



# Measurement of the cross section ratio $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$ in pp collisions at $\sqrt{s} = 8$ TeV



CMS Collaboration\*

CERN, Switzerland

## ARTICLE INFO

### Article history:

Received 20 November 2014  
 Received in revised form 31 March 2015  
 Accepted 28 April 2015  
 Available online 30 April 2015  
 Editor: M. Doser

### Keywords:

CMS  
 Physics  
 Top physics

## ABSTRACT

The first measurement of the cross section ratio  $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$  is presented using a data sample corresponding to an integrated luminosity of  $19.6 \text{ fb}^{-1}$  collected in pp collisions at  $\sqrt{s} = 8$  TeV with the CMS detector at the LHC. Events with two leptons (e or  $\mu$ ) and four reconstructed jets, including two identified as b quark jets, in the final state are selected. The ratio is determined for a minimum jet transverse momentum  $p_T$  of both 20 and 40 GeV/c. The measured ratio is  $0.022 \pm 0.003$  (stat)  $\pm 0.005$  (syst) for  $p_T > 20$  GeV/c. The absolute cross sections  $\sigma_{t\bar{t}b\bar{b}}$  and  $\sigma_{t\bar{t}jj}$  are also measured. The measured ratio for  $p_T > 40$  GeV/c is compatible with a theoretical quantum chromodynamics calculation at next-to-leading order.

© 2015 CERN for the benefit of the CMS Collaboration. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>). Funded by SCOAP<sup>3</sup>.

## 1. Introduction

With the observation of a new boson at a mass around  $125 \text{ GeV}/c^2$  [1–3] whose properties are consistent with those of the standard model (SM) Higgs boson H [4–9], the SM appears to be complete. One of the most sensitive channels in the discovery of the Higgs boson,  $H \rightarrow \gamma\gamma$ , is expected to have top quark loops both in the production and decay of the Higgs boson in the SM. Hence, it is important to determine the couplings of the new boson to fermions, especially to the top quark. In the SM, one of the most promising channels for a direct measurement of the top quark Yukawa coupling is the production of the Higgs boson in association with a  $t\bar{t}$  pair ( $t\bar{t}H$ ), where the Higgs boson decays to  $b\bar{b}$ , thus leading to a  $t\bar{t}b\bar{b}$  final state.

The expected quantum chromodynamics (QCD) cross section for  $t\bar{t}H$  production in pp collisions at  $\sqrt{s} = 8$  TeV, calculated to next-to-leading order (NLO), is  $0.128_{-0.012}^{+0.005}$  (scale)  $\pm 0.010$  pb (PDF +  $\alpha_S$ ) [10], where the uncertainty labelled “scale” refers to the uncertainty from the factorization and renormalization scales ( $\mu_F$  and  $\mu_R$ ), and the uncertainty labelled “PDF +  $\alpha_S$ ” comes from the uncertainties in the parton distribution functions (PDFs) and the strong coupling constant  $\alpha_S$ . This final state, which has not yet been observed, has an irreducible nonresonant background from the production of a top quark pair in association with a b quark pair. Calculations of the inclusive production cross section for  $t\bar{t}$  events with additional jets have been performed to NLO precision [11–16].

For a proton–proton centre-of-mass energy of 8 TeV, the predictions for the production of a top quark pair with two additional jets  $t\bar{t}jj$  and with two additional b quark jets  $t\bar{t}b\bar{b}$  are  $\sigma_{t\bar{t}jj} = 21.0 \pm 2.9$  (scale) pb and  $\sigma_{t\bar{t}b\bar{b}} = 0.23 \pm 0.05$  (scale) pb, respectively [16]. In this calculation, the additional jets are required to have transverse momenta  $p_T > 40$  GeV/c and absolute pseudorapidity  $|\eta| < 2.5$ , while for the  $t\bar{t}H$  production value quoted above, no such requirements are applied to the decay products of the Higgs boson. The dominant uncertainties in these calculations are from the factorization and renormalization scales [17,18] caused by the presence of two very different scales in this process, the top quark mass and the jet  $p_T$ . Therefore, experimental measurements of  $\sigma_{t\bar{t}jj}$  and  $\sigma_{t\bar{t}b\bar{b}}$  production can provide a good test of NLO QCD theory and important input about the main background in the search for the  $t\bar{t}H$  process.

In this Letter, the first measurements of the cross sections  $\sigma_{t\bar{t}b\bar{b}}$  and  $\sigma_{t\bar{t}jj}$  and their ratio are presented. The analyzed data sample of pp collisions at a centre-of-mass energy of 8 TeV was collected with the CMS experiment at the CERN LHC and corresponds to an integrated luminosity of  $19.6 \pm 0.5 \text{ fb}^{-1}$  [19]. The primary motivation for measuring the cross section ratio is that many kinematic distributions are expected to be similar for  $t\bar{t}b\bar{b}$  and  $t\bar{t}jj$ , leading to reduced systematic uncertainties in the ratio.

## 2. CMS detector and event reconstruction

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the superconducting solenoid volume are a sili-

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

con pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors.

The particle-flow event algorithm reconstructs and identifies each single particle with an optimized combination of all subdetector information [20,21]. The energy of photons is directly obtained from the ECAL measurement, corrected for zero-suppression effects. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for zero-suppression effects and for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energy.

Jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be within 5 to 10% of the true momentum over the whole  $p_T$  spectrum and detector acceptance. An offset correction is applied to take into account the extra energy clustered in jets due to additional proton–proton interactions within the same bunch crossing (pileup). Jet energy corrections are derived from simulation, and are confirmed with in situ measurements with the energy balance of dijet and photon+jet events. Additional selection criteria are applied to each event to remove spurious jet-like features originating from isolated noise patterns in certain HCAL regions.

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [22].

### 3. Simulation and definition of signal events

Monte Carlo (MC) simulated data samples for the  $t\bar{t}$  signal are generated by the MADGRAPH (v. 5.1.3.30) event generator [23] with matrix elements (ME) at leading order, allowing up to three additional partons including b quarks. The generated events are interfaced with PYTHIA (v. 6.426) [24] to provide the showering of the partons, and to perform the matching of the soft radiation with the contributions from the ME. The  $\tau$  lepton decays are handled with TAUOLA (v. 2.75) [25]. The POWHEG (v. 1.0) generator [26–28] at NLO, interfaced with PYTHIA, is used for cross-checks and systematic studies. A  $Z/\gamma^* + \text{jets}$  background sample is simulated in MADGRAPH. The  $t\bar{t}H$  process is modelled using PYTHIA. The electroweak production of single top quarks ( $pp \rightarrow tW$  and  $pp \rightarrow t\bar{W}$ ) is simulated in POWHEG with an approximate next-to-next-to-leading-order (NNLO) cross section calculation [29]. The CTEQ6L1 [30] set of PDFs is used for the MADGRAPH and PYTHIA samples, while the CTEQ6M [31] set is used for the POWHEG samples. The CMS detector response is simulated using GEANT4 (v. 9.4) [32]. The pileup distribution used in the simulation is weighted to match the one observed in data.

