Measurements of tt̄ cross sections in association with b jets and inclusive jets and their ratio using dilepton final states in pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

CERN, Switzerland

ABSTRACT

The cross sections for the production of $t\bar{t}b\bar{b}$ and $t\bar{t}jj$ events and their ratio $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$ are measured using data corresponding to an integrated luminosity of 2.3 fb^{-1} collected in pp collisions at $\sqrt{s} = 13$ TeV with the CMS detector at the LHC. Events with two leptons (e or μ) and at least four reconstructed jets, including at least two identified as b quark jets, in the final state are selected. In the full phase space, the measured ratio is $0.022 \pm 0.003\,(\text{stat}) \pm 0.006\,(\text{syst})$, the cross section $\sigma_{t\bar{t}b\bar{b}}$ is $4.0 \pm 0.6\,(\text{stat}) \pm 1.3\,(\text{syst})$ pb and $\sigma_{t\bar{t}jj}$ is $184 \pm 6\,(\text{stat}) \pm 33\,(\text{syst})$ pb. The measurements are compared with the standard model expectations obtained from a POWHEG simulation at next-to-leading-order interfaced with PYTHIA.

© 2017 The Author. 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 SCOAP³.

1. Introduction

Since the discovery of the Higgs boson [1–3], its properties have been measured and compared to the standard model (SM) prediction [4–9]. However, the coupling of the top quark to the Higgs boson remains to be determined. Although it appears indirectly through loops in the gluon–gluon fusion production process and in the H → $\gamma\gamma$ decay channel, a direct measurement has yet to be completed. One of the most promising channels for a direct measurement of the top quark Yukawa coupling in the SM 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. This final state, which has not been observed yet [10], has an irreducible nonresonant background from the production of a top quark pair in association with a b quark pair produced via gluon splitting (g → $b\bar{b}$).

Calculations of the inclusive production cross section for $t\bar{t}$ events with additional jets have been performed to next-to-leading-order (NLO) precision for proton–proton centre-of-mass energies of 7, 8, and 13 TeV [11]. The dominant uncertainties in these calculations are from the choice of the factorization (μ_F) and renormalization (μ_R) scales [12,13], and are complicated by the presence of two very different scales in this process: the top quark mass and the jet transverse momentum (p_T). Therefore, experi-

mental measurements of production cross sections pp → $t\bar{t}jj$ ($\sigma_{t\bar{t}jj}$) and pp → $t\bar{t}b\bar{b}$ ($\sigma_{t\bar{t}b\bar{b}}$) can provide an important test of NLO quantum chromodynamics (QCD) theory calculations and important input for describing the main background in the search for the $t\bar{t}$H process. Previous cross section and ratio measurements at $\sqrt{s} = 7$ and 8 TeV have been reported by the CMS [14,15] and ATLAS Collaborations [16].

In this Letter, the measurements of the cross sections $\sigma_{t\bar{t}b\bar{b}}$ and $\sigma_{t\bar{t}jj}$ and their ratio are presented using a data sample of pp collisions collected at a centre-of-mass energy of 13 TeV at the CERN LHC by the CMS experiment, and corresponding to an integrated luminosity of 2.3 fb^{-1} [17]. Events are selected with the final state consisting of two leptons (e or μ) and at least four reconstructed jets, of which at least two are identified as b quark jets. The cross section ratio is measured with a smaller systematic uncertainty exploiting the partial cancellation of uncertainties.

2. The CMS detector and event simulation

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 solenoid volume are a silicon 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. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and

---

endcap detectors. Muons are reconstructed in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. 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. [18].

The Monte Carlo (MC) simulated samples for the $t\bar{t}$ signal are generated by the POWHEG (v2) event generator [19–21] at NLO, interfaced with PYTHIA (v8.205) [22,23] using the tune CUETP8M1 [24] to provide the showering of the partons and to match soft radiation with the contributions from the matrix elements (MEs). The NNPDF3.0 [25] set of the parton distribution functions (PDFs) is used. The MADGRAPH (v5.1.5.11) event generator [26] with MEs at leading order (LO), allowing up to three additional partons, including b quarks, and the MADGRAPH5_aMC@NLO (v2.2.2) event generator [27] are both used for cross-checks and studies of systematic uncertainties. The $t\bar{t}$ samples are normalized to the next-to-next-to-leading-order (NNLO) cross section calculation [28]. The W+jets and Z/γ^*+jets processes are simulated in MADGRAPH5_aMC@NLO and are normalized to their NNLO cross sections [29]. The single top quark associated production with a W boson (pp → tW and pp → $\bar{t}$W) is simulated in the five-flavour scheme in POWHEG (v1) at NLO and normalized to an approximate NNLO cross section calculation [30], while the t-channel single top quark events are simulated in the four-flavour scheme in MADGRAPH5_aMC@NLO. The multijet production is modelled in PYTHIA with LO MEs. The CMS detector response is simulated using GEANT4 (v9.4) [31]. The events in simulation include the effects of additional interactions in the same or nearby bunch crossings (pileup) and are weighted according to the vertex distribution observed in data. The number of pileup interactions in data is estimated from the measured bunch-to-bunch instantaneous luminosity and the total inelastic cross section [32].

3. Definition of signal events

Measurements are reported for two different regions of the phase space: the visible and the full phase space. The result in the visible phase space is measured at the particle level, using the stable particles after the hadronization, to reduce the possible theoretical and modelling uncertainties, while the purpose of performing the result in the full phase space is to facilitate comparisons to NLO calculations or measurements in other decay modes.

To define the visible phase space, all $t\bar{t}b\bar{b}$ final-state particles 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 experimentally accessible kinematic region. The leptons must have $p_T > 20$ GeV, and $|\eta| < 2.4$. Electrons or muons originating from the leptonic decays of τ leptons produced in W → $\tau\nu$ decays are included. 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 0.4 and are required to satisfy $|\eta| < 2.5$ and $p_T > 20$ GeV, which is lower than the reconstructed minimum jet p_T due to jet resolution – to have all events that pass the reconstructed jet p_T in the visible phase space. Jets that are within $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.5$ units 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 jet and the lepton. To identify the b and c quark jets ("c jets") unambiguously, the b and c hadron momenta are scaled down to a negligible value and included in the jet clustering (so called "ghost matching") [34]. The b and c jets are then identified by the presence of the corresponding "ghost" hadrons among the jet constituents.

Simulated events are categorized as coming from the $t\bar{t}jj$ process if they contain at least four particle-level jets, including at least two jets originating from b quarks, and two leptons ($t\bar{t}jj$ → $bW^+\bar{b}W^-jj$ → $b\ell^+\nu\bar{b}\ell^-\bar{\nu}jj$). The $t\bar{t}jj$ sample contains four components according to the number of b and c 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 mainly originates from the merging of two b jets or the loss of one of the b jets caused by the acceptance requirements.

4. Event selection

The events are recorded at $\sqrt{s} = 13$ TeV using a dilepton trigger [35] that requires the presence of two isolated leptons (e or μ) both with p_T larger than 17 GeV.

The particle-flow (PF) event algorithm [36,37] reconstructs and identifies each individual particle with an optimized combination of information from the various elements of the CMS detector. The energy of photons is directly obtained from the ECAL measurement. 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 reconstructed by combining information from the silicon tracker and the muon system [38]. The energy of charged hadrons is determined from a combination of their momenta 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.

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 further required to have a high-quality fit including a minimum number of hits in both systems. Requirements on electron identification variables based on shower shape and track-cluster matching are further applied to the reconstructed electron candidates [39–41]. Muons and electrons must have $p_T > 20$ GeV 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_{rel}, is defined as the ratio of the summed p_T of all objects in a cone of $\Delta R = 0.3$ ($\Delta R = 0.4$) units around the electron (muon) direction to the lepton p_T. Different cone sizes for electron and muon are used to maximize the sensitivity. The objects considered are the charged hadrons associated with the primary vertex as well as the neutral hadrons and photons, whose energies are corrected to take into account pileup effects. Thus,

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

The muon candidates are required to have $I_{rel} < 0.15$. For the electron candidates, different I_{rel} thresholds (0.077 or 0.068) are applied depending on the pseudorapidity of the candidate ($|\eta| < 1.48$ or $1.48 \leq |\eta| < 2.40$). These thresholds are obtained from a multivariate analysis technique and result from the considerable

differences in both the ECAL and the tracker in the two pseudo-rapidity regions. The efficiencies for the above lepton identification requirements are measured using Z boson candidates in data with a dilepton invariant mass between 70 and 130 GeV, and are compared with the values from the simulation. The differences between the two evaluations 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. Lepton pairs of the same flavour (e^+e^-, $\mu^+\mu^-$) are rejected if their invariant mass is within 15 GeV of the Z boson mass. The missing transverse momentum vector $\vec{p}_T^{\text{miss}}$ is defined as the projection on the plane perpendicular to the beams of the negative vector sum of the momenta of all reconstructed PF candidates in the event. Its magnitude is referred to as p_T^{miss}. In the same-flavour channels, remaining backgrounds from Z+jets processes are suppressed by demanding $p_T^{\text{miss}} > 30$ GeV. For the $e^\pm\mu^\mp$ channel, no p_T^{miss} requirement is applied.

Jets are reconstructed using the same anti-k_T clustering algorithm as particle-level jets in the simulations, with the PF candidates as input particles. The jet momentum is determined as the vectorial sum of all PF candidate 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 jet energies to take into account the contribution from pileup interactions. Jet energy corrections are derived from simulation and confirmed with in situ measurements of the energy balance in dijet and photon+jet events [42]. Additional selection criteria are applied to each event to remove spurious jet-like features originating from isolated noise patterns in certain HCAL regions. The event must contain at least four reconstructed jets with $p_T > 30$ GeV and $|\eta| < 2.4$, of which at least two jets must be identified as b jets, using the combined secondary vertex (CSV) algorithm (v2), which combines secondary vertex information with lifetime information of single tracks to produce a b tagging discriminator [43]. A b tagging requirement on this discriminator is applied, which has an efficiency of about 60–70% for b jets and a misidentification probability of 1% for light-flavour jets and 15–20% for c-flavour jets [44].

