



Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb



# Measurements of $t\bar{t}$ 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

## ARTICLE INFO

## Article history:

Received 29 May 2017

Received in revised form 9 November 2017

Accepted 21 November 2017

Available online xxxx

Editor: M. Doser

## Keywords:

CMS

Physics

Top quark

## 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  $2.3 \text{ fb}^{-1}$  collected in pp collisions at  $\sqrt{s} = 13$  TeV with the CMS detector at the LHC. Events with two leptons (e or  $\mu$ ) 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  $0.022 \pm 0.003$  (stat)  $\pm 0.006$  (syst), the cross section  $\sigma_{t\bar{t}b\bar{b}}$  is  $4.0 \pm 0.6$  (stat)  $\pm 1.3$  (syst) pb and  $\sigma_{t\bar{t}jj}$  is  $184 \pm 6$  (stat)  $\pm 33$  (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 Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>). Funded by SCOAP<sup>3</sup>.

## 1. Introduction

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  $H \rightarrow \gamma\gamma$  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 ( $g \rightarrow b\bar{b}$ ).

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 ( $\mu_F$ ) and renormalization ( $\mu_R$ ) 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  $pp \rightarrow t\bar{t}jj$  ( $\sigma_{t\bar{t}jj}$ ) and  $pp \rightarrow t\bar{t}b\bar{b}$  ( $\sigma_{t\bar{t}b\bar{b}}$ ) 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  $2.3 \text{ fb}^{-1}$  [17]. Events are selected with the final state consisting of two leptons (e or  $\mu$ ) 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 ( $\eta$ ) coverage provided by the barrel and

\* E-mail address: [cms-publication-committee-chair@cern.ch](mailto:cms-publication-committee-chair@cern.ch).

<https://doi.org/10.1016/j.physletb.2017.11.043>

0370-2693/© 2017 Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>). Funded by SCOAP<sup>3</sup>.

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 (v5.15.11) 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  $Z/\gamma^*$ +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 ( $pp \rightarrow tW$  and  $pp \rightarrow \bar{t}W$ ) 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  $\tau$  leptons produced in  $W \rightarrow \tau\nu$  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 ( $t\bar{t}jj \rightarrow bW^+bW^-jj \rightarrow b\ell^+\nu b\ell^-\bar{\nu}jj$ ). 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  $t\bar{t}bb$  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  $\mu$ ) 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  $p_T^{\text{miss}}$ . 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  $p_T^{\text{miss}}$  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  $\eta$ -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  $t\bar{t}b\bar{b}$  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  $t\bar{t}b\bar{b}$  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
$t\bar{t}b\bar{b}$	$6.3 \pm 0.4$	$8.6 \pm 0.4$	$24 \pm 1$	$39 \pm 1$
$t\bar{t}b\bar{j}$	$16 \pm 1$	$21 \pm 1$	$57 \pm 2$	$95 \pm 2$
$t\bar{t}c\bar{c}$	$7.7 \pm 0.4$	$11 \pm 1$	$27 \pm 1$	$46 \pm 1$
$t\bar{t}l\bar{F}$	$157 \pm 2$	$220 \pm 2$	$596 \pm 3$	$972 \pm 4$
$t\bar{t}$ others	$18 \pm 1$	$19 \pm 1$	$61 \pm 1$	$99 \pm 1$
$t\bar{t}V$	$2.5 \pm 0.1$	$3.2 \pm 0.2$	$7.3 \pm 0.2$	$14 \pm 1$
Single t	$6.6 \pm 0.8$	$8.4 \pm 0.8$	$23 \pm 2$	$39 \pm 2$
Z+jets	$0.8^{+1.0}_{-0.8}$	$5.4 \pm 1.5$	$0.6 \pm 0.5$	$6.8 \pm 1.9$
Total	$215 \pm 2$	$297 \pm 3$	$796 \pm 4$	$1311 \pm 6$
Data	186	288	682	1156

## 5. Cross section measurements

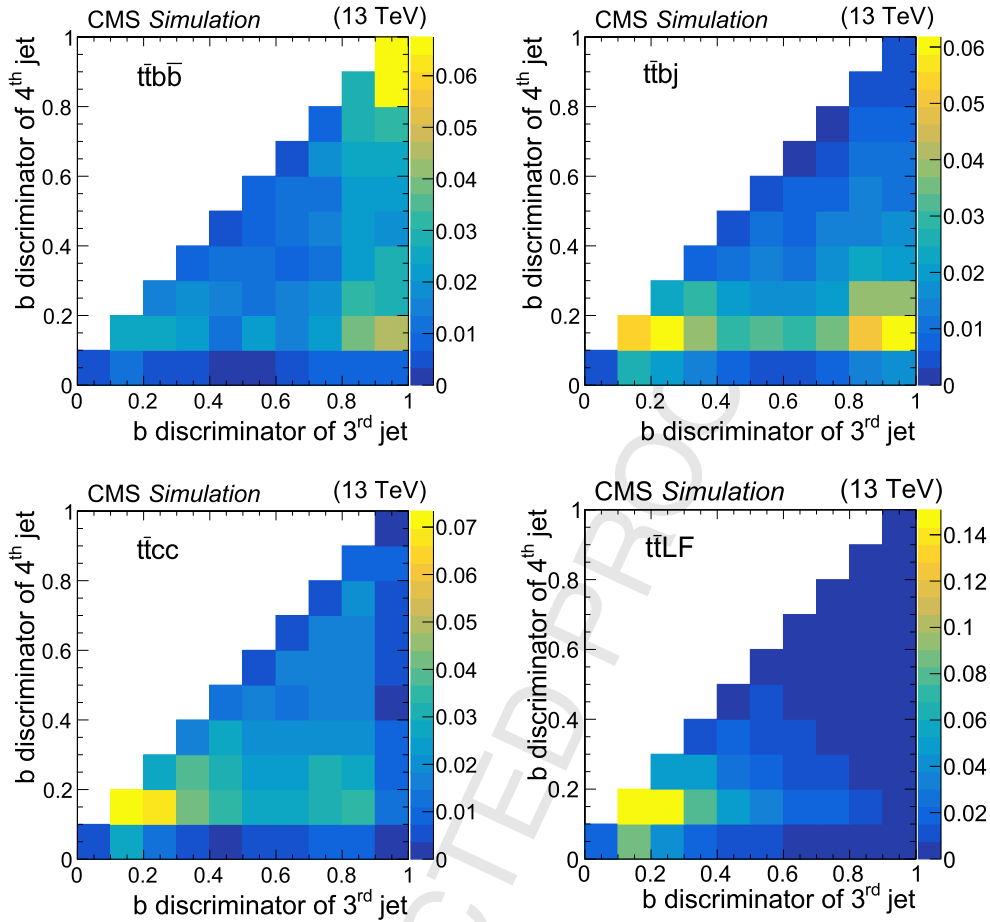
The first and the second jets in decreasing order of the b tagging discriminator usually (in 85% of  $t\bar{t}j\bar{j}$  events) correspond to the b jets from the decays of top quarks, and hence these jets provide no discriminating power between  $t\bar{t}b\bar{b}$  and  $t\bar{t}j\bar{j}$  events. The third and the fourth jets from  $t\bar{t}j\bar{j}$  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  $t\bar{t}j\bar{j}$  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  $t\bar{t}j\bar{j}$  events and the ratio of the numbers of  $t\bar{t}b\bar{b}$  events to  $t\bar{t}j\bar{j}$  events are free parameters in the fit. The  $t\bar{t}c\bar{c}$  and  $t\bar{t}l\bar{F}$  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

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

where  $\mathcal{F}_{t\bar{t}b\bar{b}}^{\text{norm}}$ ,  $\mathcal{F}_{t\bar{t}b\bar{j}}^{\text{norm}}$ , and  $\mathcal{F}_{t\bar{t}l\bar{F}+t\bar{t}c\bar{c}}^{\text{norm}}$  are the normalized expectations for each bin of  $t\bar{t}b\bar{b}$ ,  $t\bar{t}b\bar{j}$ , and the combination of  $t\bar{t}l\bar{F}$  and  $t\bar{t}c\bar{c}$ , respectively. The parameter  $N_{t\bar{t}j\bar{j}}$  denotes the number of the  $t\bar{t}j\bar{j}$  events from the fit. The quantity  $f_{t\bar{t}\text{ others}}$  reflects the fraction of other  $t\bar{t}$  processes in the  $t\bar{t}j\bar{j}$  sample as calculated in simulation ( $t\bar{t}$  others divided by the sum of the  $t\bar{t}j\bar{j}$  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  $N_{\text{bkg}}$ . The parameter  $R$  is the ratio of the number of  $t\bar{t}b\bar{b}$  events with respect to the number of  $t\bar{t}j\bar{j}$  events, and  $R'$  is the fraction of  $t\bar{t}b\bar{j}$  events at the reconstruction level and constrained to the ratio of the number of the  $t\bar{t}b\bar{j}$  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  $N_{t\bar{t}j\bar{j}}$  of  $950 \pm 30$



**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  $t\bar{t}b\bar{b}$  (upper left),  $t\bar{t}b\bar{j}$  (upper right),  $t\bar{t}c\bar{c}$  (lower left), and  $t\bar{t}LF$  (lower right) processes.

events and  $R$  of  $0.056 \pm 0.008$  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  $t\bar{t}b\bar{b}$  and  $t\bar{t}j\bar{j}$  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  $t\bar{t}b\bar{b}$  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  $t\bar{t}j\bar{j}$  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.

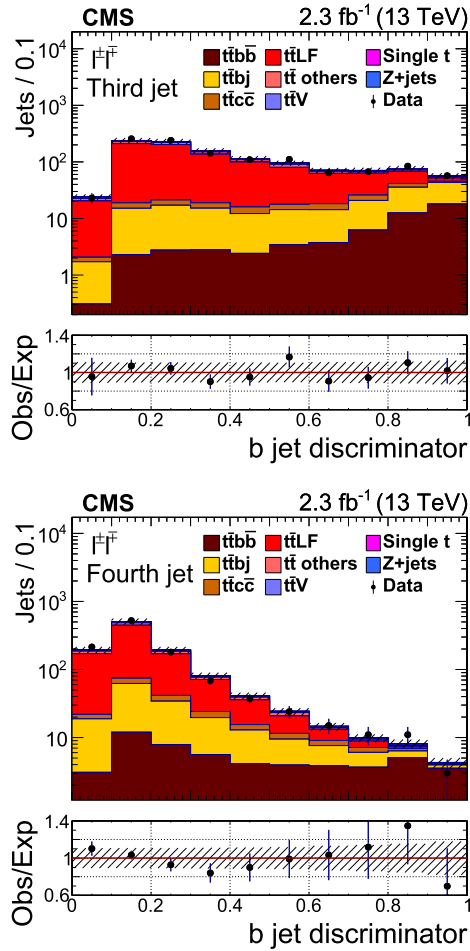
The  $t\bar{t}b\bar{b}$  and  $t\bar{t}j\bar{j}$  cross sections in the visible phase space are calculated using the relationship  $\sigma_{\text{visible}} = N/(\epsilon\mathcal{L})$ , where  $\mathcal{L}$  is the integrated luminosity,  $N$  is the number of events from the fit result, and  $\epsilon$  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  $t\bar{t}b\bar{b}$  and  $t\bar{t}j\bar{j}$ , respectively, including the leptonic branching fraction of both W bosons [46].

## 6. Estimation of systematic uncertainties

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

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  $\eta$  of about 10% [42].

The ratio of  $t\bar{t}b\bar{b}$  events with respect to  $t\bar{t}b j$  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  $\mu_F$  and  $\mu_R$  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-

**Table 2**

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

Source	$\sigma_{t\bar{t}b\bar{b}}$	$\sigma_{t\bar{t}j}$	$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}j}$
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 $t\bar{t}b j$	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
$\mu_F$ and $\mu_R$ 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

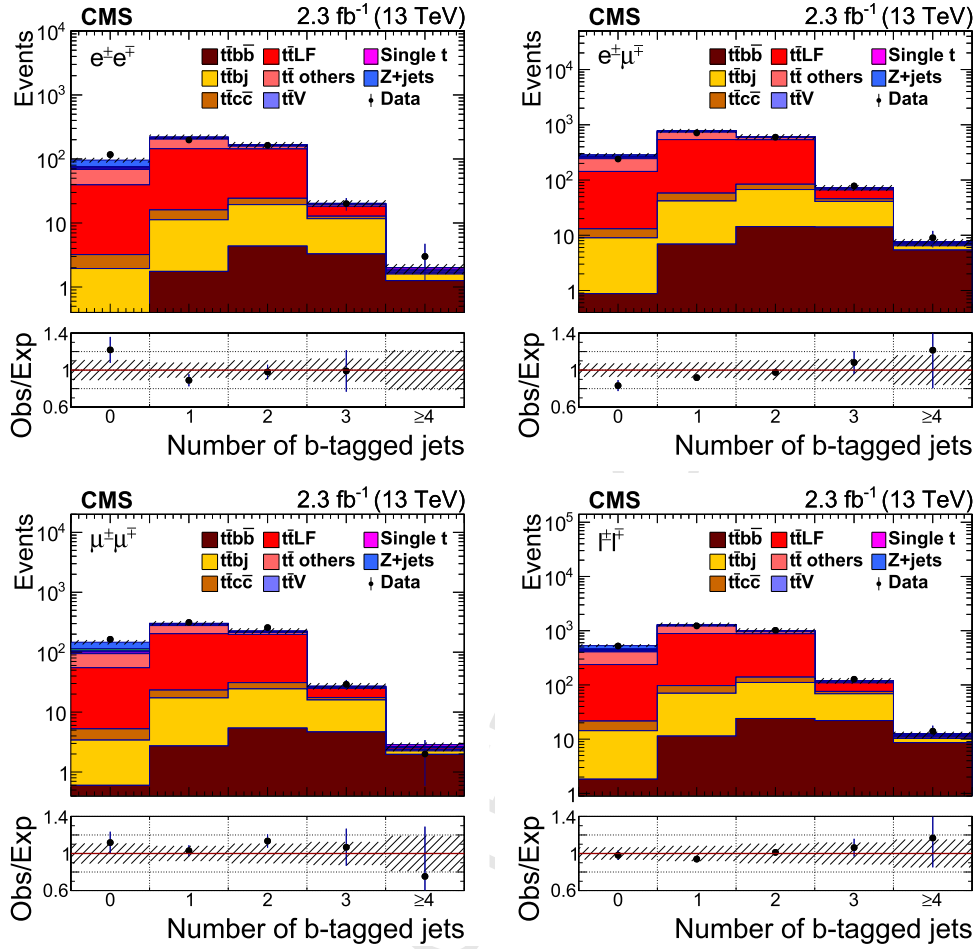
nificantly. The uncertainty caused by mismodelling of these backgrounds is assessed by varying the contribution to cover the uncertainty in the single top quark production cross section (indicated as “Background modelling” in Table 2). An uncertainty to account for the modelling of the  $t\bar{t}c\bar{c}$  fraction by simulations is also assigned by varying the contribution by 50% in the fit. This is derived from the theoretical uncertainty on the  $t\bar{t}j j$  cross section. For the efficiency of  $t\bar{t}j j$  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  $\eta$  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  $\mu_F$  and  $\mu_R$  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  $\mu_F$  and  $\mu_R$  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-



**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  $\sigma_{t\bar{t}ij}$  is significantly smaller than that in  $\sigma_{t\bar{t}bb}$  since the measurement of the latter requires the identification of multiple b jets. The uncertainty in  $\sigma_{t\bar{t}bb}$  is larger than that for the cross section ratio, since the uncertainties that are common between  $t\bar{t}bb$  and  $t\bar{t}ij$ , 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 MADGRAPH5\_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  $\sigma_{t\bar{t}bb}/\sigma_{t\bar{t}ij}$  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

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

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

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

The predicted values from POWHEG are  $0.014 \pm 0.001$  and  $0.012 \pm 0.001$  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)	$0.070 \pm 0.009$	$5.1 \pm 0.5$	$0.014 \pm 0.001$
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)	$3.2 \pm 0.4$	$257 \pm 26$	$0.012 \pm 0.001$

uncertainty in the simulation is the sum in quadrature of the statistical, and the  $\mu_F/\mu_R$  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  $2.3 \text{ fb}^{-1}$ . 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  $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj} = 0.024 \pm 0.003$  (stat)  $\pm 0.007$  (syst) and  $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj} = 0.022 \pm 0.003$  (stat)  $\pm 0.006$  (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  $0.014 \pm 0.001$  for the visible and  $0.012 \pm 0.001$  for the full phase space, which are lower than the measured values but consistent within two standard deviations. The individual cross sections  $\sigma_{t\bar{t}b\bar{b}} = 4.0 \pm 0.6$  (stat)  $\pm 1.3$  (syst) pb and  $\sigma_{t\bar{t}jj} = 184 \pm 6$  (stat)  $\pm 33$  (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.

## Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MOST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy);

MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR and RAEP (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI and FEDER (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEP-Center, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract No. 675440 (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa Clarín-COFUND del Principado de Asturias; the Thalís and Arístea programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); and the Welch Foundation, contract C-1845.

## 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](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](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  $\tau$  leptons, J. High Energy Phys. 05 (2014) 104, [https://doi.org/10.1007/JHEP05\(2014\)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](https://doi.org/10.1007/JHEP08(2016)045).
- [11] M. Worek, G. Bevilacqua, On the ratio of  $t\bar{t}b\bar{b}$  and  $t\bar{t}j$  cross sections at the CERN Large Hadron Collider, *J. High Energy Phys.* 07 (2014) 135, [https://doi.org/10.1007/JHEP07\(2014\)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  $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}j}$  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](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](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](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](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](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- $k_r$  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  $E_T^{\text{miss}}$ , 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](https://doi.org/10.1007/JHEP09(2014)087), arXiv:1408.1682, Erratum: [https://doi.org/10.1007/JHEP10\(2014\)106](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](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



1 W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, 66  
 2 R. Frühwirth<sup>1</sup>, V.M. Ghete, N. Hörmann, J. Hrubec, M. Jeitler<sup>1</sup>, A. König, I. Krätschmer, D. Liko, 67  
 3 T. Matsushita, I. Mikulec, D. Rabady, N. Rad, H. Rohringer, J. Schieck<sup>1</sup>, J. Strauss, W. Waltenberger, 68  
 4 C.-E. Wulz<sup>1</sup> 69  
 5

6 *Institut für Hochenergiephysik, Wien, Austria* 71  
 7

8 V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez 73  
 9

10 *Institute for Nuclear Problems, Minsk, Belarus* 74  
 11

12 N. Shumeiko 77  
 13

14 *National Centre for Particle and High Energy Physics, Minsk, Belarus* 78  
 15

16 S. Alderweireldt, E.A. De Wolf, X. Janssen, J. Lauwers, M. Van De Klundert, H. Van Haevermaet, 81  
 17 P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck 82  
 18

19 *Universiteit Antwerpen, Antwerpen, Belgium* 84  
 20

21 S. Abu Zeid, F. Blekman, J. D'Hondt, I. De Bruyn, J. De Clercq, K. Deroover, S. Lowette, S. Moortgat, 86  
 22 L. Moreels, A. Olbrechts, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, 87  
 23 I. Van Parijs 88  
 24

25 *Vrije Universiteit Brussel, Brussel, Belgium* 90  
 26

27 H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, 92  
 28 G. Karapostoli, T. Lenzi, J. Luetic, T. Maerschalk, A. Marinov, A. Randle-conde, T. Seva, C. Vander Velde, 93  
 29 P. Vanlaer, D. Vannerom, R. Yonamine, F. Zenoni, F. Zhang<sup>2</sup> 94  
 30

31 *Université Libre de Bruxelles, Bruxelles, Belgium* 96  
 32

33 A. Cimmino, T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov, D. Poyraz, S. Salva, R. Schöffbeck, 98  
 34 M. Tytgat, W. Van Driessche, W. Verbeke, N. Zaganidis 99  
 35

36 *Ghent University, Ghent, Belgium* 101  
 37

38 H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, A. Caudron, S. De Visscher, C. Delaere, M. Delcourt, 103  
 39 B. Francois, A. Giammanco, A. Jafari, M. Komm, G. Krintiras, V. Lemaître, A. Magitteri, A. Mertens, 104  
 40 M. Musich, K. Piotrkowski, L. Quertenmont, M. Vidal Marono, S. Wertz 105  
 41

42 *Université Catholique de Louvain, Louvain-la-Neuve, Belgium* 106  
 43

44 N. Belyi 109  
 45

46 *Université de Mons, Mons, Belgium* 110  
 47

48 W.L. Aldá Júnior, F.L. Alves, G.A. Alves, L. Brito, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles 113  
 49

50 *Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil* 114  
 51

52 E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato<sup>3</sup>, A. Custódio, E.M. Da Costa, G.G. Da Silveira<sup>4</sup>, 117  
 53 D. De Jesus Damiao, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, C. Mora Herrera, 118  
 54 L. Mundim, H. Nogima, A. Santoro, A. Sznajder, E.J. Tonelli Manganote<sup>3</sup>, F. Torres Da Silva De Araujo, 119  
 55 A. Vilela Pereira 120  
 56

57 *Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil* 121  
 58

59 S. Ahuja<sup>a</sup>, C.A. Bernardes<sup>a</sup>, T.R. Fernandez Perez Tomei<sup>a</sup>, E.M. Gregores<sup>b</sup>, P.G. Mercadante<sup>b</sup>, C.S. Moon<sup>a</sup>, 125  
 60 S.F. Novaes<sup>a</sup>, Sandra S. Padula<sup>a</sup>, D. Romero Abad<sup>b</sup>, J.C. Ruiz Vargas<sup>a</sup> 126  
 61

62 <sup>a</sup> *Universidade Estadual Paulista, São Paulo, Brazil* 127  
 63

64 <sup>b</sup> *Universidade Federal do ABC, São Paulo, Brazil* 128  
 65

1 A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova 66

2 *Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria* 67

3 4 A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov 68

5 6 *University of Sofia, Sofia, Bulgaria* 69

7 8 W. Fang<sup>5</sup>, X. Gao<sup>5</sup> 70

9 10 *Beihang University, Beijing, China* 71

11 12 M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, Z. Liu, F. Romeo, 72

13 S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, E. Yazgan, H. Zhang, J. Zhao 73

14 15 *Institute of High Energy Physics, Beijing, China* 74

16 17 Y. Ban, G. Chen, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu 75

18 19 *State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China* 76

20 21 C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, J.D. Ruiz Alvarez 77

22 23 *Universidad de Los Andes, Bogota, Colombia* 78

24 25 N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano, T. Sculac 79

26 27 *University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia* 80

28 29 Z. Antunovic, M. Kovac 81

30 31 *University of Split, Faculty of Science, Split, Croatia* 82

32 33 V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, T. Susa 83

34 35 *Institute Rudjer Boskovic, Zagreb, Croatia* 84

36 37 M.W. Ather, A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski 85

38 39 *University of Cyprus, Nicosia, Cyprus* 86

40 41 M. Finger<sup>6</sup>, M. Finger Jr.<sup>6</sup> 87

42 43 *Charles University, Prague, Czech Republic* 88

44 45 E. Carrera Jarrin 89

46 47 *Universidad San Francisco de Quito, Quito, Ecuador* 90

48 49 A.A. Abdelalim<sup>7,8</sup>, Y. Mohammed<sup>9</sup>, E. Salama<sup>10,11</sup> 91

50 51 *Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt* 92

52 53 R.K. Dewanjee, M. Kadastik, L. Perrini, M. Raidal, A. Tiko, C. Veelken 93

54 55 *National Institute of Chemical Physics and Biophysics, Tallinn, Estonia* 94

56 57 P. Eerola, J. Pekkanen, M. Voutilainen 95

58 59 *Department of Physics, University of Helsinki, Helsinki, Finland* 96

60 61 J. Härkönen, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, 97

62 P. Luukka, E. Tuominen, J. Tuominiemi, E. Tuovinen 98

63 64 *Helsinki Institute of Physics, Helsinki, Finland* 99

65 100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120 121 122 123 124 125 126 127 128 129 130

1 J. Talvitie, T. Tuuva

2 *Lappeenranta University of Technology, Lappeenranta, Finland*

3  
4 M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, S. Ghosh, A. Givernaud,  
5 P. Gras, G. Hamel de Monchenault, P. Jarry, I. Kucher, E. Locci, M. Mached, J. Malcles, J. Rander,  
6 A. Rosowsky, M.Ö. Sahin, M. Titov

7  
8  
9 *IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*

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

14  
15  
16 *Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France*

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

19  
20  
21 *Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France*

22 S. Gadrat

23  
24  
25 *Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France*

26 S. Beauceron, C. Bernet, G. Boudoul, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni,  
27 J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier,  
28 L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov<sup>13</sup>, V. Sordini, M. Vander Donckt, S. Viret

29  
30  
31 *Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France*

32 T. Toriashvili<sup>14</sup>

33  
34  
35 *Georgian Technical University, Tbilisi, Georgia*

36 D. Lomidze

37  
38  
39 *Tbilisi State University, Tbilisi, Georgia*

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

42  
43  
44 *RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*

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

49  
50  
51 *RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*

52 G. Flügge, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, T. Müller, A. Nehr Korn, A. Nowack, C. Pistone,  
53 O. Pooth, A. Stahl<sup>15</sup>

54  
55  
56 *RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*

57 M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A.A. Bin Anuar,  
58 K. Borras<sup>16</sup>, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos,  
59 G. Eckerlin, D. Eckstein, T. Eichhorn, E. Eren, E. Gallo<sup>17</sup>, J. Garay Garcia, A. Geiser, A. Gizhko,  
60 J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, A. Harb, J. Hauk, M. Hempel<sup>18</sup>, H. Jung,  
61 A. Kalogeropoulos, M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek,  
62  
63  
64

1 T. Lenz, J. Leonard, K. Lipka, W. Lohmann<sup>18</sup>, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, 66  
 2 J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M. Savitskyi, P. Saxena, 67  
 3 R. Shevchenko, S. Spannagel, N. Stefaniuk, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing 68  
 4 69

5 *Deutsches Elektronen-Synchrotron, Hamburg, Germany* 70  
 6 71

7 S. Bein, V. Blobel, M. Centis Vignali, A.R. Draeger, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, 72  
 8 M. Hoffmann, A. Junkes, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, T. Lapsien, I. Marchesini, 73  
 9 D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo<sup>15</sup>, T. Peiffer, A. Perieanu, C. Scharf, 74  
 10 P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, 75  
 11 M. Stöver, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald 76  
 12 77  
 13 78

14 *University of Hamburg, Hamburg, Germany* 79  
 15 80

16 M. Akbiyik, C. Barth, S. Baur, C. Baus, J. Berger, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, 81  
 17 A. Dierlamm, B. Freund, R. Friese, M. Giffels, A. Gilbert, D. Haitz, F. Hartmann<sup>15</sup>, S.M. Heindl, 82  
 18 U. Husemann, F. Kassel<sup>15</sup>, S. Kudella, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, 83  
 19 K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, 84  
 20 S. Williamson, C. Wöhrmann, R. Wolf 85  
 21 86  
 22 87

23 *Institut für Experimentelle Kernphysik, Karlsruhe, Germany* 88  
 24 89

25 G. Anagnostou, G. Daskalakis, T. Gerasis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, I. Topsis-Giotis 90  
 26 91  
 27 92

28 *Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece* 93  
 29 94

30 S. Kesisoglou, A. Panagiotou, N. Saoulidou 95  
 31 96

32 *National and Kapodistrian University of Athens, Athens, Greece* 97  
 33 98

34 I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, 99  
 35 F.A. Triantis 100  
 36 101

37 *University of Ioánnina, Ioánnina, Greece* 102  
 38 103

39 M. Csanad, N. Filipovic, G. Pasztor 104  
 40 105

41 *MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary* 106  
 42 107

43 G. Bencze, C. Hajdu, D. Horvath<sup>19</sup>, F. Sikler, V. Veszpremi, G. Vesztergombi<sup>20</sup>, A.J. Zsigmond 108  
 44 109

45 *Wigner Research Centre for Physics, Budapest, Hungary* 110  
 46 111

47 N. Beni, S. Czellar, J. Karancsi<sup>21</sup>, A. Makovec, J. Molnar, Z. Szillasi 112  
 48 113

49 *Institute of Nuclear Research ATOMKI, Debrecen, Hungary* 114  
 50 115

51 M. Bartók<sup>20</sup>, P. Raics, Z.L. Trocsanyi, B. Ujvari 116  
 52 117

53 *Institute of Physics, University of Debrecen, Debrecen, Hungary* 118  
 54 119

55 S. Choudhury, J.R. Komaragiri 120  
 56 121

57 *Indian Institute of Science (IISc), Bangalore, India* 122  
 58 123

59 S. Bahinipati<sup>22</sup>, S. Bhowmik, P. Mal, K. Mandal, A. Nayak<sup>23</sup>, D.K. Sahoo<sup>22</sup>, N. Sahoo, S.K. Swain 124  
 60 125

61 *National Institute of Science Education and Research, Bhubaneswar, India* 126  
 62 127

63 S. Bansal, S.B. Beri, V. Bhatnagar, U. Bhawandeep, R. Chawla, N. Dhingra, A.K. Kalsi, A. Kaur, M. Kaur, 128  
 64 R. Kumar, P. Kumari, A. Mehta, M. Mittal, J.B. Singh, G. Walia 129  
 65 130

*Panjab University, Chandigarh, India*

1 Ashok Kumar, Aashaq Shah, A. Bhardwaj, S. Chauhan, B.C. Choudhary, R.B. Garg, S. Keshri, S. Malhotra, 66  
 2 M. Naimuddin, K. Ranjan, R. Sharma, V. Sharma 67

3 University of Delhi, Delhi, India 68  
 4 69

5 R. Bhattacharya, S. Bhattacharya, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, 70  
 6 S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, 71  
 7 S. Thakur 72  
 8 73  
 9 74

10 Saha Institute of Nuclear Physics, HBNI, Kolkata, India 75  
 11 76

12 P.K. Behera 77  
 13 78

14 Indian Institute of Technology Madras, Madras, India 79  
 15 80

16 R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty<sup>15</sup>, P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar 81  
 17 82

18 Bhabha Atomic Research Centre, Mumbai, India 83  
 19 84

20 T. Aziz, S. Dugad, B. Mahakud, S. Mitra, G.B. Mohanty, B. Parida, N. Sur, B. Sutar 85  
 21 86

22 Tata Institute of Fundamental Research-A, Mumbai, India 87  
 23 88

24 S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Kumar, M. Maity<sup>24</sup>, 89  
 25 G. Majumder, K. Mazumdar, T. Sarkar<sup>24</sup>, N. Wickramage<sup>25</sup> 90  
 26 91

27 Tata Institute of Fundamental Research-B, Mumbai, India 92  
 28 93

29 S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kotheekar, S. Pandey, A. Rane, S. Sharma 94  
 30 95

31 Indian Institute of Science Education and Research (IISER), Pune, India 96  
 32 97

33 S. Chenarani<sup>26</sup>, E. Eskandari Tadavani, S.M. Etesami<sup>26</sup>, M. Khakzad, M. Mohammadi Najafabadi, 98  
 34 M. Naseri, S. Paktinat Mehdiabadi<sup>27</sup>, F. Rezaei Hosseinabadi, B. Safarzadeh<sup>28</sup>, M. Zeinali 99  
 35 100

36 Institute for Research in Fundamental Sciences (IPM), Tehran, Iran 101  
 37 102

38 M. Felcini, M. Grunewald 103  
 39 104

40 University College Dublin, Dublin, Ireland 105  
 41 106

42 M. Abbrescia<sup>a,b</sup>, C. Calabria<sup>a,b</sup>, C. Caputo<sup>a,b</sup>, A. Colaleo<sup>a</sup>, D. Creanza<sup>a,c</sup>, L. Cristella<sup>a,b</sup>, N. De Filippis<sup>a,c</sup>, 107  
 43 M. De Palma<sup>a,b</sup>, L. Fiore<sup>a</sup>, G. Iaselli<sup>a,c</sup>, G. Maggi<sup>a,c</sup>, M. Maggi<sup>a</sup>, G. Miniello<sup>a,b</sup>, S. My<sup>a,b</sup>, S. Nuzzo<sup>a,b</sup>, 108  
 44 A. Pompili<sup>a,b</sup>, G. Pugliese<sup>a,c</sup>, R. Radogna<sup>a,b</sup>, A. Ranieri<sup>a</sup>, G. Selvaggi<sup>a,b</sup>, A. Sharma<sup>a</sup>, L. Silvestris<sup>a,15</sup>, 109  
 45 R. Venditti<sup>a</sup>, P. Verwilligen<sup>a</sup> 110  
 46 111

47 <sup>a</sup> INFN Sezione di Bari, Bari, Italy 112

48 <sup>b</sup> Università di Bari, Bari, Italy 113

49 <sup>c</sup> Politecnico di Bari, Bari, Italy 114

50 G. Abbiendi<sup>a</sup>, C. Battilana, D. Bonacorsi<sup>a,b</sup>, S. Braibant-Giacomelli<sup>a,b</sup>, L. Brigliadori<sup>a,b</sup>, R. Campanini<sup>a,b</sup>, 115  
 51 P. Capiluppi<sup>a,b</sup>, A. Castro<sup>a,b</sup>, F.R. Cavallo<sup>a</sup>, S.S. Chhibra<sup>a,b</sup>, M. Cuffiani<sup>a,b</sup>, G.M. Dallavalle<sup>a</sup>, F. Fabbri<sup>a</sup>, 116  
 52 A. Fanfani<sup>a,b</sup>, D. Fasanella<sup>a,b</sup>, P. Giacomelli<sup>a</sup>, L. Guiducci<sup>a,b</sup>, S. Marcellini<sup>a</sup>, G. Masetti<sup>a</sup>, F.L. Navarria<sup>a,b</sup>, 117  
 53 A. Perrotta<sup>a</sup>, A.M. Rossi<sup>a,b</sup>, T. Rovelli<sup>a,b</sup>, G.P. Siroli<sup>a,b</sup>, N. Tosi<sup>a,b,15</sup> 118  
 54 119  
 55 120

56 <sup>a</sup> INFN Sezione di Bologna, Bologna, Italy 121

57 <sup>b</sup> Università di Bologna, Bologna, Italy 122  
 58 123

59 S. Albergo<sup>a,b</sup>, S. Costa<sup>a,b</sup>, A. Di Mattia<sup>a</sup>, F. Giordano<sup>a,b</sup>, R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b</sup>, C. Tuve<sup>a,b</sup> 124  
 60 125

61 <sup>a</sup> INFN Sezione di Catania, Catania, Italy 126

62 <sup>b</sup> Università di Catania, Catania, Italy 127  
 63 128  
 64 129  
 65 130

1 G. Barbagli <sup>a</sup>, K. Chatterjee <sup>a,b</sup>, V. Ciulli <sup>a,b</sup>, C. Civinini <sup>a</sup>, R. D'Alessandro <sup>a,b</sup>, E. Focardi <sup>a,b</sup>, P. Lenzi <sup>a,b</sup>, 66  
 2 M. Meschini <sup>a</sup>, S. Paoletti <sup>a</sup>, L. Russo <sup>a,29</sup>, G. Sguazzoni <sup>a</sup>, D. Strom <sup>a</sup>, L. Viliani <sup>a,b,15</sup> 67  
 3

4 <sup>a</sup> INFN Sezione di Firenze, Firenze, Italy 69

5 <sup>b</sup> Università di Firenze, Firenze, Italy 70

6 L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera <sup>15</sup> 71  
 7

8 INFN Laboratori Nazionali di Frascati, Frascati, Italy 72  
 9

10 V. Calvelli <sup>a,b</sup>, F. Ferro <sup>a</sup>, E. Robutti <sup>a</sup>, S. Tosi <sup>a,b</sup> 73  
 11

12 <sup>a</sup> INFN Sezione di Genova, Genova, Italy 74  
 13

14 <sup>b</sup> Università di Genova, Genova, Italy 75  
 15

16 L. Brianza <sup>a,b,15</sup>, F. Brivio <sup>a,b</sup>, V. Ciriolo, M.E. Dinardo <sup>a,b</sup>, S. Fiorendi <sup>a,b,15</sup>, S. Gennai <sup>a</sup>, A. Ghezzi <sup>a,b</sup>, 76  
 17 P. Govoni <sup>a,b</sup>, M. Malberti <sup>a,b</sup>, S. Malvezzi <sup>a</sup>, R.A. Manzoni <sup>a,b</sup>, D. Menasce <sup>a</sup>, L. Moroni <sup>a</sup>, M. Paganoni <sup>a,b</sup>, 77  
 18 K. Pauwels, D. Pedrini <sup>a</sup>, S. Pigazzini <sup>a,b</sup>, S. Ragazzi <sup>a,b</sup>, T. Tabarelli de Fatis <sup>a,b</sup> 78  
 19

20 <sup>a</sup> INFN Sezione di Milano-Bicocca, Milano, Italy 79  
 21

22 <sup>b</sup> Università di Milano-Bicocca, Milano, Italy 80  
 23

24 S. Buontempo <sup>a</sup>, N. Cavallo <sup>a,c</sup>, S. Di Guida <sup>a,d,15</sup>, M. Esposito <sup>a,b</sup>, F. Fabozzi <sup>a,c</sup>, F. Fienga <sup>a,b</sup>, A.O.M. Iorio <sup>a,b</sup>, 81  
 25 W.A. Khan <sup>a</sup>, G. Lanza <sup>a</sup>, L. Lista <sup>a</sup>, S. Meola <sup>a,d,15</sup>, P. Paolucci <sup>a,15</sup>, C. Sciacca <sup>a,b</sup>, F. Thyssen <sup>a</sup> 82  
 26

27 <sup>a</sup> INFN Sezione di Napoli, Napoli, Italy 83  
 28

29 <sup>b</sup> Università di Napoli 'Federico II', Napoli, Italy 84  
 30

31 <sup>c</sup> Università della Basilicata, Potenza, Italy 85  
 32

33 <sup>d</sup> Università G. Marconi, Roma, Italy 86  
 34

35 P. Azzi <sup>a,15</sup>, N. Bacchetta <sup>a</sup>, L. Benato <sup>a,b</sup>, A. Boletti <sup>a,b</sup>, R. Carlin <sup>a,b</sup>, A. Carvalho Antunes De Oliveira <sup>a,b</sup>, 87  
 36 P. Checchia <sup>a</sup>, M. Dall'Osso <sup>a,b</sup>, P. De Castro Manzano <sup>a</sup>, T. Dorigo <sup>a</sup>, U. Gasparini <sup>a,b</sup>, A. Gozzelino <sup>a</sup>, 88  
 37 S. Lacaprarà <sup>a</sup>, M. Margoni <sup>a,b</sup>, A.T. Meneguzzo <sup>a,b</sup>, M. Michelotto <sup>a</sup>, F. Montecassiano <sup>a</sup>, M. Passaseo <sup>a</sup>, 89  
 38 N. Pozzobon <sup>a,b</sup>, P. Ronchese <sup>a,b</sup>, R. Rossin <sup>a,b</sup>, F. Simonetto <sup>a,b</sup>, E. Torassa <sup>a</sup>, M. Zanetti <sup>a,b</sup>, P. Zotto <sup>a,b</sup>, 90  
 39 G. Zumerle <sup>a,b</sup> 91  
 40

41 <sup>a</sup> INFN Sezione di Padova, Padova, Italy 92  
 42

43 <sup>b</sup> Università di Padova, Padova, Italy 93  
 44

45 <sup>c</sup> Università di Trento, Trento, Italy 94  
 46

47 A. Braghieri <sup>a</sup>, F. Fallavollita <sup>a,b</sup>, A. Magnani <sup>a,b</sup>, P. Montagna <sup>a,b</sup>, S.P. Ratti <sup>a,b</sup>, V. Re <sup>a</sup>, M. Ressegotti, 95  
 48 C. Riccardi <sup>a,b</sup>, P. Salvini <sup>a</sup>, I. Vai <sup>a,b</sup>, P. Vitulo <sup>a,b</sup> 96  
 49

50 <sup>a</sup> INFN Sezione di Pavia, Pavia, Italy 97  
 51

52 <sup>b</sup> Università di Pavia, Pavia, Italy 98  
 53

54 L. Alunni Solestizi <sup>a,b</sup>, G.M. Bilei <sup>a</sup>, D. Ciangottini <sup>a,b</sup>, L. Fanò <sup>a,b</sup>, P. Lariccia <sup>a,b</sup>, R. Leonardi <sup>a,b</sup>, 99  
 55 G. Mantovani <sup>a,b</sup>, V. Mariani <sup>a,b</sup>, M. Menichelli <sup>a</sup>, A. Saha <sup>a</sup>, A. Santocchia <sup>a,b</sup>, D. Spiga 100  
 56

57 <sup>a</sup> INFN Sezione di Perugia, Perugia, Italy 101  
 58

59 <sup>b</sup> Università di Perugia, Perugia, Italy 102  
 60

61 K. Androsov <sup>a</sup>, P. Azzurri <sup>a,15</sup>, G. Bagliesi <sup>a</sup>, J. Bernardini <sup>a</sup>, T. Boccali <sup>a</sup>, L. Borrello, R. Castaldi <sup>a</sup>, 103  
 62 M.A. Ciocci <sup>a,b</sup>, R. Dell'Orso <sup>a</sup>, G. Fedi <sup>a</sup>, A. Giassi <sup>a</sup>, M.T. Grippo <sup>a,29</sup>, F. Ligabue <sup>a,c</sup>, T. Lomtadze <sup>a</sup>, 104  
 63 L. Martini <sup>a,b</sup>, A. Messineo <sup>a,b</sup>, F. Palla <sup>a</sup>, A. Rizzi <sup>a,b</sup>, A. Savoy-Navarro <sup>a,30</sup>, P. Spagnolo <sup>a</sup>, R. Tenchini <sup>a</sup>, 105  
 64 G. Tonelli <sup>a,b</sup>, A. Venturi <sup>a</sup>, P.G. Verdini <sup>a</sup> 106  
 65

66 <sup>a</sup> INFN Sezione di Pisa, Pisa, Italy 107  
 67

68 <sup>b</sup> Università di Pisa, Pisa, Italy 108  
 69

70 <sup>c</sup> Scuola Normale Superiore di Pisa, Pisa, Italy 109  
 71

72 L. Barone <sup>a,b</sup>, F. Cavallari <sup>a</sup>, M. Cipriani <sup>a,b</sup>, D. Del Re <sup>a,b,15</sup>, M. Diemoz <sup>a</sup>, S. Gelli <sup>a,b</sup>, E. Longo <sup>a,b</sup>, 110  
 73 F. Margaroli <sup>a,b</sup>, B. Marzocchi <sup>a,b</sup>, P. Meridiani <sup>a</sup>, G. Organtini <sup>a,b</sup>, R. Paramatti <sup>a,b</sup>, F. Preiato <sup>a,b</sup>, 111  
 74

1 S. Rahatlou <sup>a,b</sup>, C. Rovelli <sup>a</sup>, F. Santanastasio <sup>a,b</sup>

2  
3 <sup>a</sup> INFN Sezione di Roma, Rome, Italy

4 <sup>b</sup> Sapienza Università di Roma, Rome, Italy

5  
6 N. Amapane <sup>a,b</sup>, R. Arcidiacono <sup>a,c,15</sup>, S. Argiro <sup>a,b</sup>, M. Arneodo <sup>a,c</sup>, N. Bartosik <sup>a</sup>, R. Bellan <sup>a,b</sup>, C. Biino <sup>a</sup>,  
7 N. Cartiglia <sup>a</sup>, F. Cenna <sup>a,b</sup>, M. Costa <sup>a,b</sup>, R. Covarelli <sup>a,b</sup>, A. Degano <sup>a,b</sup>, N. Demaria <sup>a</sup>, B. Kiani <sup>a,b</sup>,  
8 C. Mariotti <sup>a</sup>, S. Maselli <sup>a</sup>, E. Migliore <sup>a,b</sup>, V. Monaco <sup>a,b</sup>, E. Monteil <sup>a,b</sup>, M. Monteno <sup>a</sup>, M.M. Obertino <sup>a,b</sup>,  
9 L. Pacher <sup>a,b</sup>, N. Pastrone <sup>a</sup>, M. Pelliccioni <sup>a</sup>, G.L. Pinna Angioni <sup>a,b</sup>, F. Ravera <sup>a,b</sup>, A. Romero <sup>a,b</sup>, M. Ruspa <sup>a,c</sup>,  
10 R. Sacchi <sup>a,b</sup>, K. Shchelina <sup>a,b</sup>, V. Sola <sup>a</sup>, A. Solano <sup>a,b</sup>, A. Staiano <sup>a</sup>, P. Traczyk <sup>a,b</sup>

11  
12 <sup>a</sup> INFN Sezione di Torino, Torino, Italy

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

14 <sup>c</sup> Università del Piemonte Orientale, Novara, Italy

15  
16 S. Belforte <sup>a</sup>, M. Casarsa <sup>a</sup>, F. Cossutti <sup>a</sup>, G. Della Ricca <sup>a,b</sup>, A. Zanetti <sup>a</sup>

17  
18 <sup>a</sup> INFN Sezione di Trieste, Trieste, Italy

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

20  
21 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

22 *Kyungpook National University, Daegu, Republic of Korea*

23  
24 A. Lee

25  
26 *Chonbuk National University, Jeonju, Republic of Korea*

27  
28 H. Kim, D.H. Moon

29  
30 *Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Republic of Korea*

31  
32 J.A. Brochero Cifuentes, J. Goh, T.J. Kim

33  
34 *Hanyang University, Seoul, Republic of Korea*

35  
36 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

37  
38 *Korea University, Seoul, Republic of Korea*

39  
40 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

41  
42 *Seoul National University, Seoul, Republic of Korea*

43  
44 M. Choi, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park, G. Ryu

45  
46 *University of Seoul, Seoul, Republic of Korea*

47  
48 Y. Choi, C. Hwang, J. Lee, I. Yu

49  
50 *Sungkyunkwan University, Suwon, Republic of Korea*

51  
52 V. Dudenas, A. Juodagalvis, J. Vaitkus

53  
54 *Vilnius University, Vilnius, Lithuania*

55 I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali <sup>31</sup>, F. Mohamad Idris <sup>32</sup>, W.A.T. Wan Abdullah, M.N. Yusli,  
56 Z. Zolkapli

57  
58 *National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia*

59  
60 H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz <sup>33</sup>, R. Lopez-Fernandez, J. Mejia Guisao,  
61 A. Sanchez-Hernandez

62  
63 *Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico*

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

2 *Universidad Iberoamericana, Mexico City, Mexico*

3  
4 I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

5  
6 *Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*

7  
8 A. Morelos Pineda

9  
10 *Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico*

11  
12 D. Krofcheck

13  
14 *University of Auckland, Auckland, New Zealand*

15  
16 P.H. Butler

17  
18 *University of Canterbury, Christchurch, New Zealand*

19  
20 A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas

21  
22 *National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*

23  
24 H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki,  
25 K. Romanowska-Rybinska, M. Szleper, P. Zalewski

26  
27 *National Centre for Nuclear Research, Swierk, Poland*

28  
29 K. Bunkowski, A. Byszuk<sup>34</sup>, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura,  
30 M. Olszewski, A. Pyskir, M. Walczak

31  
32 *Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*

33  
34 P. Bargassa, C. Beirão Da Cruz E Silva, B. Calpas, A. Di Francesco, P. Faccioli, M. Gallinaro, J. Hollar,  
35 N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Seixas, O. Toldaiev, D. Vadrucchio, J. Varela

36  
37 *Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal*

38  
39 S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev,  
40 A. Malakhov, V. Matveev<sup>35,36</sup>, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov,  
41 N. Voytishin, A. Zarubin

42  
43 *Joint Institute for Nuclear Research, Dubna, Russia*

44  
45 Y. Ivanov, V. Kim<sup>37</sup>, E. Kuznetsova<sup>38</sup>, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov,  
46 L. Uvarov, S. Vavilov, A. Vorobyev

47  
48 *Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia*

49  
50 Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov,  
51 A. Pashenkov, D. Tlisov, A. Toropin

52  
53 *Institute for Nuclear Research, Moscow, Russia*

54  
55 V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, M. Toms,  
56 E. Vlasov, A. Zhokin

57  
58 *Institute for Theoretical and Experimental Physics, Moscow, Russia*

59  
60 T. Aushev, A. Bylinkin<sup>36</sup>

61  
62 *Moscow Institute of Physics and Technology, Moscow, Russia*

63  
64  
65

66  
67  
68  
69  
70  
71  
72  
73  
74  
75  
76  
77  
78  
79  
80  
81  
82  
83  
84  
85  
86  
87  
88  
89  
90  
91  
92  
93  
94  
95  
96  
97  
98  
99  
100  
101  
102  
103  
104  
105  
106  
107  
108  
109  
110  
111  
112  
113  
114  
115  
116  
117  
118  
119  
120  
121  
122  
123  
124  
125  
126  
127  
128  
129  
130



1 M. Chadeeva<sup>39</sup>, S. Polikarpov, V. Rusinov

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

3 V. Andreev, M. Azarkin<sup>36</sup>, I. Dremin<sup>36</sup>, M. Kirakosyan, A. Terkulov

4 P.N. Lebedev Physical Institute, Moscow, Russia

5 A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin<sup>40</sup>, L. Dudko, V. Klyukhin, O. Kodolova,  
6 N. Korneeva, I. Lokhtin, I. Miagkov, S. Obraztsov, M. Perfilov, V. Savrin, P. Volkov

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

8 V. Blinov<sup>41</sup>, Y. Skovpen<sup>41</sup>, D. Shtol<sup>41</sup>

9 Novosibirsk State University (NSU), Novosibirsk, Russia

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

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

13 P. Adzic<sup>42</sup>, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic

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

15 J. Alcaraz Maestre, M. Barrio Luna, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris,  
16 A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia,  
17 O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo,  
18 A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares

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

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

21 Universidad Autónoma de Madrid, Madrid, Spain

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

24 Universidad de Oviedo, Oviedo, Spain

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

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

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

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

1 W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, 66  
 2 T. Rohe, S.A. Wiederkehr 67

3 Paul Scherrer Institut, Villigen, Switzerland 68  
 4 69

5 F. Bachmair, L. Bäni, P. Berger, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, C. Grab, 70  
 6 C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, T. Kljnsma, W. Lustermann, B. Mangano, M. Marionneau, 71  
 7 C. Martinez Ruiz del Arbol, M. Masciovecchio, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, 72  
 8 F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Rossini, 73  
 9 M. Schönenberger, A. Starodumov<sup>48</sup>, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, 74  
 10 D.H. Zhu 75  
 11 76  
 12 77

13 Institute for Particle Physics, ETH Zurich, Zurich, Switzerland 78  
 14 79

15 T.K. Aarrestad, C. Amsler<sup>49</sup>, L. Caminada, M.F. Canelli, A. De Cosa, S. Donato, C. Galloni, A. Hinzmann, 80  
 16 T. Hreus, B. Kilminster, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, C. Seitz, Y. Yang, 81  
 17 A. Zucchetta 82  
 18 83  
 19 84

20 Universität Zürich, Zurich, Switzerland 85  
 21 86

22 V. Candelise, T.H. Doan, Sh. Jain, R. Khurana, M. Konyushikhin, C.M. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu 87  
 23 88

24 National Central University, Chung-Li, Taiwan 89  
 25 90

26 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, 91  
 27 R.-S. Lu, M. Miñano Moya, E. Paganis, A. Psallidas, J.f. Tsai 92  
 28 93

29 National Taiwan University (NTU), Taipei, Taiwan 94  
 30 95

31 B. Asavapibhop, K. Kovitangoon, G. Singh, N. Srimanobhas 96  
 32 97

33 Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand 98  
 34 99

35 A. Adiguzel, M.N. Bakirci<sup>50</sup>, F. Boran, S. Damarseckin, Z.S. Demiroglu, C. Dozen, E. Eskut, S. Girgis, 100  
 36 G. Gokbulut, Y. Guler, I. Hos<sup>51</sup>, E.E. Kangal<sup>52</sup>, O. Kara, U. Kiminsu, M. Oglakci, G. Onengut<sup>53</sup>, 101  
 37 K. Ozdemir<sup>54</sup>, S. Ozturk<sup>50</sup>, A. Polatoz, D. Sunar Cerci<sup>55</sup>, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez 102  
 38 103

39 Cukurova University, Physics Department, Science and Art Faculty, Adana, Turkey 104  
 40 105

41 B. Bilin, G. Karapinar<sup>56</sup>, K. Ocalan<sup>57</sup>, M. Yalvac, M. Zeyrek 106  
 42 107

43 Middle East Technical University, Physics Department, Ankara, Turkey 108  
 44 109

45 E. Gülmez, M. Kaya<sup>58</sup>, O. Kaya<sup>59</sup>, E.A. Yetkin<sup>60</sup> 110  
 46 111

47 Bogazici University, Istanbul, Turkey 112  
 48 113

49 A. Cakir, K. Cankocak 114  
 50 115

51 Istanbul Technical University, Istanbul, Turkey 116  
 52 117

53 B. Grynyov 118  
 54 119

55 Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine 120  
 56 121

57 L. Levchuk, P. Sorokin 122  
 58 123

59 National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine 124  
 60 125

61 R. Aggleton, F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, H. Flacher, J. Goldstein, 126  
 62 M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, D.M. Newbold<sup>61</sup>, S. Paramesvaran, 127  
 63 A. Poll, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith 128  
 64 129  
 65 130

University of Bristol, Bristol, United Kingdom

1 K.W. Bell, A. Belyaev<sup>62</sup>, C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, 66  
 2 K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams 67  
 3 68

4 *Rutherford Appleton Laboratory, Didcot, United Kingdom* 69  
 5 70

6 M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, S. Casasso, M. Citron, D. Colling, L. Corpe, 71  
 7 P. Dauncey, G. Davies, A. De Wit, M. Della Negra, R. Di Maria, P. Dunne, A. Elwood, D. Futyan, Y. Haddad, 72  
 8 G. Hall, G. Iles, T. James, R. Lane, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, J. Nash, 73  
 9 A. Nikitenko<sup>48</sup>, J. Pela, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, S. Summers, 74  
 10 A. Tapper, K. Uchida, M. Vazquez Acosta<sup>63</sup>, T. Virdee<sup>15</sup>, J. Wright, S.C. Zenz 75  
 11 76  
 12 77

13 *Imperial College, London, United Kingdom* 78  
 14 79

15 J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner 80  
 16 81

17 *Brunel University, Uxbridge, United Kingdom* 82  
 18 83

19 A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika 84  
 20 85

21 *Baylor University, Waco, USA* 86  
 22 87

23 R. Bartek, A. Dominguez 88  
 24 89

25 *Catholic University of America, Washington, USA* 90  
 26 91

27 A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West 92  
 28 93

29 *The University of Alabama, Tuscaloosa, USA* 94  
 30 95

31 D. Arcaro, A. Avetisyan, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou 96  
 32 97

33 *Boston University, Boston, USA* 98  
 34 99

35 G. Benelli, D. Cutts, A. Garabedian, J. Hakala, U. Heintz, J.M. Hogan, K.H.M. Kwok, E. Laird, G. Landsberg, 100  
 36 Z. Mao, M. Narain, S. Piperov, S. Sagir, E. Spencer, R. Syarif 101  
 37 102

38 *Brown University, Providence, USA* 103  
 39 104

40 R. Band, C. Brainerd, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, 105  
 41 P.T. Cox, R. Erbacher, C. Flores, G. Funk, M. Gardner, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, 106  
 42 J. Pilot, S. Shalhout, M. Shi, J. Smith, M. Squires, D. Stolp, K. Tos, M. Tripathi, Z. Wang 107  
 43 108

44 *University of California, Davis, Davis, USA* 109  
 45 110

46 M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, D. Saltzberg, 111  
 47 C. Schnaible, V. Valuev 112  
 48 113

49 *University of California, Los Angeles, USA* 114  
 50 115

51 E. Bouvier, K. Burt, R. Clare, J. Ellison, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, J. Heilman, P. Jandir, 116  
 52 E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, A. Shrinivas, W. Si, H. Wei, 117  
 53 S. Wimpenny, B.R. Yates 118  
 54 119

55 *University of California, Riverside, Riverside, USA* 120  
 56 121

57 J.G. Branson, G.B. Cerati, S. Cittolin, M. Derdzinski, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, 122  
 58 I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, 123  
 59 S. Wasserbaech<sup>64</sup>, F. Würthwein, A. Yagil, G. Zevi Della Porta 124  
 60 125

61 *University of California, San Diego, La Jolla, USA* 126  
 62 127  
 63 128  
 64 129  
 65 130

1 N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, M. Franco Sevilla, C. George, 66  
 2 F. Golf, L. Gouskos, J. Gran, R. Heller, J. Incandela, S.D. Mullin, A. Ovcharova, H. Qu, J. Richman, D. Stuart, 67  
 3 I. Suarez, J. Yoo 68  
 4 69

5 *University of California, Santa Barbara - Department of Physics, Santa Barbara, USA* 70  
 6 71

7 D. Anderson, J. Bendavid, A. Bornheim, J.M. