, M. Wayne, M. Wolf, A. Woodard

*University of Notre Dame, Notre Dame, USA*

L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, D. Puigh, M. Rodenburg, G. Smith, B.L. Winer, H. Wolfe, H.W. Wulsin

*The Ohio State University, Columbus, USA*

O. Driga, P. Elmer, P. Hebda, A. Hunt, S.A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, H. Saka, D. Stickland<sup>2</sup>, C. Tully, J.S. Werner, S.C. Zenz, A. Zuranski

*Princeton University, Princeton, USA*

E. Brownson, H. Mendez, J.E. Ramirez Vargas

*University of Puerto Rico, Mayaguez, USA*

E. Alagoz, V.E. Barnes, D. Benedetti, G. Bolla, D. Bortoletto, M. De Mattia, Z. Hu, M.K. Jha, M. Jones, K. Jung, M. Kress, N. Leonardo, D. Lopes Pegna, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, B.C. Radburn-Smith, X. Shi, I. Shipsey, D. Silvers, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu, H.D. Yoo, J. Zablocki, Y. Zheng

*Purdue University, West Lafayette, USA*

N. Parashar, J. Stupak

*Purdue University Calumet, Hammond, USA*

A. Adair, B. Akgun, K.M. Ecklund, F.J.M. Geurts, W. Li, B. Michlin, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

*Rice University, Houston, USA*

B. Betchart, A. Bodek, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, A. Khukhunaishvili, G. Petrillo, D. Vishnevskiy

*University of Rochester, Rochester, USA*

R. Ciesielski, L. Demortier, K. Goulianos, G. Lungu, C. Mesropian

*The Rockefeller University, New York, USA*

S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, A. Lath, S. Panwalkar, M. Park, R. Patel, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

*Rutgers, The State University of New Jersey, Piscataway, USA*

K. Rose, S. Spanier, A. York

*University of Tennessee, Knoxville, USA*

O. Bouhali<sup>54</sup>, A. Castaneda Hernandez, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon<sup>55</sup>, V. Khotilovich, V. Krutelyov, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Rose, A. Safonov, T. Sakuma, I. Suarez, A. Tatarinov

*Texas A&M University, College Station, USA*

N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Duderov, J. Faulkner, K. Kovitangoon, S. Kunori, S.W. Lee, T. Libeiro, I. Volobouev

*Texas Tech University, Lubbock, USA*

E. Appelt, A.G. Delannoy, S. Greene, A. Gurrola, W. Johns, C. Maguire, Y. Mao, A. Melo, M. Sharma, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

*Vanderbilt University, Nashville, USA*

M.W. Arenton, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Lin, C. Neu, J. Wood

*University of Virginia, Charlottesville, USA*

C. Clarke, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, J. Sturdy

*Wayne State University, Detroit, USA*

D.A. Belknap, D. Carlsmith, M. Cepeda, S. Dasu, L. Dodd, S. Duric, E. Friis, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbbers, A. Lanaro, C. Lazaridis, A. Levine, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, I. Ross, T. Sarangi, A. Savin, W.H. Smith, C. Vuosalo, N. Woods

*University of Wisconsin, Madison, USA*

<sup>†</sup> Deceased.

<sup>1</sup> Also at Vienna University of Technology, Vienna, Austria.

<sup>2</sup> Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

<sup>3</sup> Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.

<sup>4</sup> Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.

<sup>5</sup> Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

<sup>6</sup> Also at Universidade Estadual de Campinas, Campinas, Brazil.

<sup>7</sup> Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3–CNRS, Palaiseau, France.

<sup>8</sup> Also at Joint Institute for Nuclear Research, Dubna, Russia.

<sup>9</sup> Also at Suez University, Suez, Egypt.

- 10 Also at Cairo University, Cairo, Egypt.
- 11 Also at Fayoum University, El-Fayoum, Egypt.
- 12 Also at British University in Egypt, Cairo, Egypt.
- 13 Now at Ain Shams University, Cairo, Egypt.
- 14 Also at Université de Haute Alsace, Mulhouse, France.
- 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 University of Debrecen, Debrecen, Hungary.
- 19 Also at University of Visva-Bharati, Santiniketan, India.
- 20 Now at King Abdulaziz University, Jeddah, Saudi Arabia.
- 21 Also at University of Ruhuna, Matara, Sri Lanka.
- 22 Also at Isfahan University of Technology, Isfahan, Iran.
- 23 Also at Sharif University of Technology, Tehran, Iran.
- 24 Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
- 25 Also at Università degli Studi di Siena, Siena, Italy.
- 26 Also at Centre National de la Recherche Scientifique (CNRS) – IN2P3, Paris, France.
- 27 Also at Purdue University, West Lafayette, USA.
- 28 Also at Universidad Michoacana de San Nicolas de Hidalgo, Morelia, Mexico.
- 29 Also at Institute for Nuclear Research, Moscow, Russia.
- 30 Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- 31 Also at California Institute of Technology, Pasadena, USA.
- 32 Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- 33 Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.
- 34 Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
- 35 Also at University of Athens, Athens, Greece.
- 36 Also at Paul Scherrer Institut, Villigen, Switzerland.
- 37 Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
- 38 Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
- 39 Also at Gaziosmanpasa University, Tokat, Turkey.
- 40 Also at Adiyaman University, Adiyaman, Turkey.
- 41 Also at Cag University, Mersin, Turkey.
- 42 Also at Mersin University, Mersin, Turkey.
- 43 Also at Izmir Institute of Technology, Izmir, Turkey.
- 44 Also at Ozyegin University, Istanbul, Turkey.
- 45 Also at Marmara University, Istanbul, Turkey.
- 46 Also at Kafkas University, Kars, Turkey.
- 47 Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
- 48 Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- 49 Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- 50 Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
- 51 Also at Argonne National Laboratory, Argonne, USA.
- 52 Also at Erzincan University, Erzincan, Turkey.
- 53 Also at Yildiz Technical University, Istanbul, Turkey.
- 54 Also at Texas A&M University at Qatar, Doha, Qatar.
- 55 Also at Kyungpook National University, Daegu, Republic of Korea.