Differences in the b tagging efficiencies between data and simulation [43] are accounted for by reweighting the shape of the CSV b tagging discriminator distribution in the simulation to match that in the data. Data/simulation p_T- and η-dependent correction factors are derived from the control samples separately for light- and heavy-flavour jets, that are described in Section 6.

The diboson, W+jets and multijet contributions are found to be negligible after the full event selection. The Z+jets background is estimated from data using control samples enriched in Z boson events.

Table 1 gives the predicted number of events for each physics process and for each lepton category, 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, a condition which is usually satisfied by $t\bar{t}$ events, only 5% of the events are from non-$t\bar{t}$ processes. The $t\bar{t}$bj final state is predominantly composed of $t\bar{t}b\bar{b}$ events where there is one lost b jet due to acceptance requirements (73% of $t\bar{t}$bj events). The background contribution from $t\bar{t}$ events that fail the visible phase space requirements is labelled "$t\bar{t}$ others". The number of observed events with four or more reconstructed jets is lower than the prediction from the simulation, a condition that is also observed in the lepton+jets decay mode [45].

Table 1
Predicted number of events for each physics process and for each dilepton category, their total, and the observed number of events. Results are shown after the final event selection. The Z+jets normalization and uncertainty are calculated from data, while all other predictions and statistical uncertainties come from the simulated data samples. The $t\bar{t}$ sample for event categorization is from the POWHEG (v2) event generator interfaced with PYTHIA (v8.205).

| Process	e^+e^-	$\mu^+\mu^-$	$e^\pm\mu^\mp$	All
$t\bar{t}b\bar{b}$	6.3 ± 0.4	8.6 ± 0.4	24 ± 1	39 ± 1
$t\bar{t}$bj	16 ± 1	21 ± 1	57 ± 2	95 ± 2
$t\bar{t}c\bar{c}$	7.7 ± 0.4	11 ± 1	27 ± 1	46 ± 1
$t\bar{t}$LF	157 ± 2	220 ± 2	596 ± 3	972 ± 4
$t\bar{t}$ others	18 ± 1	19 ± 1	61 ± 1	99 ± 1
$t\bar{t}$ V	2.5 ± 0.1	3.2 ± 0.2	7.3 ± 0.2	14 ± 1
Single t	6.6 ± 0.8	8.4 ± 0.8	23 ± 2	39 ± 2
Z+jets	$0.8^{+1.0}_{-0.8}$	5.4 ± 1.5	0.6 ± 0.5	6.8 ± 1.9
Total	215 ± 2	297 ± 3	796 ± 4	1311 ± 6
Data	186	288	682	1156

5. Cross section measurements

The first and the second jets in decreasing order of the b tagging discriminator usually (in 85% of $t\bar{t}$jj events) correspond to the b jets from the decays of top quarks, and hence these jets provide no discriminating power between $t\bar{t}b\bar{b}$ and $t\bar{t}$jj events. The third and the fourth jets from $t\bar{t}$jj events are mostly light-flavour jets, while these are heavy-flavour jets for $t\bar{t}b\bar{b}$ events. The normalized 2D distributions of the discriminators from simulation for the third and the fourth jets are shown in Fig. 1. These 2D distributions are used to separate $t\bar{t}b\bar{b}$ events from other processes. To extract the ratio of the number of $t\bar{t}b\bar{b}$ events to $t\bar{t}$jj events, a binned maximum-likelihood fit is performed on the 2D distribution of the CSV b tagging discriminators of the third and the fourth jets, where the three event categories $e^\pm e^\mp$, $e^\pm\mu^\mp$, and $\mu^\pm\mu^\mp$ are merged.

The number of $t\bar{t}$jj events and the ratio of the numbers of $t\bar{t}b\bar{b}$ events to $t\bar{t}$jj events are free parameters in the fit. The $t\bar{t}c\bar{c}$ and $t\bar{t}$LF processes have similar 2D distributions so their contributions are combined based on the MC simulation.

The likelihood function is constructed as the product over all bins of a Poisson probability with a mean defined in each bin by

$$\mathcal{M}(N_{t\bar{t}jj}, R) = N_{t\bar{t}jj}\left[R\,\mathcal{F}_{t\bar{t}b\bar{b}}^{\text{norm}} + R'\,\mathcal{F}_{t\bar{t}bj}^{\text{norm}} + (1 - R - R')\,\mathcal{F}_{t\bar{t}\text{LF}+t\bar{t}c\bar{c}}^{\text{norm}} \right] + N_{t\bar{t}jj}f_{t\bar{t}\text{ others}} + N_{\text{bkg}}, \quad (2)$$

where $\mathcal{F}_{t\bar{t}b\bar{b}}^{\text{norm}}$, $\mathcal{F}_{t\bar{t}bj}^{\text{norm}}$, and $\mathcal{F}_{t\bar{t}\text{LF}+t\bar{t}c\bar{c}}^{\text{norm}}$ are the normalized expectations for each bin of $t\bar{t}b\bar{b}$, $t\bar{t}$bj, and the combination of $t\bar{t}$LF and $t\bar{t}c\bar{c}$, respectively. The parameter $N_{t\bar{t}jj}$ denotes the number of the $t\bar{t}$jj events from the fit. The quantity $f_{t\bar{t}\text{ others}}$ reflects the fraction of other $t\bar{t}$ processes in the $t\bar{t}$jj sample as calculated in simulation ($t\bar{t}$ others divided by the sum of the $t\bar{t}$jj components in Table 1). The other backgrounds, such as $t\bar{t}$ V (V = W or Z) and single top quark processes are fixed to the simulation expectations, while the Z+jets background is fixed to its estimation from control samples in data. This remaining background not from the $t\bar{t}$ process is labelled N_{bkg}. The parameter R is the ratio of the number of $t\bar{t}b\bar{b}$ events with respect to the number of $t\bar{t}$jj events, and R' is the fraction of $t\bar{t}$bj events at the reconstruction level and constrained to the ratio of the number of the $t\bar{t}$bj events to $t\bar{t}b\bar{b}$ events. It is fixed to 2.43 as calculated from the MC simulation (POWHEG interfaced with PYTHIA). The effect of this assumption is estimated as a systematic uncertainty in Section 6. Values for $N_{t\bar{t}jj}$ of 950 ± 30
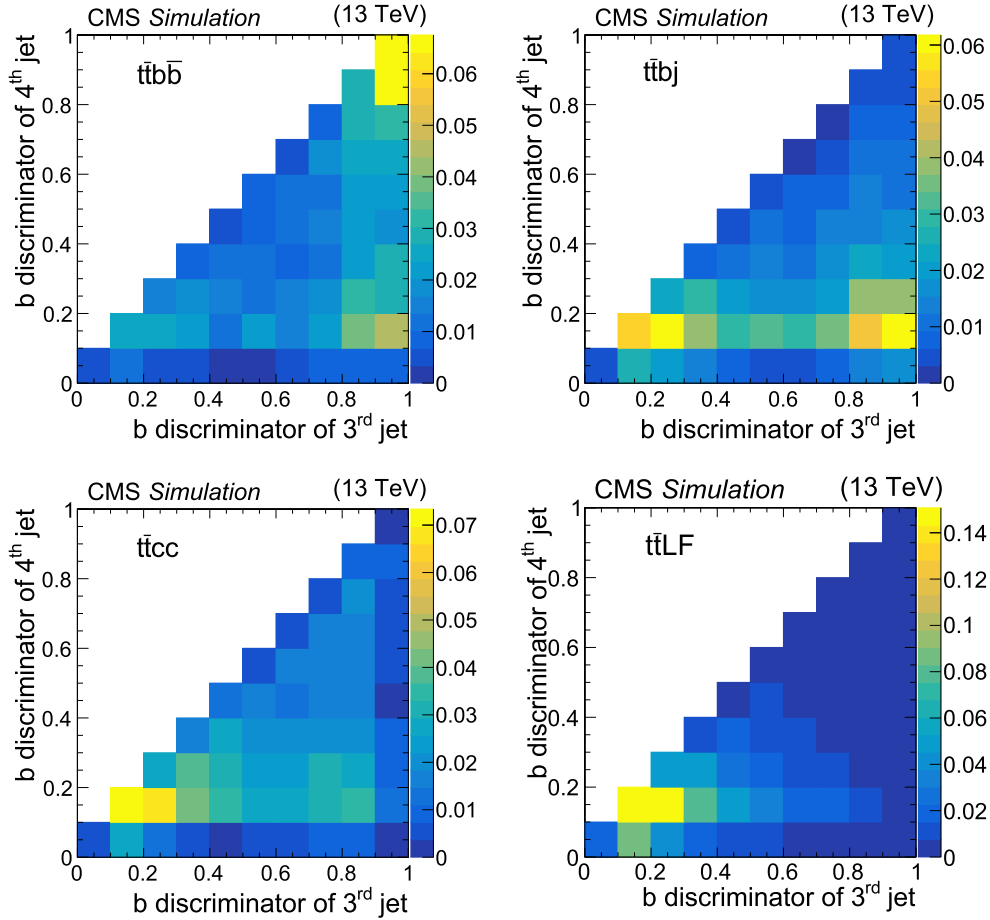
Fig. 1. Normalized 2D distributions of the b jet discriminators of the third (*x*-axis) and the fourth (*y*-axis) jets sorted in decreasing order of b tagging discriminator value, after the full event selection for t$\bar{\text{t}}$b$\bar{\text{b}}$ (upper left), t$\bar{\text{t}}$bj (upper right), t$\bar{\text{t}}$c$\bar{\text{c}}$ (lower left), and t$\bar{\text{t}}$LF (lower right) processes.

events and R of 0.056 ± 0.008 are obtained from the fit. The correlation coefficient between the two parameters is 0.002.

The result obtained for R is corrected to account for the different selection efficiencies for the two processes. The event selection efficiencies, defined as the number of t$\bar{\text{t}}$b$\bar{\text{b}}$ and t$\bar{\text{t}}$jj events after the full event selection divided by the number of events in the corresponding visible phase space, are 27% and 12%, respectively. For the t$\bar{\text{t}}$b$\bar{\text{b}}$ process, there are at least 4 b jets in the events, therefore, it is easier to fulfill the requirement of at least two b-tagged jets than the t$\bar{\text{t}}$jj process.

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

The b-tagged jet multiplicity distribution in Fig. 3 shows the comparison between data and the simulation after the requirement of at least four jets, together with the ratio of the number of data events to the expectation in the lower panel, where the simulated histograms have been scaled to the fit result.

The t$\bar{\text{t}}$b$\bar{\text{b}}$ and t$\bar{\text{t}}$jj cross sections in the visible phase space are calculated using the relationship $\sigma_{\text{visible}} = N/(\epsilon \mathcal{L})$, where $\mathcal{L}$ is the integrated luminosity, N is the number of events from the fit result, and ϵ is the efficiency for each process. For the purpose of comparing with the theoretical prediction and the measurements in the other decay modes, the cross sections in the full phase space are extrapolated from the cross sections in the visible phase space using the relation $\sigma_{\text{full}} = \sigma_{\text{visible}}/\mathcal{A}$, where $\mathcal{A}$ is the acceptance, defined as the number of 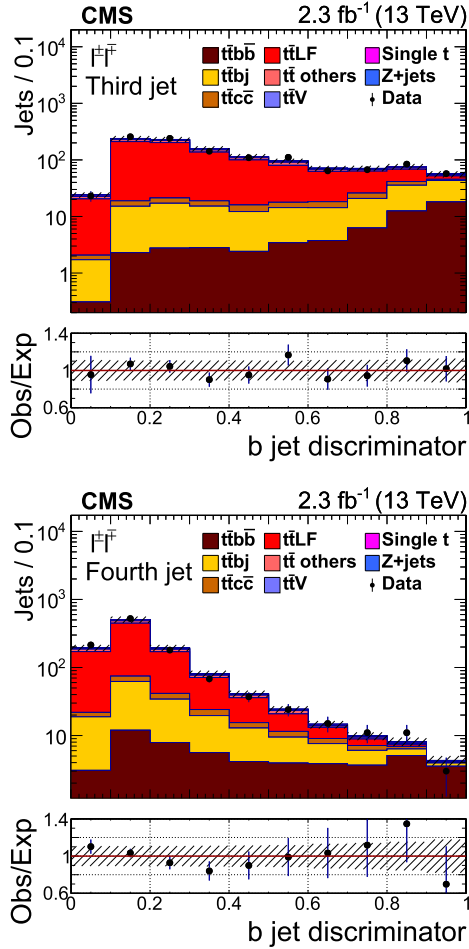events in the corresponding visible phase space divided by the number of events in the full phase space. The acceptances are calculated based on the POWHEG simulation and are 2.2% and 2.0% for t$\bar{\text{t}}$b$\bar{\text{b}}$ and t$\bar{\text{t}}$jj, respectively, including the leptonic branching fraction of both W bosons [46].

6. Estimation of systematic uncertainties

The systematic uncertainties are determined separately for the t$\bar{\text{t}}$b$\bar{\text{b}}$ and t$\bar{\text{t}}$jj 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 2 for the visible phase space.

The systematic uncertainties associated with the b tagging efficiency for heavy- and light-flavour jets are studied separately, varying their values within the corresponding uncertainties. The b-flavour correction factors are obtained using t$\bar{\text{t}}$ enriched events by tagging one b jet and probing the other b jet. Their dominant uncertainty comes from the contamination when one of the b jets is not reconstructed [47] (indicated as "b quark flavour" in Table 2). The light-flavour jet correction factors are determined from Z+jets enriched events with at least two jets (indicated as "light flavour" in Table 2). The uncertainty arises because in this control sample of Z+jets, the contamination from the Z+b$\bar{\text{b}}$ process is not well modelled. The correction factor for c jets is not measured, owing to the limited amount of data, and is assumed to be unity with an

Fig. 2. Distributions of b jet discriminator for the third (top) and the fourth (bottom) jets in decreasing order of b tagging discriminator value, after the full event selection. The points show the data and the stacked histograms are from simulated events, normalized by the results of the fit. The ratio of the number of data events to the expected number, as given by the stacked histograms, is shown in the lower panels. The hatched region indicates the modelling uncertainty in the MC simulation.

Table 2

Summary of the systematic uncertainties in percentage (%) 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 in the visible phase space.

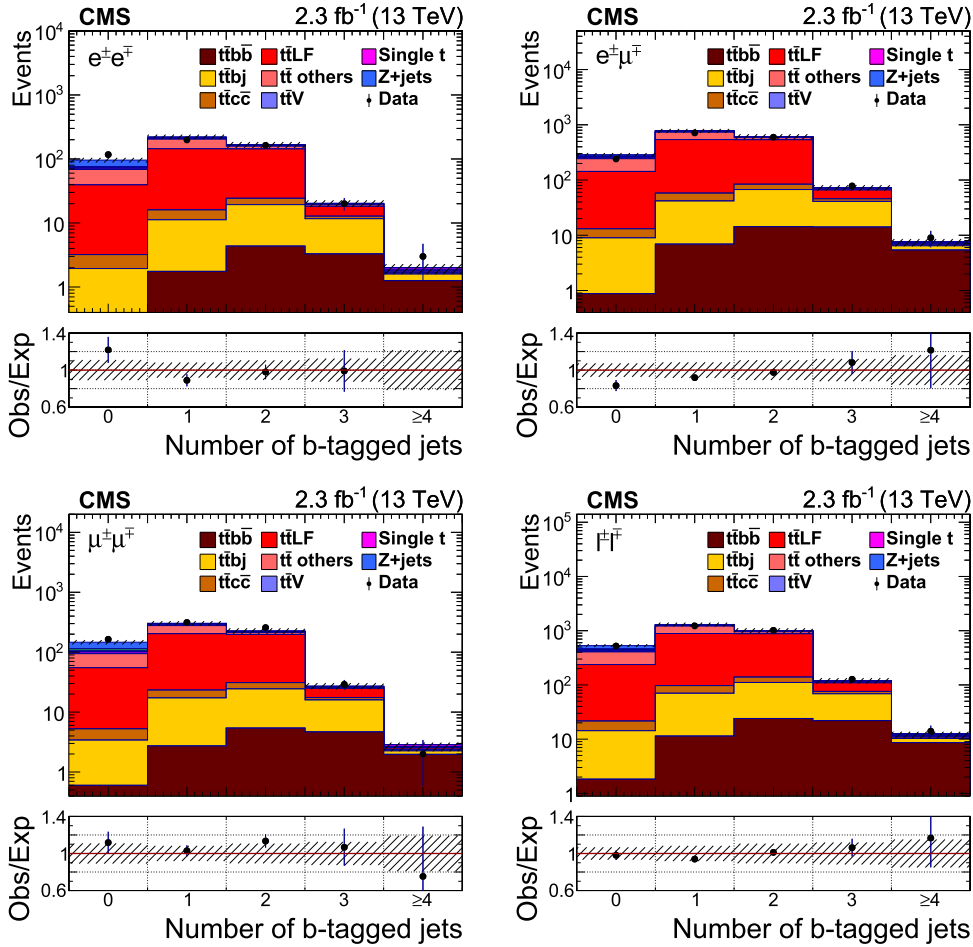| Source	$\sigma_{t\bar{t}b\bar{b}}$	$\sigma_{t\bar{t}jj}$	$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$
b tag (b quark flavour)	19	4.7	19
b tag (c quark flavour)	14	1.3	14
b tag (light flavour)	14	9.8	9.7
JES & JER	7.8	7.4	2.6
Ratio of t$\bar{t}$b$\bar{b}$ and t$\bar{t}$bj	2.6	0.5	2.6
Background modelling	3.8	3.5	1.6
t$\bar{t}$c$\bar{c}$ fraction in the fit	5.2	1.9	4.8
Lepton trigger/identification	3.0	3.0	0
Pileup	0.4	<0.1	0.4
MC generator	9.4	6.2	3.0
μ_F and μ_R scale	2.0	2.0	1.0
scale in PS	13	9.9	10
PDFs	0.5	0.5	<0.1
Efficiency (t$\bar{t}$c$\bar{c}$ fraction)	0	1.3	1.3
Jet multiplicity modelling	5.0	5.0	5.0
Simulation (statistical)	1.5	1.5	1.5
Top quark p_T modelling	0.8	0.3	0.5
Integrated Luminosity	2.3	2.3	0
Total uncertainty	34	19	28

nificantly. The uncertainty caused by mismodelling of these backgrounds is assessed by varying the contribution to cover the uncertainty in the single top quark production cross section (indicated as "Background modelling" in Table 2). An uncertainty to account for the modelling of the t$\bar{t}$c$\bar{c}$ fraction by simulations is also assigned by varying the contribution by 50% in the fit. This is derived from the theoretical uncertainty on the t$\bar{t}$jj cross section. For the efficiency of t$\bar{t}$jj events, the uncertainty owing to the heavy-flavour fraction is negligible because of their small fraction.

The systematic uncertainty in the lepton identification is calculated by varying the correction factor for the efficiency within its uncertainty, as derived from Z boson candidates as a function of lepton η and p_T, and also taking into account the different phase space between Z boson and t$\bar{t}$ events.

The systematic uncertainty in the number of pileup events is estimated by varying the total inelastic cross section by 5% to cover all of the uncertainties in the modelling of the pileup [32].

The dependence of the correction factor at the particle level on the assumptions made in the MC simulation is another source of systematic uncertainty: the generators POWHEG and MadGraph5_aMC@NLO are compared and the difference in the efficiency is taken as systematic uncertainty. The uncertainties from the μ_F and μ_R scales at the ME level are estimated by making use of a weighting scheme implemented in POWHEG to vary the scales by a factor of two up and down with respect to their reference values $\mu_F = \mu_R = \sqrt{m_t^2 + p_{T,t}^2}$, where m_t is 172.5 GeV, with $p_{T,t}$ being the top quark transverse momentum. The uncertainties from the μ_F and μ_R scales at the PS level are assessed by using additional simulations where the scales are changed by a factor of two up and down relative to their reference values. In simulation, event weights are calculated that represent the usage of the uncertainty eigenvector sets of the PDF. The uncertainties in the PDFs are accounted for by using these various event weights. The uncertainty from the modelling of jet multiplicity, in particular, the mismodelling for events with more than five jets, is also taken into account. It is estimated to be 5% by comparing the rates of high-multiplicity events in data and simulation.

The size of the MC sample used for t$\bar{t}$b$\bar{b}$ simulation being limited, the uncertainty from the statistical fluctuations in the sim-

uncertainty twice as large as for b jets [43] (indicated as "c quark flavour" in Table 2). In the correction factor evaluation, the statistical uncertainty, which can arise owing to low event yields in certain regions, e.g. at values of the b tagging discriminator near one, is also taken into account.

The b tagging discriminator can also be affected by the jet energy scale (JES) variations [42] since the efficiency correction changes through its p_T dependence. The corresponding systematic uncertainty is obtained by varying the JES correction within its uncertainty and repeating the whole analysis. The uncertainty induced by the jet energy resolution (JER) is assessed by smearing the jet energy resolution in simulation by an additional uncertainty dependent on η of about 10% [42].

The ratio of t$\bar{t}$b$\bar{b}$ events with respect to t$\bar{t}$bj events is based on the POWHEG MC simulation. The uncertainty arising from this rate is evaluated by comparing the reference value (POWHEG) with that of a MadGraph5_aMC@NLO sample, and POWHEG samples with different μ_F and μ_R scales in the ME and parton shower (PS) calculations.

The contributions from Z+jets and single top quark processes are small, and the 2D b tagging discriminator distributions from these backgrounds are similar to those of the t$\bar{t}$LF component. Therefore, these backgrounds do not affect the measurement sig-

Fig. 3. Distribution of b jet multiplicity after the four-jet requirement, but without the b tagging requirement, for the $e^{\pm}e^{\mp}$ (upper left), $e^{\pm}\mu^{\mp}$ (upper right), and $\mu^{\pm}\mu^{\mp}$ (lower left) final states and the sum of the three final states (lower right). The points show the data and the stacked histograms are from simulated events, normalized by the results of the fit. The ratio of the number of data events to the expected number, as given by the stacked histograms, is shown in the lower panels. The hatched region indicates the modelling uncertainty in the MC simulation.

ulated event samples is assessed by repeating the fit with the method described in Ref. [48]. The difference of 1.5% in the result is accounted for in the systematic uncertainty.

In addition to the theoretical and modelling uncertainties described above, the uncertainty coming from the modelling of the top quark p_T distribution in the ME calculations is taken into account. The uncertainty is calculated by taking the difference in shape between the parton-level p_T spectrum from the ME generator and the unfolded p_T spectrum from the data [49]. The uncertainty due to the top quark p_T modelling is negligible in this analysis, as shown in Table 2.

Adding all these contributions in quadrature gives a total systematic uncertainty of 28% in the cross section ratio, with the dominant contributions coming from the b tagging efficiency and the misidentification of light- and c-flavoured partons, followed by the 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 the uncertainties that are common between $t\bar{t}b\bar{b}$ and $t\bar{t}jj$, such as the JES uncertainty, partially or completely cancel in the ratio.

When 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 Mad-Graph5_amc@nlo and powheg. This uncertainty amounts to 4% for each of the cross section measurements and 1% for the cross section ratio.

7. Results

After accounting for all corrections and systematic effects, 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. The measured cross section ratio in the visible phase space for events with particle-level jets is

$$(\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj})^{\text{vis}} = 0.024 \pm 0.003\,(\text{stat}) \pm 0.007\,(\text{syst}). \quad (3)$$

The result is obtained in the visible phase space, defined as events having two leptons with $p_T > 20$ GeV and $|\eta| < 2.4$, plus at least four jets, including at least two b jets with $p_T > 20$ GeV and $|\eta| < 2.5$. The cross section ratio in the full phase space that uses the acceptance correction described in Section 5 is

$$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj} = 0.022 \pm 0.003\,(\text{stat}) \pm 0.006\,(\text{syst}). \quad (4)$$

The predicted values from powheg are 0.014 ± 0.001 and 0.012 ± 0.001 for the visible and full phase space, respectively, where the

Table 3

The measured cross sections $\sigma_{t\bar{t}b\bar{b}}$ and $\sigma_{t\bar{t}jj}$ and their ratio for the visible and the full phase space, corrected for acceptance and branching fractions. The uncertainties on the measurements show separately the statistical and systematic components, while those are combined for the POWHEG predictions.

Phase space		$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$\sigma_{t\bar{t}jj}$ [pb]	$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$
Visible	Measurement	$0.088 \pm 0.012 \pm 0.029$	$3.7 \pm 0.1 \pm 0.7$	$0.024 \pm 0.003 \pm 0.007$
	SM (POWHEG)	0.070 ± 0.009	5.1 ± 0.5	0.014 ± 0.001
Full	Measurement	$4.0 \pm 0.6 \pm 1.3$	$184 \pm 6 \pm 33$	$0.022 \pm 0.003 \pm 0.006$
	SM (POWHEG)	3.2 ± 0.4	257 ± 26	0.012 ± 0.001

uncertainty in the simulation is the sum in quadrature of the statistical, and the μ_F/μ_R scale systematic uncertainties. The prediction obtained from POWHEG simulation (interfaced with PYTHIA) underpredicts the measured cross section ratio by a factor of 1.8, but it is compatible with the observation within two standard deviations. The measured cross sections in the visible and the full phase space are presented in Table 3.

8. Summary

Measurements of the cross sections $\sigma_{t\bar{t}b\bar{b}}$ and $\sigma_{t\bar{t}jj}$ and their ratio $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$ are presented using a data sample recorded in pp collisions at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 2.3 fb^{-1}. The cross section ratio has been 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 ratios in the visible and the full phase space are $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj} = 0.024 \pm 0.003\,(\text{stat}) \pm 0.007\,(\text{syst})$ and $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj} = 0.022 \pm 0.003\,(\text{stat}) \pm 0.006\,(\text{syst})$, respectively, where a minimum transverse momentum for the particle-level jets of 20 GeV is required. The $t\bar{t}H$ contribution, being negligible, is not removed from data. Theoretical ratios predicted from the POWHEG simulation (interfaced with PYTHIA) are 0.014 ± 0.001 for the visible and 0.012 ± 0.001 for the full phase space, which are lower than the measured values but consistent within two standard deviations. The individual cross sections $\sigma_{t\bar{t}b\bar{b}} = 4.0 \pm 0.6\,(\text{stat}) \pm 1.3\,(\text{syst})$ pb and $\sigma_{t\bar{t}jj} = 184 \pm 6\,(\text{stat}) \pm 33\,(\text{syst})$ pb have also been measured. These results, in particular the ratio of the cross sections, provide important information for the $t\bar{t}H$ search, permitting the reduction of a dominant systematic uncertainty that derives from the uncertainty in the $t\bar{t}b\bar{b}$ background. They can also be used as a figure of merit for testing the validity of next-to-leading-order QCD calculations at $\sqrt{s} = 13$ TeV.

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, https://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, https://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, https://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, https://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, https://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 τ leptons, J. High Energy Phys. 05 (2014) 104, https://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, https://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, https://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, https://doi.org/10.1016/j.physletb.2013.08.026, arXiv:1307.1432.

[10] G. Aad, et al., ATLAS, CMS, Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s} = 7$ and 8 TeV, J. High Energy Phys. 08 (2016) 045, https://doi.org/10.1007/JHEP08(2016)045.

[11] M. Worek, G. Bevilacqua, On the ratio of $t\bar{t}b\bar{b}$ and $t\bar{t}jj$ cross sections at the CERN Large Hadron Collider, J. High Energy Phys. 07 (2014) 135, https://doi.org/10.1007/JHEP07(2014)135, arXiv:1403.2046.

[12] 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, https://doi.org/10.1103/PhysRevLett.103.012002, arXiv:0905.0110.

[13] 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, https://doi.org/10.1088/1126-6708/2008/08/108, arXiv:0807.1248.

[14] CMS Collaboration, 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, Phys. Lett. B 746 (2015) 132, https://doi.org/10.1016/j.physletb.2015.04.060.

[15] CMS Collaboration, Measurement of $t\bar{t}$ production with additional jet activity, including b quark jets, in the dilepton decay channel using pp collisions at $\sqrt{s} = 8$ TeV, Eur. Phys. J. C 76 (2016) 379, https://doi.org/10.1140/epjc/s10052-016-4105-x.

[16] ATLAS Collaboration, Measurements of fiducial cross-sections for $t\bar{t}$ production with one of two additional b-jets in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector, Eur. Phys. J. C 76 (2016) 11, https://doi.org/10.1140/epjc/s10052-015-3852-4, arXiv:1508.06868.

[17] CMS Collaboration, CMS luminosity measurement for the 2015 data-taking period, CMS Physics Analysis Summary CMS-PAS-LUM-15-001, 2016, https://cds.cern.ch/record/2138682.

[18] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. 3 (2008) S08004, https://doi.org/10.1088/1748-0221/3/08/S08004.

[19] P. Nason, A new method for combining NLO QCD with shower Monte Carlo algorithms, J. High Energy Phys. 11 (2004) 040, https://doi.org/10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.

[20] S. Frixione, P. Nason, C. Oleari, Matching NLO QCD computations with parton shower simulations: the POWHEG method, J. High Energy Phys. 11 (2007) 070, https://doi.org/10.1088/1126-6708/2007/11/070, arXiv:0709.2092.

[21] 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, https://doi.org/10.1007/JHEP06(2010)043, arXiv:1002.2581.

[22] T. Sjöstrand, S. Mrenna, P. Skands, PYTHIA 6.4 physics and manual, J. High Energy Phys. 05 (2006) 026, https://doi.org/10.1088/1126-6708/2006/05/026, arXiv:hep-ph/0603175.

[23] T. Sjöstrand, S. Mrenna, P. Skands, A brief introduction to PYTHIA 8.1, Comput. Phys. Commun. 178 (2008) 852, https://doi.org/10.1016/j.cpc.2008.01.036, arXiv:0710.3820.

[24] P. Skands, S. Carrazza, J. Rojo, Tuning PYTHIA 8.1: the Monash 2013 tune, Eur. Phys. J. C 74 (2014) 3024, https://doi.org/10.1140/epjc/s10052-014-3024-y.

[25] R.D. Ball, et al., NNPDF, Parton distributions for the LHC Run II, J. High Energy Phys. 04 (2015) 040, https://doi.org/10.1007/JHEP04(2015)040, arXiv:1410.8849.

[26] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, T. Stelzer, MadGraph 5: going beyond, J. High Energy Phys. 06 (2011) 128, https://doi.org/10.1007/JHEP06(2011)128, arXiv:1106.0522.

[27] 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, https://doi.org/10.1007/JHEP07(2014)079, arXiv:1405.0301.

[28] M. Czakon, A. Mitov, Top++: a program for the calculation of the top-pair cross-section at hadron colliders, Comput. Phys. Commun. 185 (2014) 2930, https://doi.org/10.1016/j.cpc.2014.06.021, arXiv:1112.5675.

[29] Y. Li, F. Petriello, Combining QCD and electroweak corrections to dilepton production in FEWZ, Phys. Rev. D 86 (2012) 094034, https://doi.org/10.1103/PhysRevD.86.094034, arXiv:1208.5967.

[30] N. Kidonakis, NNLL threshold resummation for top-pair and single-top production, Phys. Part. Nucl. 45 (2014) 714, https://doi.org/10.1134/S1063779614040091, arXiv:1210.7813.

[31] S. Agostinelli, et al., GEANT4, GEANT4—a simulation toolkit, Nucl. Instrum. Methods A 506 (2003) 250, https://doi.org/10.1016/S0168-9002(03)01368-8.

[32] ATLAS Collaboration, Measurement of the inelastic proton–proton cross section at $\sqrt{s} = 13$ TeV with ATLAS detector at the LHC, Phys. Rev. Lett. 117 (2016) 182002, https://doi.org/10.1103/PhysRevLett.117.182002, arXiv:1606.02625.

[33] M. Cacciari, G.P. Salam, G. Soyez, The anti-k_t jet clustering algorithm, J. High Energy Phys. 04 (2008) 063, https://doi.org/10.1088/1126-6708/2008/04/063, arXiv:0802.1189.

[34] M. Cacciari, G.P. Salam, G. Soyez, The catchment area of jets, J. High Energy Phys. 04 (2008) 005, https://doi.org/10.1088/1126-6708/2008/04/005, arXiv:0802.1188.

[35] CMS Collaboration, The CMS trigger system, J. Instrum. 12 (2017) P01020, https://doi.org/10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.

[36] CMS Collaboration, Particle-flow event reconstruction in CMS and performance for jets, taus, and E_T^{miss}, CMS Physics Analysis Summary CMS-PAS-PFT-09-001, 2009, http://cds.cern.ch/record/1194487.

[37] CMS Collaboration, Commissioning of the particle-flow event reconstruction with the first LHC collisions recorded in the CMS detector, CMS Physics Analysis Summary CMS-PAS-PFT-10-001, 2010, http://cds.cern.ch/record/1247373.

[38] CMS Collaboration, Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV, J. Instrum. 7 (2012) P10002, https://doi.org/10.1088/1748-0221/7/10/P10002.

[39] CMS Collaboration, Performance of electron reconstruction and selection with the CMS detector in proton–proton collisions at $\sqrt{s} = 8$ TeV, J. Instrum. 10 (2015) P06005, https://doi.org/10.1088/1748-0221/10/06/P06005, arXiv:1502.02701.

[40] CMS Collaboration, Performance of photon reconstruction and identification with the CMS detector in proton–proton collisions at $\sqrt{s} = 8$ TeV, J. Instrum. 10 (2015) P08010, https://doi.org/10.1088/1748-0221/10/08/P08010, arXiv:1502.02702.

[41] CMS Collaboration, Electron and Photon performance using data collected by CMS at $\sqrt{s} = 13$ TeV and 25 ns, CMS Detector Performance Note CMS-DP-2015-067, 2015, http://cds.cern.ch/record/2118397.

[42] CMS Collaboration, Determination of jet energy calibration and transverse momentum resolution in CMS, J. Instrum. 6 (2011) P11002, https://doi.org/10.1088/1748-0221/6/11/P11002, arXiv:1107.4277.

[43] CMS Collaboration, Identification of b-quark jets with the CMS experiment, J. Instrum. 8 (2013) P04013, https://doi.org/10.1088/1748-0221/8/04/P04013, arXiv:1211.4462.

[44] CMS Collaboration, Identification of b quark jets at the CMS experiment in the LHC Run 2, CMS Physics Analysis Summary CMS-PAS-BTV-15-001, 2016, https://cds.cern.ch/record/2138504.

[45] CMS Collaboration, Measurement of differential cross sections for top quark pair production using the lepton+jets final state in proton–proton collisions at 13 TeV, Phys. Rev. D 95 (2017) 092001, https://doi.org/10.1103/PhysRevD.95.092001, arXiv:1610.04191.

[46] Particle Data Group, C. Patrignani, et al., Review of particle physics, Chin. Phys. C 40 (2016) 100001, https://doi.org/10.1088/1674-1137/40/10/100001.

[47] CMS Collaboration, Search for the associated production of the Higgs boson with a top-quark pair, J. High Energy Phys. 09 (2014) 087, https://doi.org/10.1007/JHEP09(2014)087, arXiv:1408.1682, Erratum: https://doi.org/10.1007/JHEP10(2014)106.

[48] R. Barlow, C. Beeston, Fitting using finite Monte Carlo samples, Comput. Phys. Commun. 77 (1993) 219, https://doi.org/10.1016/0010-4655(93)90005-W.

[49] CMS Collaboration, Measurement of the differential cross section for top quark pair production in pp collisions at $\sqrt{s} = 8$ TeV, Eur. Phys. J. C 75 (2015) 542, https://doi.org/10.1140/epjc/s10052-015-3709-x.

The CMS Collaboration

A.M. Sirunyan, A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth [1], V.M. Ghete, N. Hörmann, J. Hrubec, M. Jeitler [1], A. König, I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady, N. Rad, H. Rohringer, J. Schieck [1], J. Strauss, W. Waltenberger, C.-E. Wulz [1]

Institut für Hochenergiephysik, Wien, Austria

V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

Institute for Nuclear Problems, Minsk, Belarus

N. Shumeiko

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

S. Alderweireldt, E.A. De Wolf, X. Janssen, J. Lauwers, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Universiteit Antwerpen, Antwerpen, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, I. De Bruyn, J. De Clercq, K. Deroover, S. Lowette, S. Moortgat, L. Moreels, A. Olbrechts, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Vrije Universiteit Brussel, Brussel, Belgium

H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, J. Luetic, T. Maerschalk, A. Marinov, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, D. Vannerom, R. Yonamine, F. Zenoni, F. Zhang [2]

Université Libre de Bruxelles, Bruxelles, Belgium

A. Cimmino, T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov, D. Poyraz, S. Salva, R. Schöfbeck, M. Tytgat, W. Van Driessche, W. Verbeke, N. Zaganidis

Ghent University, Ghent, Belgium

H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, A. Caudron, S. De Visscher, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, A. Jafari, M. Komm, G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, K. Piotrzkowski, L. Quertenmont, M. Vidal Marono, S. Wertz

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

N. Beliy

Université de Mons, Mons, Belgium

W.L. Aldá Júnior, F.L. Alves, G.A. Alves, L. Brito, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato [3], A. Custódio, E.M. Da Costa, G.G. Da Silveira [4], D. De Jesus Damiao, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, C. Mora Herrera, L. Mundim, H. Nogima, A. Santoro, A. Sznajder, E.J. Tonelli Manganote [3], F. Torres Da Silva De Araujo, A. Vilela Pereira

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

S. Ahuja [a], C.A. Bernardes [a], T.R. Fernandez Perez Tomei [a], E.M. Gregores [b], P.G. Mercadante [b], C.S. Moon [a], S.F. Novaes [a], Sandra S. Padula [a], D. Romero Abad [b], J.C. Ruiz Vargas [a]

[a] *Universidade Estadual Paulista, São Paulo, Brazil*
[b] *Universidade Federal do ABC, São Paulo, Brazil*

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

University of Sofia, Sofia, Bulgaria

W. Fang [5], X. Gao [5]

Beihang University, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, Z. Liu, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, E. Yazgan, H. Zhang, J. Zhao

Institute of High Energy Physics, Beijing, China

Y. Ban, G. Chen, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

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

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, J.D. Ruiz Alvarez

Universidad de Los Andes, Bogota, Colombia

N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano, T. Sculac

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, D. Ferencek, K. Kadija, B. Mesic, T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

M.W. Ather, A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

University of Cyprus, Nicosia, Cyprus

M. Finger [6], M. Finger Jr. [6]

Charles University, Prague, Czech Republic

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

A.A. Abdelalim [7,8], Y. Mohammed [9], E. Salama [10,11]

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

R.K. Dewanjee, M. Kadastik, L. Perrini, M. Raidal, A. Tiko, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, J. Pekkanen, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

J. Härkönen, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, E. Tuominen, J. Tuominiemi, E. Tuovinen

Helsinki Institute of Physics, Helsinki, Finland

J. Talvitie, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, S. Ghosh, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, I. Kucher, E. Locci, M. Machet, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, M. Titov

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

A. Abdulsalam, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, O. Davignon, R. Granier de Cassagnac, M. Jo, S. Lisniak, A. Lobanov, P. Miné, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, Y. Sirois, A.G. Stahl Leiton, T. Strebler, Y. Yilmaz, A. Zabi, A. Zghiche

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France

J.-L. Agram [12], J. Andrea, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte [12], X. Coubez, J.-C. Fontaine [12], D. Gelé, U. Goerlach, A.-C. Le Bihan, P. Van Hove

Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 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, C. Bernet, G. Boudoul, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov [13], V. Sordini, M. Vander Donckt, S. Viret

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

T. Toriashvili [14]

Georgian Technical University, Tbilisi, Georgia

D. Lomidze

Tbilisi State University, Tbilisi, Georgia

C. Autermann, S. Beranek, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, C. Schomakers, J. Schulz, T. Verlage

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

A. Albert, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, M. Hamer, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, M. Olschewski, K. Padeken, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, L. Sonnenschein, D. Teyssier, S. Thüer

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

G. Flügge, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, A. Stahl [15]

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

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A.A. Bin Anuar, K. Borras [16], V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Eckerlin, D. Eckstein, T. Eichhorn, E. Eren, E. Gallo [17], J. Garay Garcia, A. Geiser, A. Gizhko, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, A. Harb, J. Hauk, M. Hempel [18], H. Jung, A. Kalogeropoulos, M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek,

T. Lenz, J. Leonard, K. Lipka, W. Lohmann [18], R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M. Savitskyi, P. Saxena, R. Shevchenko, S. Spannagel, N. Stefaniuk, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing

Deutsches Elektronen-Synchrotron, Hamburg, Germany

S. Bein, V. Blobel, M. Centis Vignali, A.R. Draeger, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, M. Hoffmann, A. Junkes, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, T. Lapsien, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo [15], T. Peiffer, A. Perieanu, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

University of Hamburg, Hamburg, Germany

M. Akbiyik, C. Barth, S. Baur, C. Baus, J. Berger, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, B. Freund, R. Friese, M. Giffels, A. Gilbert, D. Haitz, F. Hartmann [15], S.M. Heindl, U. Husemann, F. Kassel [15], S. Kudella, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

G. Anagnostou, G. Daskalakis, T. Geralis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, I. Topsis-Giotis

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

S. Kesisoglou, A. Panagiotou, N. Saoulidou

National and Kapodistrian University of Athens, Athens, Greece

I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F.A. Triantis

University of Ioánnina, Ioánnina, Greece

M. Csanad, N. Filipovic, G. Pasztor

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath [19], F. Sikler, V. Veszpremi, G. Vesztergombi [20], A.J. Zsigmond

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi [21], A. Makovec, J. Molnar, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

M. Bartók [20], P. Raics, Z.L. Trocsanyi, B. Ujvari

Institute of Physics, University of Debrecen, Debrecen, Hungary

S. Choudhury, J.R. Komaragiri

Indian Institute of Science (IISc), Bangalore, India

S. Bahinipati [22], S. Bhowmik, P. Mal, K. Mandal, A. Nayak [23], D.K. Sahoo [22], N. Sahoo, S.K. Swain

National Institute of Science Education and Research, Bhubaneswar, India

S. Bansal, S.B. Beri, V. Bhatnagar, U. Bhawandeep, R. Chawla, N. Dhingra, A.K. Kalsi, A. Kaur, M. Kaur, R. Kumar, P. Kumari, A. Mehta, M. Mittal, J.B. Singh, G. Walia

Panjab University, Chandigarh, India

Ashok Kumar, Aashaq Shah, A. Bhardwaj, S. Chauhan, B.C. Choudhary, R.B. Garg, S. Keshri, S. Malhotra, M. Naimuddin, K. Ranjan, R. Sharma, V. Sharma

University of Delhi, Delhi, India

R. Bhattacharya, S. Bhattacharya, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

P.K. Behera

Indian Institute of Technology Madras, Madras, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty [15], P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Dugad, B. Mahakud, S. Mitra, G.B. Mohanty, B. Parida, N. Sur, B. Sutar

Tata Institute of Fundamental Research-A, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Kumar, M. Maity [24], G. Majumder, K. Mazumdar, T. Sarkar [24], N. Wickramage [25]

Tata Institute of Fundamental Research-B, Mumbai, India

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

Indian Institute of Science Education and Research (IISER), Pune, India

S. Chenarani [26], E. Eskandari Tadavani, S.M. Etesami [26], M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi [27], F. Rezaei Hosseinabadi, B. Safarzadeh [28], M. Zeinali

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

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia [a,b], C. Calabria [a,b], C. Caputo [a,b], A. Colaleo [a], D. Creanza [a,c], L. Cristella [a,b], N. De Filippis [a,c], M. De Palma [a,b], L. Fiore [a], G. Iaselli [a,c], G. Maggi [a,c], M. Maggi [a], G. Miniello [a,b], S. My [a,b], S. Nuzzo [a,b], A. Pompili [a,b], G. Pugliese [a,c], R. Radogna [a,b], A. Ranieri [a], G. Selvaggi [a,b], A. Sharma [a], L. Silvestris [a,15], R. Venditti [a], P. Verwilligen [a]

[a] *INFN Sezione di Bari, Bari, Italy*
[b] *Università di Bari, Bari, Italy*
[c] *Politecnico di Bari, Bari, Italy*

G. Abbiendi [a], C. Battilana, D. Bonacorsi [a,b], S. Braibant-Giacomelli [a,b], L. Brigliadori [a,b], R. Campanini [a,b], P. Capiluppi [a,b], A. Castro [a,b], F.R. Cavallo [a], S.S. Chhibra [a,b], M. Cuffiani [a,b], G.M. Dallavalle [a], F. Fabbri [a], A. Fanfani [a,b], D. Fasanella [a,b], P. Giacomelli [a], L. Guiducci [a,b], S. Marcellini [a], G. Masetti [a], F.L. Navarria [a,b], A. Perrotta [a], A.M. Rossi [a,b], T. Rovelli [a,b], G.P. Siroli [a,b], N. Tosi [a,b,15]

[a] *INFN Sezione di Bologna, Bologna, Italy*
[b] *Università di Bologna, Bologna, Italy*

S. Albergo [a,b], S. Costa [a,b], A. Di Mattia [a], F. Giordano [a,b], R. Potenza [a,b], A. Tricomi [a,b], C. Tuve [a,b]

[a] *INFN Sezione di Catania, Catania, Italy*
[b] *Università di Catania, Catania, Italy*

G. Barbagli [a], K. Chatterjee [a,b], V. Ciulli [a,b], C. Civinini [a], R. D'Alessandro [a,b], E. Focardi [a,b], P. Lenzi [a,b], M. Meschini [a], S. Paoletti [a], L. Russo [a,29], G. Sguazzoni [a], D. Strom [a], L. Viliani [a,b,15]

[a] *INFN Sezione di Firenze, Firenze, Italy*
[b] *Università di Firenze, Firenze, Italy*

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera [15]

INFN Laboratori Nazionali di Frascati, Frascati, Italy

V. Calvelli [a,b], F. Ferro [a], E. Robutti [a], S. Tosi [a,b]

[a] *INFN Sezione di Genova, Genova, Italy*
[b] *Università di Genova, Genova, Italy*

L. Brianza [a,b,15], F. Brivio [a,b], V. Ciriolo, M.E. Dinardo [a,b], S. Fiorendi [a,b,15], S. Gennai [a], A. Ghezzi [a,b], P. Govoni [a,b], M. Malberti [a,b], S. Malvezzi [a], R.A. Manzoni [a,b], D. Menasce [a], L. Moroni [a], M. Paganoni [a,b], K. Pauwels, D. Pedrini [a], S. Pigazzini [a,b], S. Ragazzi [a,b], T. Tabarelli de Fatis [a,b]

[a] *INFN Sezione di Milano-Bicocca, Milano, Italy*
[b] *Università di Milano-Bicocca, Milano, Italy*

S. Buontempo [a], N. Cavallo [a,c], S. Di Guida [a,d,15], M. Esposito [a,b], F. Fabozzi [a,c], F. Fienga [a,b], A.O.M. Iorio [a,b], W.A. Khan [a], G. Lanza [a], L. Lista [a], S. Meola [a,d,15], P. Paolucci [a,15], C. Sciacca [a,b], F. Thyssen [a]

[a] *INFN Sezione di Napoli, Napoli, Italy*
[b] *Università di Napoli 'Federico II', Napoli, Italy*
[c] *Università della Basilicata, Potenza, Italy*
[d] *Università G. Marconi, Roma, Italy*

P. Azzi [a,15], N. Bacchetta [a], L. Benato [a,b], A. Boletti [a,b], R. Carlin [a,b], A. Carvalho Antunes De Oliveira [a,b], P. Checchia [a], M. Dall'Osso [a,b], P. De Castro Manzano [a], T. Dorigo [a], U. Gasparini [a,b], A. Gozzelino [a], S. Lacaprara [a], M. Margoni [a,b], A.T. Meneguzzo [a,b], M. Michelotto [a], F. Montecassiano [a], M. Passaseo [a], N. Pozzobon [a,b], P. Ronchese [a,b], R. Rossin [a,b], F. Simonetto [a,b], E. Torassa [a], M. Zanetti [a,b], P. Zotto [a,b], G. Zumerle [a,b]

[a] *INFN Sezione di Padova, Padova, Italy*
[b] *Università di Padova, Padova, Italy*
[c] *Università di Trento, Trento, Italy*

A. Braghieri [a], F. Fallavollita [a,b], A. Magnani [a,b], P. Montagna [a,b], S.P. Ratti [a,b], V. Re [a], M. Ressegotti, C. Riccardi [a,b], P. Salvini [a], I. Vai [a,b], P. Vitulo [a,b]

[a] *INFN Sezione di Pavia, Pavia, Italy*
[b] *Università di Pavia, Pavia, Italy*

L. Alunni Solestizi [a,b], G.M. Bilei [a], D. Ciangottini [a,b], L. Fanò [a,b], P. Lariccia [a,b], R. Leonardi [a,b], G. Mantovani [a,b], V. Mariani [a,b], M. Menichelli [a], A. Saha [a], A. Santocchia [a,b], D. Spiga

[a] *INFN Sezione di Perugia, Perugia, Italy*
[b] *Università di Perugia, Perugia, Italy*

K. Androsov [a], P. Azzurri [a,15], G. Bagliesi [a], J. Bernardini [a], T. Boccali [a], L. Borrello, R. Castaldi [a], M.A. Ciocci [a,b], R. Dell'Orso [a], G. Fedi [a], A. Giassi [a], M.T. Grippo [a,29], F. Ligabue [a,c], T. Lomtadze [a], L. Martini [a,b], A. Messineo [a,b], F. Palla [a], A. Rizzi [a,b], A. Savoy-Navarro [a,30], P. Spagnolo [a], R. Tenchini [a], G. Tonelli [a,b], A. Venturi [a], P.G. Verdini [a]

[a] *INFN Sezione di Pisa, Pisa, Italy*
[b] *Università di Pisa, Pisa, Italy*
[c] *Scuola Normale Superiore di Pisa, Pisa, Italy*

L. Barone [a,b], F. Cavallari [a], M. Cipriani [a,b], D. Del Re [a,b,15], M. Diemoz [a], S. Gelli [a,b], E. Longo [a,b], F. Margaroli [a,b], B. Marzocchi [a,b], P. Meridiani [a], G. Organtini [a,b], R. Paramatti [a,b], F. Preiato [a,b],

S. Rahatlou [a,b], C. Rovelli [a], F. Santanastasio [a,b]

[a] *INFN Sezione di Roma, Rome, Italy*
[b] *Sapienza Università di Roma, Rome, Italy*

N. Amapane [a,b], R. Arcidiacono [a,c,15], S. Argiro [a,b], M. Arneodo [a,c], N. Bartosik [a], R. Bellan [a,b], C. Biino [a], N. Cartiglia [a], F. Cenna [a,b], M. Costa [a,b], R. Covarelli [a,b], A. Degano [a,b], N. Demaria [a], B. Kiani [a,b], C. Mariotti [a], S. Maselli [a], E. Migliore [a,b], V. Monaco [a,b], E. Monteil [a,b], M. Monteno [a], M.M. Obertino [a,b], L. Pacher [a,b], N. Pastrone [a], M. Pelliccioni [a], G.L. Pinna Angioni [a,b], F. Ravera [a,b], A. Romero [a,b], M. Ruspa [a,c], R. Sacchi [a,b], K. Shchelina [a,b], V. Sola [a], A. Solano [a,b], A. Staiano [a], P. Traczyk [a,b]

[a] *INFN Sezione di Torino, Torino, Italy*
[b] *Università di Torino, Torino, Italy*
[c] *Università del Piemonte Orientale, Novara, Italy*

S. Belforte [a], M. Casarsa [a], F. Cossutti [a], G. Della Ricca [a,b], A. Zanetti [a]

[a] *INFN Sezione di Trieste, Trieste, Italy*
[b] *Università di Trieste, Trieste, Italy*

D.H. Kim, G.N. Kim, M.S. Kim, J. Lee, S. Lee, S.W. Lee, Y.D. Oh, S. Sekmen, D.C. Son, Y.C. Yang

Kyungpook National University, Daegu, Republic of Korea

A. Lee

Chonbuk National University, Jeonju, Republic of Korea

H. Kim, D.H. Moon

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

J.A. Brochero Cifuentes, J. Goh, T.J. Kim

Hanyang University, Seoul, Republic of Korea

S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, Y. Kim, K. Lee, K.S. Lee, S. Lee, J. Lim, S.K. Park, Y. Roh

Korea University, Seoul, Republic of Korea

J. Almond, J. Kim, H. Lee, S.B. Oh, B.C. Radburn-Smith, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

Seoul National University, Seoul, Republic of Korea

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

University of Seoul, Seoul, Republic of Korea

Y. Choi, C. Hwang, J. Lee, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

V. Dudenas, A. Juodagalvis, J. Vaitkus

Vilnius University, Vilnius, Lithuania

I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali [31], F. Mohamad Idris [32], W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz [33], R. Lopez-Fernandez, J. Mejia Guisao, A. Sanchez-Hernandez

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

S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

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

D. Krofcheck

University of Auckland, Auckland, New Zealand

P.H. Butler

University of Canterbury, Christchurch, New Zealand

A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas

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

K. Bunkowski, A. Byszuk [34], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura,
M. Olszewski, A. Pyskir, M. Walczak

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

P. Bargassa, C. Beirão Da Cruz E Silva, B. Calpas, A. Di Francesco, P. Faccioli, M. Gallinaro, J. Hollar,
N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Seixas, O. Toldaiev, D. Vadruccio, J. Varela

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

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev,
A. Malakhov, V. Matveev [35,36], V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov,
N. Voytishin, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

Y. Ivanov, V. Kim [37], E. Kuznetsova [38], P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov,
L. Uvarov, S. Vavilov, A. Vorobyev

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

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov,
A. Pashenkov, D. Tlisov, A. Toropin

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, M. Toms,
E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics, Moscow, Russia

T. Aushev, A. Bylinkin [36]

Moscow Institute of Physics and Technology, Moscow, Russia

M. Chadeeva [39], S. Polikarpov, V. Rusinov

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia

V. Andreev, M. Azarkin [36], I. Dremin [36], M. Kirakosyan, A. Terkulov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin [40], L. Dudko, V. Klyukhin, O. Kodolova,
N. Korneeva, I. Lokhtin, I. Miagkov, S. Obraztsov, M. Perfilov, V. Savrin, P. Volkov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

V. Blinov [41], Y. Skovpen [41], D. Shtol [41]

Novosibirsk State University (NSU), Novosibirsk, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, D. Elumakhov, V. Kachanov, A. Kalinin, D. Konstantinov,
V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

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

P. Adzic [42], P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

J. Alcaraz Maestre, M. Barrio Luna, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris,
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, 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

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

Universidad Autónoma de Madrid, Madrid, Spain

J. Cuevas, C. Erice, J. Fernandez Menendez, I. Gonzalez Caballero, J.R. González Fernández,
E. Palencia Cortezon, S. Sanchez Cruz, I. Suárez Andrés, P. Vischia, J.M. Vizan Garcia

Universidad de Oviedo, Oviedo, Spain

I.J. Cabrillo, A. Calderon, B. Chazin Quero, E. Curras, M. Fernandez, J. Garcia-Ferrero, G. Gomez,
A. Lopez Virto, J. Marco, C. Martinez Rivero, F. Matorras, J. Piedra Gomez, T. Rodrigo, A. Ruiz-Jimeno,
L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

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

D. Abbaneo, E. Auffray, P. Baillon, A.H. Ball, D. Barney, M. Bianco, P. Bloch, A. Bocci, C. Botta,
T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, Y. Chen, D. d'Enterria, A. Dabrowski, V. Daponte,
A. David, M. De Gruttola, A. De Roeck, E. Di Marco [43], M. Dobson, B. Dorney, T. du Pree, M. Dünser,
N. Dupont, A. Elliott-Peisert, P. Everaerts, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, F. Glege,
D. Gulhan, S. Gundacker, M. Guthoff, P. Harris, J. Hegeman, V. Innocente, P. Janot, O. Karacheban [18],
J. Kieseler, H. Kirschenmann, V. Knünz, A. Kornmayer [15], M.J. Kortelainen, C. Lange, P. Lecoq, C. Lourenço,
M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi,
P. Milenovic [44], F. Moortgat, M. Mulders, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez,
M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, A. Racz, T. Reis, G. Rolandi [45], M. Rovere,
H. Sakulin, J.B. Sauvan, C. Schäfer, C. Schwick, M. Seidel, A. Sharma, P. Silva, P. Sphicas [46], J. Steggemann,
M. Stoye, M. Tosi, D. Treille, A. Triossi, A. Tsirou, V. Veckalns [47], G.I. Veres [20], M. Verweij, N. Wardle,
A. Zagozdzinska [34], 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, T. Rohe, S.A. Wiederkehr

Paul Scherrer Institut, Villigen, Switzerland

F. Bachmair, L. Bäni, P. Berger, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, T. Klijnsma, W. Lustermann, B. Mangano, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Rossini, M. Schönenberger, A. Starodumov [48], V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler [49], L. Caminada, M.F. Canelli, A. De Cosa, S. Donato, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, C. Seitz, Y. Yang, A. Zucchetta

Universität Zürich, Zurich, Switzerland

V. Candelise, T.H. Doan, Sh. Jain, R. Khurana, M. Konyushikhin, C.M. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu

National Central University, Chung-Li, Taiwan

Arun Kumar, P. Chang, Y.H. Chang, Y. Chao, K.F. Chen, P.H. Chen, F. Fiori, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, M. Miñano Moya, E. Paganis, A. Psallidas, J.f. Tsai

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, K. Kovitanggoon, G. Singh, N. Srimanobhas

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

A. Adiguzel, M.N. Bakirci [50], F. Boran, S. Damarseckin, Z.S. Demiroglu, C. Dozen, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, I. Hos [51], E.E. Kangal [52], O. Kara, U. Kiminsu, M. Oglakci, G. Onengut [53], K. Ozdemir [54], S. Ozturk [50], A. Polatoz, D. Sunar Cerci [55], S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Cukurova University, Physics Department, Science and Art Faculty, Adana, Turkey

B. Bilin, G. Karapinar [56], K. Ocalan [57], M. Yalvac, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

E. Gülmez, M. Kaya [58], O. Kaya [59], E.A. Yetkin [60]

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak

Istanbul Technical University, Istanbul, Turkey

B. Grynyov

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine

L. Levchuk, P. Sorokin

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

R. Aggleton, F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, D.M. Newbold [61], S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

University of Bristol, Bristol, United Kingdom

K.W. Bell, A. Belyaev [62], C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, R. Di Maria, P. Dunne, A. Elwood, D. Futyan, Y. Haddad, G. Hall, G. Iles, T. James, R. Lane, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, J. Nash, A. Nikitenko [48], J. Pela, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta [63], T. Virdee [15], J. Wright, S.C. Zenz

Imperial College, London, United Kingdom

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

Brunel University, Uxbridge, United Kingdom

A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika

Baylor University, Waco, USA

R. Bartek, A. Dominguez

Catholic University of America, Washington, USA

A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

The University of Alabama, Tuscaloosa, USA

D. Arcaro, A. Avetisyan, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Boston University, Boston, USA

G. Benelli, D. Cutts, A. Garabedian, J. Hakala, U. Heintz, J.M. Hogan, K.H.M. Kwok, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Piperov, S. Sagir, E. Spencer, R. Syarif

Brown University, Providence, USA

R. Band, C. Brainerd, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, M. Gardner, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, J. Smith, M. Squires, D. Stolp, K. Tos, M. Tripathi, Z. Wang

University of California, Davis, Davis, USA

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, D. Saltzberg, C. Schnaible, V. Valuev

University of California, Los Angeles, USA

E. Bouvier, K. Burt, R. Clare, J. Ellison, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, J. Heilman, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, A. Shrinivas, W. Si, H. Wei, S. Wimpenny, B.R. Yates

University of California, Riverside, Riverside, USA

J.G. Branson, G.B. Cerati, S. Cittolin, M. Derdzinski, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech [64], F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, San Diego, La Jolla, USA

N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, M. Franco Sevilla, C. George, F. Golf, L. Gouskos, J. Gran, R. Heller, J. Incandela, S.D. Mullin, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, J. Yoo

University of California, Santa Barbara - Department of Physics, Santa Barbara, USA

D. Anderson, J. Bendavid, A. Bornheim, J.M. Lawhorn, H.B. Newman, C. Pena, M. Spiropulu, J.R. Vlimant, S. Xie, R.Y. Zhu

California Institute of Technology, Pasadena, USA

M.B. Andrews, T. Ferguson, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev, M. Weinberg

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, S. Leontsinis, T. Mulholland, K. Stenson, S.R. Wagner

University of Colorado Boulder, Boulder, USA

J. Alexander, J. Chaves, J. Chu, S. Dittmer, K. Mcdermott, N. Mirman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Cornell University, Ithaca, USA

D. Winn

Fairfield University, Fairfield, USA

S. Abdullin, M. Albrow, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, A. Canepa, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, I. Fisk, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, B. Schneider, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, P. Bortignon, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, S. Das, R.D. Field, I.K. Furic, J. Konigsberg, A. Korytov, K. Kotov, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, D. Rank, L. Shchutska, D. Sperka, N. Terentyev, L. Thomas, J. Wang, S. Wang, J. Yelton

University of Florida, Gainesville, USA

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

Florida International University, Miami, USA

A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, T. Perry, H. Prosper, A. Santra, R. Yohay

Florida State University, Tallahassee, USA

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, T. Roy, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, I.D. Sandoval Gonzalez, M.B. Tonjes, H. Trauger, N. Varelas, H. Wang, Z. Wu, J. Zhang

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

B. Bilki [65], W. Clarida, K. Dilsiz [66], S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya [67], A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul [68], Y. Onel, F. Ozok [69], A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

The University of Iowa, Iowa City, USA

B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao, C. You

Johns Hopkins University, Baltimore, USA

A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, J. Castle, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, C. Royon, S. Sanders, R. Stringer, J.D. Tapia Takaki, Q. Wang

The University of Kansas, Lawrence, USA

A. Ivanov, K. Kaadze, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

Kansas State University, Manhattan, USA

F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, S.C. Tonwar

University of Maryland, College Park, USA

D. Abercrombie, B. Allen, V. Azzolini, R. Barbieri, A. Baty, R. Bi, K. Bierwagen, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, D. Hsu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, B. Maier, A.C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephans, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

Massachusetts Institute of Technology, Cambridge, USA

A.C. Benvenuti, R.M. Chatterjee, A. Evans, P. Hansen, S. Kalafut, S.C. Kao, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, N. Tambe, J. Turkewitz

University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

University of Nebraska-Lincoln, Lincoln, USA

M. Alyari, J. Dolen, A. Godshalk, C. Harrington, I. Iashvili, A. Kharchilava, A. Parker, S. Rappoccio, B. Roozbahani

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, A. Hortiangtham, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, R.-J. Wang, D. Wood

Northeastern University, Boston, USA

S. Bhattacharya, O. Charaf, K.A. Hahn, N. Mucia, N. Odell, B. Pollack, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

Northwestern University, Evanston, USA

N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko [35], M. Planer, A. Reinsvold, R. Ruchti, N. Rupprecht, G. Smith, S. Taroni, M. Wayne, M. Wolf, A. Woodard

University of Notre Dame, Notre Dame, USA

J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, B. Liu, W. Luo, D. Puigh, B.L. Winer, H.W. Wulsin

The Ohio State University, Columbus, USA

A. Benaglia, S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, D. Lange, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, A. Svyatkovskiy, C. Tully

Princeton University, Princeton, USA

S. Malik, S. Norberg

University of Puerto Rico, Mayaguez, USA

A. Barker, V.E. Barnes, S. Folgueras, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, A. Khatiwada, D.H. Miller, N. Neumeister, J.F. Schulte, J. Sun, F. Wang, W. Xie

Purdue University, West Lafayette, USA

T. Cheng, N. Parashar, J. Stupak

Purdue University Northwest, Hammond, USA

A. Adair, B. Akgun, Z. Chen, K.M. Ecklund, F.J.M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B.P. Padley, J. Roberts, J. Rorie, Z. Tu, J. Zabel

Rice University, Houston, USA

B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, M. Verzetti

University of Rochester, Rochester, USA

R. Ciesielski, K. Goulianos, C. Mesropian

The Rockefeller University, New York, USA

A. Agapitos, J.P. Chou, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

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

M. Foerster, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

University of Tennessee, Knoxville, USA

O. Bouhali [70], A. Castaneda Hernandez [70], A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon [71], R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov, K.A. Ulmer

Texas A&M University, College Station, USA

N. Akchurin, J. Damgov, F. De Guio, C. Dragoiu, P.R. Dudero, J. Faulkner, E. Gurpinar, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Texas Tech University, Lubbock, USA

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

Vanderbilt University, Nashville, USA

M.W. Arenton, P. Barria, B. Cox, R. Hirosky, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, X. Sun, Y. Wang, E. Wolfe, F. Xia

University of Virginia, Charlottesville, USA

C. Clarke, R. Harr, P.E. Karchin, J. Sturdy, S. Zaleski

Wayne State University, Detroit, USA

D.A. Belknap, J. Buchanan, C. Caillol, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, G.A. Pierro, G. Polese, T. Ruggles, A. Savin, N. Smith, W.H. Smith, D. Taylor, N. Woods

University of Wisconsin - Madison, Madison, WI, USA

[1] Also at Vienna University of Technology, Vienna, Austria.
[2] Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.
[3] Also at Universidade Estadual de Campinas, Campinas, Brazil.
[4] Also at Universidade Federal de Pelotas, Pelotas, Brazil.
[5] Also at Université Libre de Bruxelles, Bruxelles, Belgium.
[6] Also at Joint Institute for Nuclear Research, Dubna, Russia.
[7] Also at Helwan University, Cairo, Egypt.
[8] Now at Zewail City of Science and Technology, Zewail, Egypt.
[9] Now at Fayoum University, El-Fayoum, Egypt.
[10] Also at British University in Egypt, Cairo, Egypt.
[11] Now at Ain Shams University, Cairo, Egypt.
[12] Also at Université de Haute Alsace, Mulhouse, France.
[13] Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
[14] Also at Tbilisi State University, Tbilisi, Georgia.
[15] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[16] Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[17] Also at University of Hamburg, Hamburg, Germany.
[18] Also at Brandenburg University of Technology, Cottbus, Germany.
[19] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[20] Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
[21] Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
[22] Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India.
[23] Also at Institute of Physics, Bhubaneswar, India.
[24] Also at University of Visva-Bharati, Santiniketan, India.
[25] Also at University of Ruhuna, Matara, Sri Lanka.
[26] Also at Isfahan University of Technology, Isfahan, Iran.
[27] Also at Yazd University, Yazd, Iran.
[28] Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
[29] Also at Università degli Studi di Siena, Siena, Italy.
[30] Also at Purdue University, West Lafayette, USA.
[31] Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
[32] Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
[33] Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.
[34] Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
[35] Also at Institute for Nuclear Research, Moscow, Russia.

[36] Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.

[37] Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.

[38] Also at University of Florida, Gainesville, USA.

[39] Also at P.N. Lebedev Physical Institute, Moscow, Russia.

[40] Also at California Institute of Technology, Pasadena, USA.

[41] Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.

[42] Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.

[43] Also at INFN Sezione di Roma; Sapienza Università di Roma, Rome, Italy.

[44] Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.

[45] Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.

[46] Also at National and Kapodistrian University of Athens, Athens, Greece.

[47] Also at Riga Technical University, Riga, Latvia.

[48] Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.

[49] Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.

[50] Also at Gaziosmanpasa University, Tokat, Turkey.

[51] Also at Istanbul Aydin University, Istanbul, Turkey.

[52] Also at Mersin University, Mersin, Turkey.

[53] Also at Cag University, Mersin, Turkey.

[54] Also at Piri Reis University, Istanbul, Turkey.

[55] Also at Adiyaman University, Adiyaman, Turkey.

[56] Also at Izmir Institute of Technology, Izmir, Turkey.

[57] Also at Necmettin Erbakan University, Konya, Turkey.

[58] Also at Marmara University, Istanbul, Turkey.

[59] Also at Kafkas University, Kars, Turkey.

[60] Also at Istanbul Bilgi University, Istanbul, Turkey.

[61] Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.

[62] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.

[63] Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.

[64] Also at Utah Valley University, Orem, USA.

[65] Also at BEYKENT UNIVERSITY, Istanbul, Turkey.

[66] Also at Bingol University, Bingol, Turkey.

[67] Also at Erzincan University, Erzincan, Turkey.

[68] Also at Sinop University, Sinop, Turkey.

[69] Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.

[70] Also at Texas A&M University at Qatar, Doha, Qatar.

[71] Also at Kyungpook National University, Daegu, Korea.