Measurements are reported for two different regions of the phase space: a visible phase space and the full phase space. In the visible phase space, all  $t\bar{t}b\bar{b}$  final state particles ( $t\bar{t}b\bar{b} \rightarrow bW^+ \bar{b}W^- b\bar{b} \rightarrow b\ell^+ \nu \bar{b}\ell^- \bar{\nu} b\bar{b}$ ) except the neutrinos, i.e. the charged leptons and jets originating from the decays of the top quarks, as well as the two additional b quark jets (“b jets”), are required

to be within the same experimentally accessible kinematic region. Simulated  $t\bar{t}b\bar{b}$  events are defined to be in the visible phase space and are categorized as coming from the  $t\bar{t}jj$  process if they contain, at the generator level, at least four particle-level jets, including at least two jets originating from b quarks, and two leptons ( $t\bar{t}jj \rightarrow bW^+ \bar{b}W^- jj \rightarrow b\ell^+ \nu \bar{b}\ell^- \bar{\nu} jj$ ). Each lepton must have  $p_T > 20$  GeV/c,  $|\eta| < 2.4$ , and come from the decay of a W boson from one of the top quarks. Electrons or muons originating from the leptonic decays of  $\tau$  leptons produced in  $W \rightarrow \tau\nu$  decays are included. Jets which are within  $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} < 0.5$  of an identified electron or muon are removed, where  $\Delta\phi$  and  $\Delta\eta$  are the differences in azimuthal angle and pseudorapidity between the directions of the jets and the lepton. The particle-level jets are obtained by combining all final-state particles, excluding neutrinos, at the generator level with an anti- $k_T$  clustering algorithm [33] with a distance parameter of 0.5 and are required to satisfy  $|\eta| < 2.5$  and  $p_T > 20$  GeV/c, which is lower than the reconstructed minimum jet  $p_T$ , as described below. The b and c quark jets (“c jets”) are identified by the presence of corresponding hadrons containing a b or c quark among the ancestors of the jet constituents. In the case where two jets contain the decay products of the same b hadron, the jet with the higher  $p_T$  is selected as the b jet. When a b hadron is successfully matched, the c quarks are not considered.

The  $t\bar{t}jj$  sample is composed of four components, distinguished by the flavour of the two jets in addition to the two b jets required from the top quark decays. The four components are the  $t\bar{t}b\bar{b}$  final state with two b jets, the  $t\bar{t}bj$  final state with one b jet and one lighter-flavour jet, the  $t\bar{t}c\bar{c}$  final state with two c jets, and the  $t\bar{t}LF$  final state with two light-flavour jets (from a gluon or u, d, or s quark) or one light-flavour jet and one c jet. The  $t\bar{t}bj$  final state is mainly from the merging of two b jets or the loss of one of the b jets caused by the acceptance requirements. Efficiency corrections to the measurement for the visible phase space are mainly from detector effects. The results for the visible phase space are compared with those from MC simulations.

The goal of the full phase space result is to provide a comparison to theoretical calculations, which are generally performed at the parton level. To obtain a full phase space MC sample, the jet reconstruction is performed on the partons (gluons, as well as quarks lighter than top) before hadronization, as well as  $\tau$  leptons that decay hadronically. As the full hadronization and decay chain is known, only  $\tau$  leptons that decay hadronically and partons that lead to hadrons are included. The jet reconstruction algorithm is the same as for the visible phase space. Following the jet reconstruction, b jets are identified with a  $\Delta R < 0.5$  requirement between the b quarks and parton-level jets, where  $\Delta\phi$  and  $\Delta\eta$  are the azimuthal angle and pseudorapidity differences, respectively, between the directions of the b quark and the parton-level jet. For comparison with theoretical predictions [16], results are quoted for two different jet  $p_T$  thresholds of  $p_T > 20$  and  $> 40$  GeV/c on the jets not arising from top quark decays. To clarify the phase space definition, the objects on which the selections are applied are listed in Table 1.

### 4. Event selection and background estimation

The events are recorded using dilepton triggers with asymmetric thresholds of 8 and 17 GeV/c on the transverse momentum of the leptons. Jets are reconstructed using the same algorithm as in the simulations. The leptons and all charged hadrons that are associated with jets are required to originate from the primary vertex, defined as the vertex with the highest  $\sum p_T^2$  of its associated tracks. Muon candidates are reconstructed by combining information from the silicon tracker and the muon system [34]. Muon candidates are further required to have a minimum number of hits

**Table 1**

The objects used to define the visible and full phase space are listed. Details of the parton- and particle-level definitions are described in the text. The symbol  $t$  denotes a top quark.

Phase Space (PS)	Parton level	Particle level
Visible PS	–	4 (b) jets and 2 leptons ( $e, \mu$ )
Full PS	$t, \bar{t}$ and 2 (b) jets (not from $t$ or $\bar{t}$ )	–

in the silicon tracker and to have a high-quality global fit including a minimum number of hits in the muon detector. Electron candidates are reconstructed by combining a track with energy deposits in the ECAL, taking into account bremsstrahlung photons. Requirements on electron identification variables based on shower shape and track-cluster matching are applied to the reconstructed candidates [35,36]. Muons and electrons must have  $p_T > 20$  GeV/ $c$  and  $|\eta| < 2.4$ .

To reduce the background contributions of muons or electrons from semileptonic heavy-flavour decays, relative isolation criteria are applied. The relative isolation parameter,  $I_{\text{rel}}$ , is defined as the ratio of the sum of the transverse momenta of all objects in a cone of  $\Delta R < 0.3$  around the lepton  $p_T$  direction to the lepton  $p_T$ . The objects considered are the charged hadrons associated with the primary vertex as well as the neutral hadrons and photons, whose energies are corrected for the energy from pileup. Thus,

$$I_{\text{rel}} = \frac{\sum p_T^{\text{charged hadron}} + \sum p_T^{\text{neutral hadron}} + \sum p_T^{\text{photon}}}{p_T^{\text{lepton}}}. \quad (1)$$

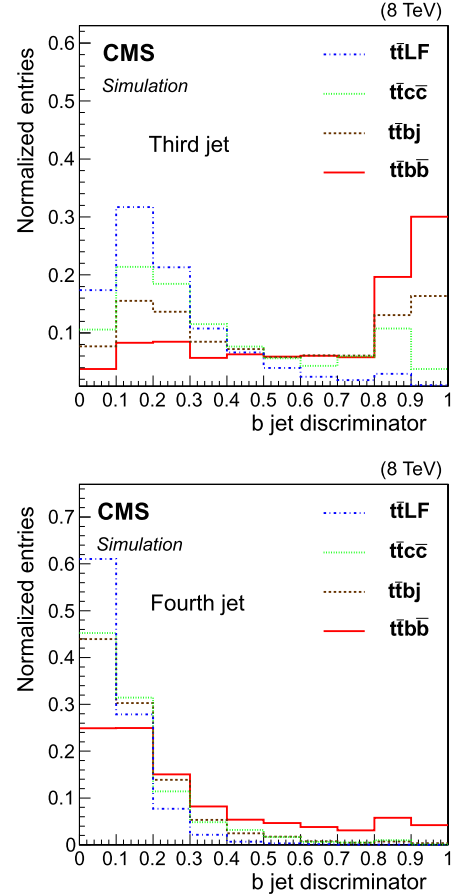
Leptons are required to have  $I_{\text{rel}} < 0.15$ . The efficiencies for the above lepton identification requirements are measured using Z boson candidates in data and are found to be consistent with the values from the simulation. The residual differences are applied as a correction to the simulation.

The event selection requires the presence of two isolated opposite-sign leptons of invariant mass  $M_{\ell\ell} > 12$  GeV/ $c^2$ . Lepton pairs of the same flavour ( $e^+e^-$ ,  $\mu^+\mu^-$ ) are rejected if their invariant mass is within 15 GeV/ $c^2$  of the Z boson mass. The missing transverse energy ( $E_T^{\text{miss}}$ ) is defined as the magnitude of the vectorial sum of the transverse momenta of all reconstructed particles in the event [37]. In the same-flavour channels, remaining backgrounds from  $Z/\gamma^* + \text{jets}$  processes are suppressed by demanding  $E_T^{\text{miss}} > 30$  GeV. For the  $e^\pm\mu^\mp$  channel, no  $E_T^{\text{miss}}$  requirement is applied.

Four or more reconstructed jets are required with  $|\eta| < 2.5$  and  $p_T > 30$  GeV/ $c$ , of which at least two jets must be identified as b jets, using a combined secondary vertex (CSV) algorithm, which combines secondary vertex information with lifetime information of single tracks to produce a b-tagging discriminator [38]. A tight b-tagging requirement on this discriminator is applied, which has an efficiency of about 45% for b jets and a misidentification probability of 0.1% for light-flavour jets.

Differences in the b-tagging efficiencies between data and simulation [38] are accounted for by reweighting the shape of the CSV b-tagging discriminator distribution in the simulation to match that in the data. Data/MC scale factors for this  $p_T$ - and  $\eta$ -dependent correction are derived separately for light- and heavy-flavour jets. The scale factor for c jets is not measured, owing to the limited amount of data, and is set to unity. Light-flavour scale factors are determined from a control sample enriched in events with a Z boson and exactly two jets. Heavy-flavour scale factors are derived from a  $t\bar{t}$  enriched sample with exactly two jets, excluding  $Z \rightarrow \ell\ell$  events.

The background contributions arising from  $Z/\gamma^* + \text{jets}$  events is estimated in data using the number of events having a dilepton invariant mass of  $76 < M_{\ell\ell} < 106$  GeV/ $c^2$ , scaled by the ratio



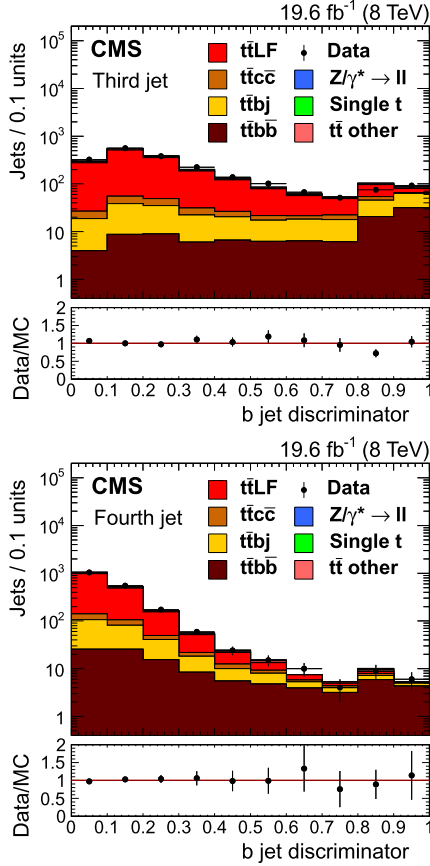
**Fig. 1.** Normalized distributions of the b jet discriminator for the third (top) and fourth (bottom) jets in an event, sorted in decreasing order of b-tagging discriminator value, after the full event selection. The histograms are obtained from MC simulation and are separated according to jet flavour.

of events that fail and pass this selection in the Drell–Yan simulation [39,40]. The multijet and diboson background contributions are negligible after the full event selection.

## 5. Measurement

After the full event selection, the three dilepton categories  $ee$ ,  $\mu\mu$ , and  $e\mu$  are combined, and the ratio of the number of  $t\bar{t}b\bar{b}$  events to  $t\bar{t}j\bar{j}$  events is obtained from the data by fitting the CSV b-tagging discriminator distributions. The distributions of the discriminator from simulation for the third and fourth jets in decreasing order of the b-tagging discriminator, i.e. for the two additional jets not identified as coming from the top quark decays, are shown in Fig. 1. The third and fourth jets from  $t\bar{t}j\bar{j}$  events tend to be light-flavour jets, while these are heavy-flavour jets for  $t\bar{t}b\bar{b}$  events. These two distributions are used to separate  $t\bar{t}b\bar{b}$  from other processes.

Fig. 2 shows the b-tagging discriminator distributions of the third and fourth jets in the events from data and simulation, where the simulation histograms have been scaled to the fit result. The



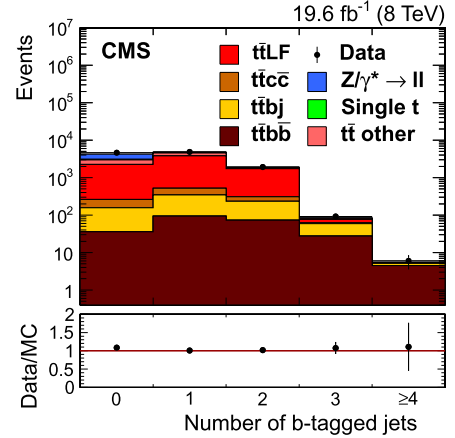
**Fig. 2.** Distributions of b jet discriminator for the third (top) and fourth (bottom) jets in events in decreasing order of b-tagging discriminator value, after the full event selection. Points are from data and stacked histograms from MC simulation using results from the fit to data. The ratio of the number of data events to the total number of MC events after the fit is shown in the lower panels.

fit is performed on both distributions simultaneously, and contains two free parameters, an overall normalization and the ratio of the number of  $t\bar{t}b\bar{b}$  events to  $t\bar{t}j$  events. The  $t\bar{t}c\bar{c}$  and  $t\bar{t}LF$  contributions are combined, and the ratio of the  $t\bar{t}b\bar{b}$  to  $t\bar{t}bj$  contributions is constrained using the predictions from the MC simulation. Additionally, the background contributions from single top production and from  $t\bar{t}$  events that fail the visible phase space requirements (labelled “tt other”) are scaled by the normalization parameter. The contribution from  $Z/\gamma^* +$  jets is fixed from data, as described above. Nuisance parameters are used to account for the uncertainties in the background contributions.

The b-tagged jet multiplicity distribution in Fig. 3 shows the comparison between data and the MC simulation, scaled by the fit results to the data. The results, which include the requirement of four jets but not the b-tagging requirement, indicate that the fit is a good match to the data, as made clear in the lower panel showing the data/MC ratio.

Table 2 gives the predicted number of events for each physics process and for each dilepton category after fitting to the data, as well as a comparison of the total number of events expected from the simulation and observed in data. Since the full event selection requires at least two b-tagged jets, which is usually satisfied by  $t\bar{t}$  events, only 3% of the events are from non- $t\bar{t}$  processes. The expected contribution from the  $t\bar{t}H$  process is 12 events. This contribution is not subtracted from the data.

The ratio of the number of  $t\bar{t}b\bar{b}$  to  $t\bar{t}j$  events at the reconstruction level obtained from the fit is corrected for the ratio of efficiencies. The event selection efficiencies, defined as the num-



**Fig. 3.** Distribution of b jet multiplicity after the four-jet requirement but without the b-tagging requirement. Points are from data and stacked histograms from MC simulation using results from the fit to data. The ratio of the number of data events to the total number of MC events after the fit is shown in the lower panel.

**Table 2**

The number of events for each physics process and for each dilepton category after fitting to the data, their total, and the observed total number of events. The results are after the final event selection. The  $Z/\gamma^* \rightarrow \ell\ell$  uncertainty is from data, while all other uncertainties include only the statistical uncertainties in the MC samples.

Final state	$e^+e^-$	$\mu^+\mu^-$	$e^\pm\mu^\mp$	All
$t\bar{t}b\bar{b}$	18	26	61	$105 \pm 2$
$t\bar{t}bj$	35	48	109	$191 \pm 3$
$t\bar{t}c\bar{c}$	13	19	45	$78 \pm 2$
$t\bar{t}LF$	249	347	840	$1438 \pm 9$
tt others	21	25	64	$109 \pm 3$
Single top	7.4	11	24	$43 \pm 5$
$Z/\gamma^* \rightarrow \ell\ell$	5.7	5.4	3.1	$14 \pm 7$
Total	350	483	1149	$1983 \pm 13$
Data	367	506	1145	2018

ber of  $t\bar{t}b\bar{b}$  and  $t\bar{t}j$  events after the full event selection divided by the number of events in the corresponding visible phase space are 18.7% and 7.2%, respectively. The  $t\bar{t}b\bar{b}$  and  $t\bar{t}j$  cross sections in the visible phase space are measured using  $\sigma_{\text{visible}} = N/(\epsilon\mathcal{L})$ , where  $\mathcal{L}$  is the integrated luminosity,  $N$  is the number of observed events, and  $\epsilon$  is the efficiency for each process. However, the NLO theoretical calculation is based on parton-level jets being clustered with partons before hadronization in the full phase space. For the purpose of comparing with the theoretical prediction, the cross sections in the full phase space are extrapolated from the cross sections in the visible phase space using  $\sigma_{\text{full}} = \sigma_{\text{visible}}/\mathcal{A}$ , where  $\mathcal{A}$  is the acceptance. The acceptances for extending  $t\bar{t}b\bar{b}$  and  $t\bar{t}j$  to the full phase space based on the MADGRAPH simulation are 2.6% and 2.4%, respectively, including the  $t\bar{t}$  to dilepton branching fraction, calculated using the leptonic branching fraction of the W boson [41]. The acceptance is defined as the number of events in the corresponding visible phase space divided by the number of events in the full phase space.

## 6. Estimation of systematic uncertainties

The systematic uncertainties are determined separately for the  $t\bar{t}b\bar{b}$  and  $t\bar{t}j$  cross sections and their ratio. In the ratio, many systematic effects cancel, specifically normalization uncertainties such as the ones related to the measurement of the integrated luminosity and the lepton identification including trigger efficiencies, since they are common to both processes. The various systematic uncertainties in the measured values are shown in Table 3 for the visible



**Table 3**

Summary of the systematic uncertainties from various sources contributing to  $\sigma_{t\bar{t}b\bar{b}}$ ,  $\sigma_{t\bar{t}jj}$ , and the ratio  $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$  for a jet  $p_T$  threshold of  $p_T > 20$  GeV/c in the visible phase space.

Source	$\sigma_{t\bar{t}b\bar{b}}$ (%)	$\sigma_{t\bar{t}jj}$ (%)	$\frac{\sigma_{t\bar{t}b\bar{b}}}{\sigma_{t\bar{t}jj}}$ (%)
Pileup	1.0	1.0	1.0
JES & JER	11	8.0	5.0
b tag (b quark flavour)	15	< 0.1	15
b tag (c quark flavour)	4.0	< 0.1	4.0
b tag (light flavour)	7.0	< 0.1	7.0
Ratio of $t\bar{t}b\bar{b}$ and $t\bar{t}bj$	9.0	< 0.1	9.0
Bkgnd modelling	1.0	1.0	1.0
$t\bar{t}c\bar{c}$ fraction in the fit	4.2	0.2	4.0
Lepton identification	4.0	4.0	–
MC generator	3.0	3.0	3.0
Scale ( $\mu_F$ and $\mu_R$ )	8.0	3.0	6.0
PS matching	12	5.0	3.0
PDF	4.0	4.0	< 0.1
Eff. ( $t\bar{t}c\bar{c}$ fraction)	–	1.6	1.6
Luminosity	2.6	2.6	–
Total uncertainty	28	12	22

phase space and a jet  $p_T$  threshold of 20 GeV/c, including the luminosity uncertainty [19] and lepton identification [42], which only affect the absolute cross section measurements. The systematic uncertainty in the lepton identification is assessed using the scale factor obtained from Z boson candidates and also taking into account the different phase space between Z boson and  $t\bar{t}$  events.

The systematic uncertainties associated with the b-tagging discriminator scale factors for b jets and light-flavour jets are studied separately, varying their values within their uncertainties. The b-flavour scale factors are obtained using  $t\bar{t}$  enriched events, and their dominant uncertainty comes from the contamination when one of the b jets is not reconstructed [43] (indicated as “b quark flavour” in Table 3). The c jet scale factor is assumed to be unity with an uncertainty twice as large as the b-tagging scale factor [38] (indicated as “c quark flavour” in Table 3). The light-flavour jet scale factors are determined from Z boson enriched events. Their uncertainty arises because the contribution from the Z +  $b\bar{b}$  process in this control sample is not well modelled (indicated as “light flavour” in Table 3). The b-tagging discriminator can be affected by the jet energy scale (JES) variations. The systematic uncertainty in the jet energy scale [44] is obtained by varying the jet energy scale factor by one standard deviation for each quark flavour. The uncertainty in the jet energy resolution (JER) is assessed by smearing the simulated jet energy resolution by 10% on average, taking into account the  $\eta$  dependence [44].

The uncertainty arising from constraining the ratio of the  $t\bar{t}bj$  to  $t\bar{t}b\bar{b}$  contributions in the fit to match the MC prediction is evaluated by comparing the result with and without the constraint. The number of pileup interactions in data is estimated from the measured bunch-to-bunch instantaneous luminosity and the total inelastic cross section. The systematic uncertainty in the number of pileup events is estimated by conservatively varying this cross section by 5% to cover all the uncertainties in the modelling of the pileup physics. The contributions from Drell–Yan and single top quark processes are small, and the shapes of the distributions from these backgrounds are similar to those of the  $t\bar{t}LF$  component. Therefore, these backgrounds do not affect the measurement significantly. For the efficiency of  $t\bar{t}jj$  events, the uncertainty owing to the heavy-flavour fraction is estimated by varying the contribution by 50%. An uncertainty to account for the variation of the  $t\bar{t}c\bar{c}$  fraction in the fit is also assigned by varying the contribution by 50%. This variation is chosen because the theoretical uncertainty in the  $t\bar{t}j$  cross section is less than 50%, and the fitted  $t\bar{t}c\bar{c}$  fraction re-

mains within 50% of the input value when fitting with the  $t\bar{t}c\bar{c}$  contribution as a free parameter.

The dependence of the correction factor for the particle level on the assumptions made in the MC simulation is another source of systematic uncertainty: the generators MADGRAPH and POWHEG are compared and the difference in the efficiency ratio is taken as the systematic uncertainty. The uncertainties from the factorization/renormalization scales and the matching scale that separates jets from ME and from parton showers in MADGRAPH are estimated by varying the scales a factor of two up and down with respect to their reference values. The uncertainties in the PDFs are accounted for by following the PDF4LHC prescription [45].

The total systematic uncertainty in the cross section ratio is 22%, with the dominant contributions from the b-tagging efficiency and the misidentification of light-flavoured partons, followed by the renormalization/factorization and matching scale systematic uncertainties.

The uncertainty in  $\sigma_{t\bar{t}jj}$  is significantly smaller than that in  $\sigma_{t\bar{t}b\bar{b}}$  since the measurement of the latter requires the identification of multiple b jets. The uncertainty in  $\sigma_{t\bar{t}b\bar{b}}$  is larger than that for the cross section ratio since uncertainties that are common between  $t\bar{t}b\bar{b}$  and  $t\bar{t}jj$ , such as the jet energy scale uncertainty, partially or completely cancel in the ratio.

The systematic uncertainties in the measurements with a  $p_T$  threshold of 40 GeV/c are found to be very similar to those with a 20 GeV/c threshold. The uncertainty from the factorization and renormalization scales for the higher- $p_T$  threshold of 40 GeV/c cannot be accurately determined owing to the statistical uncertainties in the MC sample. Thus, the  $p_T > 40$  GeV/c threshold measurements use the same scale ( $\mu_F$  and  $\mu_R$ ) systematic uncertainties as those found for the  $p_T > 20$  GeV/c threshold results.

In extrapolating the measurements from the visible phase space to the full phase space, the systematic uncertainty in the acceptance is included. The effect of the MC modelling of the acceptance is estimated by comparing the results between MADGRAPH and POWHEG. This uncertainty equals 5% for each of the cross section measurements and 2% for the cross section ratio.

## 7. Results

After correcting for the efficiency ratio and taking into account the systematic uncertainties, the cross section ratio  $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$  is measured in the visible phase space from a fit to the measured CSV b-tagging discriminator distributions shown in Fig. 2. The measured cross section ratio in the visible phase space for events with particle-level jets and a minimum jet  $p_T$  of 20 GeV/c is

$$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj} = 0.022 \pm 0.003 \text{ (stat)} \pm 0.005 \text{ (syst)}. \quad (2)$$

This result is for the visible phase space, defined as events having two leptons with  $p_T > 20$  GeV/c and  $|\eta| < 2.4$ , plus four jets, including two b jets with  $p_T > 20$  GeV/c and  $|\eta| < 2.5$ . The predicted value from both MADGRAPH and POWHEG is found to be  $0.016 \pm 0.002$ , where the MC uncertainty is the sum in quadrature of the statistical uncertainty and the systematic uncertainties from the factorization/renormalization and the matching scales. The measured cross sections are presented in Table 4. When the  $t\bar{t}H$  contribution is subtracted from the data, the ratio is reduced by only 4%, much less than the overall uncertainty. Therefore, compared to the uncertainties, the contribution from  $t\bar{t}H$  can be considered negligible. The measured full phase space ratio with a minimum  $p_T$  of 20 GeV/c for parton-level jets is consistent within the uncertainties with the result in the visible phase space.

A NLO theoretical QCD calculation is available for parton-level jets with a  $p_T > 40$  GeV/c threshold [16]. The NLO cross section

**Table 4**

The measured cross sections  $\sigma_{t\bar{t}b\bar{b}}$  and  $\sigma_{t\bar{t}jj}$  and their ratio are given for the visible phase space (PS) defined as two leptons with  $p_T > 20$  GeV/c and  $|\eta| < 2.4$  plus four jets, including two b jets with  $p_T > 20$  GeV/c and  $|\eta| < 2.5$ , and the full phase space, corrected for acceptance and branching fractions. The full phase space results are given for jet thresholds of  $p_T > 20$  and 40 GeV/c. The uncertainties shown are statistical and systematic, respectively. The predictions of a NLO theoretical calculation for the full phase space and  $p_T > 40$  GeV/c are also given [16].

Phase Space (PS)	$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$\sigma_{t\bar{t}jj}$ [pb]	$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$
Visible PS (particle)			
Jet $p_T > 20$ GeV/c	$0.029 \pm 0.003 \pm 0.008$	$1.28 \pm 0.03 \pm 0.15$	$0.022 \pm 0.003 \pm 0.005$
Full PS (parton)			
Jet $p_T > 20$ GeV/c	$1.11 \pm 0.11 \pm 0.31$	$52.1 \pm 1.0 \pm 6.8$	$0.021 \pm 0.003 \pm 0.005$
Jet $p_T > 40$ GeV/c	$0.36 \pm 0.08 \pm 0.10$	$16.1 \pm 0.7 \pm 2.1$	$0.022 \pm 0.004 \pm 0.005$
NLO calculation			
Jet $p_T > 40$ GeV/c	$0.23 \pm 0.05$	$21.0 \pm 2.9$	$0.011 \pm 0.003$

values for  $\sigma_{t\bar{t}b\bar{b}}$ ,  $\sigma_{t\bar{t}jj}$ , and the ratio  $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$  are given in Table 4. To compare with this theoretical prediction, the analysis is repeated for a jet threshold of  $p_T > 40$  GeV/c. Correspondingly with a higher jet  $p_T$  threshold in the event selection, 24  $t\bar{t}b\bar{b}$  events and 478  $t\bar{t}jj$  events remain after the full event selection, with the acceptance (including the event selection efficiency) of 0.34% and 0.15%, respectively. The measured cross section ratio in the full phase space with the  $p_T > 40$  GeV/c threshold is

$$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj} = 0.022 \pm 0.004 (\text{stat}) \pm 0.005 (\text{syst}). \quad (3)$$

The cross sections in the full phase space for this  $p_T$  threshold are summarized in Table 4. The measured cross section ratio is higher, but compatible within 1.6 standard deviations with the prediction from the NLO calculation of  $0.011 \pm 0.003$ .

## 8. Summary

A measurement of the cross section ratio  $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$  has been presented by the CMS experiment, using a data sample of pp collisions at a centre-of-mass energy of 8 TeV, corresponding to an integrated luminosity of  $19.6 \text{ fb}^{-1}$ . The individual cross sections  $\sigma_{t\bar{t}jj}$  and  $\sigma_{t\bar{t}b\bar{b}}$  have also been determined. The cross section ratio was measured in a visible phase space region using the dilepton decay mode of  $t\bar{t}$  events and corrected to the particle level, corresponding to the detector acceptance. The measured cross section ratio in the visible phase space is  $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj} = 0.022 \pm 0.003 (\text{stat}) \pm 0.005 (\text{syst})$  with a minimum  $p_T$  for the particle-level jets of 20 GeV/c. The cross section ratio has also been measured in the full phase space with minimum parton-jet  $p_T$  thresholds of  $p_T > 20$  and  $> 40$  GeV/c in order to compare with a NLO QCD calculation of the cross section ratio. The measurement is compatible within 1.6 standard deviations with the theoretical prediction. These are the first measurements of the cross sections  $\sigma_{t\bar{t}b\bar{b}}$  and  $\sigma_{t\bar{t}jj}$ , and their ratio. The result will provide important information about the main background in the search for  $t\bar{t}H$  and as a figure of merit for testing the validity of NLO QCD calculations.

## 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: BMWFW 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); MSIP and NRF (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 A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the 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 Thalis 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, Observation of a new particle in the search for the standard model Higgs boson with the ATLAS detector at the LHC, Phys. Lett. B 716 (2012) 1, <http://dx.doi.org/10.1016/j.physletb.2012.08.020>, arXiv:1207.7214.
- [2] CMS Collaboration, Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, Phys. Lett. B 716 (2012) 30, <http://dx.doi.org/10.1016/j.physletb.2012.08.021>, arXiv:1207.7235.
- [3] CMS Collaboration, Observation of a new boson with mass near 125 GeV in pp collisions at  $\sqrt{s} = 7$  and 8 TeV, J. High Energy Phys. 06 (2013) 081, [http://dx.doi.org/10.1007/JHEP06\(2013\)081](http://dx.doi.org/10.1007/JHEP06(2013)081), arXiv:1303.4571.
- [4] CMS Collaboration, Measurement of the properties of a Higgs boson in the four-lepton final state, Phys. Rev. D 89 (2014) 092007, <http://dx.doi.org/10.1103/PhysRevD.89.092007>, arXiv:1312.5353.
- [5] CMS Collaboration, Measurement of Higgs boson production and properties in the WW decay channel with leptonic final states, J. High Energy Phys. 01 (2014) 096, [http://dx.doi.org/10.1007/JHEP01\(2014\)096](http://dx.doi.org/10.1007/JHEP01(2014)096), arXiv:1312.1129.
- [6] 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.
- [7] CMS Collaboration, Search for the standard model Higgs boson produced in association with a W or a Z boson and decaying to bottom quarks, Phys.

- Rev. D 89 (2014) 012003, <http://dx.doi.org/10.1103/PhysRevD.89.012003>, arXiv:1310.3687.
- [8] ATLAS Collaboration, Measurements of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC, Phys. Lett. B 726 (2013) 88, <http://dx.doi.org/10.1016/j.physletb.2013.08.010>, arXiv:1307.1427.
- [9] ATLAS Collaboration, Evidence for the spin-0 nature of the Higgs boson using ATLAS data, Phys. Lett. B 726 (2013) 120, <http://dx.doi.org/10.1016/j.physletb.2013.08.026>, arXiv:1307.1432.
- [10] S. Heinemeyer, et al., Handbook of LHC Higgs cross sections: 3. Higgs properties, CERN Report CERN-2013-004, <http://dx.doi.org/10.5170/CERN-2013-004>, 2013, arXiv:1307.1347.
- [11] G. Bevilacqua, M. Czakon, C.G. Papadopoulos, R. Pittau, M. Worek, Assault on the NLO wishlist:  $pp \rightarrow t\bar{t}b\bar{b}$ , J. High Energy Phys. 09 (2009) 109, <http://dx.doi.org/10.1088/1126-6708/2009/09/109>, arXiv:0907.4723.
- [12] G. Bevilacqua, M. Czakon, C.G. Papadopoulos, M. Worek, Hadronic top-quark pair production in association with two jets at next-to-leading order QCD, Phys. Rev. D 84 (2011) 114017, <http://dx.doi.org/10.1103/PhysRevD.84.114017>, arXiv:1108.2851.
- [13] G. Bevilacqua, M. Czakon, C.G. Papadopoulos, M. Worek, Dominant QCD backgrounds in Higgs boson analyses at the LHC: a study of  $pp \rightarrow t\bar{t} + 2$  jets at next-to-leading order, Phys. Rev. Lett. 104 (2010) 162002, <http://dx.doi.org/10.1103/PhysRevLett.104.162002>, arXiv:1002.4009.
- [14] A. Bredenstein, A. Denner, S. Dittmaier, S. Pozzorini, NLO QCD corrections to  $t\bar{t}b\bar{b}$  production at the LHC: 2. full hadronic results, J. High Energy Phys. 03 (2010) 021, [http://dx.doi.org/10.1007/JHEP03\(2010\)021](http://dx.doi.org/10.1007/JHEP03(2010)021), arXiv:1001.4006.
- [15] M. Worek, On the next-to-leading order QCD K-factor for  $t\bar{t}b\bar{b}$  production at the Tevatron, J. High Energy Phys. 02 (2011) 043, [http://dx.doi.org/10.1007/JHEP02\(2011\)043](http://dx.doi.org/10.1007/JHEP02(2011)043), arXiv:1112.4325.
- [16] M. Worek, G. Bevilacqua, On the ratio of  $t\bar{t}b\bar{b}$  and  $t\bar{t}j$  cross sections at the CERN large hadron collider, J. High Energy Phys. 07 (2014) 135, [http://dx.doi.org/10.1007/JHEP07\(2014\)135](http://dx.doi.org/10.1007/JHEP07(2014)135), arXiv:1403.2046.
- [17] A. Bredenstein, A. Denner, S. Dittmaier, S. Pozzorini, Next-to-leading order QCD corrections to  $pp \rightarrow t\bar{t}b\bar{b} + x$  at the LHC, Phys. Rev. Lett. 103 (2009) 012002, <http://dx.doi.org/10.1103/PhysRevLett.103.012002>, arXiv:0905.0110.
- [18] A. Bredenstein, A. Denner, S. Dittmaier, S. Pozzorini, NLO QCD corrections to  $t\bar{t}b\bar{b}$  production at the LHC: 1. quark-antiquark annihilation, J. High Energy Phys. 08 (2008) 108, <http://dx.doi.org/10.1088/1126-6708/2008/08/108>, arXiv:0807.1248.
- [19] CMS Collaboration, CMS luminosity based on pixel cluster counting – summer 2013 update, CMS Physics Analysis Summary CMS-PAS-LUM-13-001, <https://cds.cern.ch/record/1598864>, 2013.
- [20] 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, <http://cds.cern.ch/record/1194487>, 2009.
- [21] 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, <http://cds.cern.ch/record/1247373>, 2010.
- [22] 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>.
- [23] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. Shao, T. Stelzer, P. Torrielli, 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.
- [24] T. Sjöstrand, S. Mrenna, P. 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.
- [25] N. Davidson, G. Nanava, T. Przedziński, E. Richter-Wąs, Z. Wąs, Universal interface of TAUOLA: technical and physics documentation, Comput. Phys. Commun. 183 (2010) 821, <http://dx.doi.org/10.1016/j.cpc.2011.12.009>, arXiv:1002.0543.
- [26] 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.
- [27] 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.
- [28] 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.
- [29] N. Kidonakis, NNLL threshold resummation for top-pair and single-top production, Phys. Part. Nucl. 45 (2014) 714, <http://dx.doi.org/10.1134/S1063779614040091>, arXiv:1210.7813.
- [30] J. Pumplin, D.R. Stump, J. Huston, H.-L. Lai, P. Nadolsky, W.-K. Tung, New generation of parton distributions with uncertainties from global QCD analysis, J. High Energy Phys. 07 (2002) 012, <http://dx.doi.org/10.1088/1126-6708/2002/07/012>, arXiv:hep-ph/0201195.
- [31] 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.
- [32] S. Agostinelli, et al., GEANT4, 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).
- [33] M. Cacciari, G.P. Salam, G. Soyez, The anti- $k_r$  jet clustering algorithm, J. High Energy Phys. 04 (2008) 063, <http://dx.doi.org/10.1088/1126-6708/2008/04/063>, arXiv:0802.1189.
- [34] 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>.
- [35] CMS Collaboration, Particle-flow commissioning with muons and electrons from  $J/\psi$  and W events at  $\sqrt{s} = 7$  TeV, CMS Physics Analysis Summary CMS-PAS-PFT-10-003, <http://cds.cern.ch/record/1279347>, 2010.
- [36] CMS Collaboration, Electromagnetic physics objects commissioning with first LHC data, CMS Physics Analysis Summary CMS-PAS-EGM-10-001, <http://cds.cern.ch/record/1247384>, 2010.
- [37] CMS Collaboration, Missing transverse energy performance of the CMS detector, J. Instrum. 6 (2011) P09001, <http://dx.doi.org/10.1088/1748-0221/6/09/P09001>.
- [38] 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>.
- [39] CMS Collaboration, First measurement of the cross section for top-quark pair production in proton–proton collisions at  $\sqrt{s} = 7$  TeV, Phys. Lett. B 695 (2011) 424, <http://dx.doi.org/10.1016/j.physletb.2010.11.058>, arXiv:1010.5994.
- [40] CMS Collaboration, Measurement of the top-quark pair-production cross section and the top-quark mass in the dilepton channel 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).
- [41] Particle Data Group, K.A. Olive, et al., Review of particle physics, Chin. Phys. C 38 (2014) 090001, <http://dx.doi.org/10.1088/1674-1137/38/9/090001>.
- [42] 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 (2013) 024, [http://dx.doi.org/10.1007/JHEP02\(2013\)024](http://dx.doi.org/10.1007/JHEP02(2013)024).
- [43] CMS Collaboration, Search for the associated production of the Higgs boson with a top-quark pair, J. High Energy Phys. 09 (2014) 087, [http://dx.doi.org/10.1007/JHEP09\(2014\)087](http://dx.doi.org/10.1007/JHEP09(2014)087); CMS Collaboration, [http://dx.doi.org/10.1007/JHEP10\(2014\)106](http://dx.doi.org/10.1007/JHEP10(2014)106) (Erratum).
- [44] 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>.
- [45] 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.

## 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-Treiberspurg, 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 Haeevermaet, 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. Caebegs, 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*

J. Talvitie, 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, M. Brodski, 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, 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, G. Mittag, 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. Agapitos, S. Kesisoglou, 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, 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, F. Rezaei Hosseinabadi, 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>, S. Fiorendi <sup>a,b,2</sup>, S. Gennai <sup>a,2</sup>, R. Gerosa <sup>a,b,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 <sup>a,b</sup>, D. Menasce <sup>a</sup>, L. Moroni <sup>a</sup>, M. Paganoni <sup>a,b</sup>, D. Pedrini <sup>a</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>, F. Fanzago <sup>a</sup>, M. Galanti <sup>a,b</sup>, F. Gasparini <sup>a,b</sup>, U. Gasparini <sup>a,b</sup>, F. Gonella <sup>a</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>, 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. Androsov <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>, P.P. Trapani <sup>a,b</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

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

T.J. Kim

Chonbuk National University, Jeonju, 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 Ibarquen**

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

**S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, V. Konoplyanikov, A. Lanev, A. Malakhov, V. Matveev<sup>29</sup>, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, N. Skatchkov, V. Smirnov, 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, V. Bunichev, M. Dubinin<sup>31</sup>, L. Dudko, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, M. Perfilov, V. Savrin, A. Snigirev

*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, B. Dorney, 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, Y. Takahashi, 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. Lustermann, 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*

K. Cankocak, F.I. Vardarli

*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>47</sup>, S. Paramesvaran, A. Poll, S. Senkin, V.J. Smith, T. Williams

*University of Bristol, Bristol, United Kingdom*



K.W. Bell, A. Belyaev<sup>48</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>47</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, S.C. Zenz

*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, N. Dhingra, 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>49</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>50</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>50</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, 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, A. Zuranski

*Princeton University, Princeton, USA*

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

*University of Puerto Rico, Mayaguez, USA*

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, S. Kaplan, 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. Klabbers, 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, D. Taylor, 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.

<sup>10</sup> Also at Cairo University, Cairo, Egypt.

<sup>11</sup> Also at Fayoum University, El-Fayoum, Egypt.

<sup>12</sup> Also at British University in Egypt, Cairo, Egypt.

<sup>13</sup> Now at Sultan Qaboos University, Muscat, Oman.

<sup>14</sup> Also at Université de Haute Alsace, Mulhouse, France.

<sup>15</sup> Also at Brandenburg University of Technology, Cottbus, Germany.

<sup>16</sup> Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

<sup>17</sup> Also at Eötvös Loránd University, Budapest, Hungary.

<sup>18</sup> Also at University of Debrecen, Debrecen, Hungary.

<sup>19</sup> Also at University of Visva-Bharati, Santiniketan, India.

<sup>20</sup> Now at King Abdulaziz University, Jeddah, Saudi Arabia.

<sup>21</sup> Also at University of Ruhuna, Matara, Sri Lanka.

<sup>22</sup> Also at Isfahan University of Technology, Isfahan, Iran.

<sup>23</sup> Also at Sharif University of Technology, Tehran, Iran.

<sup>24</sup> Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.

<sup>25</sup> Also at Università degli Studi di Siena, Siena, Italy.

<sup>26</sup> Also at Centre National de la Recherche Scientifique (CNRS) – IN2P3, Paris, France.

<sup>27</sup> Also at Purdue University, West Lafayette, USA.

<sup>28</sup> Also at Universidad Michoacana de San Nicolas de Hidalgo, Morelia, Mexico.

<sup>29</sup> Also at Institute for Nuclear Research, Moscow, Russia.

<sup>30</sup> Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.

<sup>31</sup> Also at California Institute of Technology, Pasadena, USA.

<sup>32</sup> Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.

<sup>33</sup> Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.

<sup>34</sup> Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.

<sup>35</sup> Also at University of Athens, Athens, Greece.

<sup>36</sup> Also at Paul Scherrer Institut, Villigen, Switzerland.

<sup>37</sup> Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.

<sup>38</sup> Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.

<sup>39</sup> Also at Gaziosmanpasa University, Tokat, Turkey.

<sup>40</sup> Also at Adiyaman University, Adiyaman, Turkey.

<sup>41</sup> Also at Cag University, Mersin, Turkey.

<sup>42</sup> Also at Mersin University, Mersin, Turkey.

<sup>43</sup> Also at Izmir Institute of Technology, Izmir, Turkey.

<sup>44</sup> Also at Ozyegin University, Istanbul, Turkey.

<sup>45</sup> Also at Marmara University, Istanbul, Turkey.

<sup>46</sup> Also at Kafkas University, Kars, Turkey.

<sup>47</sup> Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.

<sup>48</sup> Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.

<sup>49</sup> Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.

<sup>50</sup> Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.

<sup>51</sup> Also at Argonne National Laboratory, Argonne, USA.

<sup>52</sup> Also at Erzincan University, Erzincan, Turkey.

<sup>53</sup> Also at Yildiz Technical University, Istanbul, Turkey.

<sup>54</sup> Also at Texas A&M University at Qatar, Doha, Qatar.

<sup>55</sup> Also at Kyungpook National University, Daegu, Republic of Korea.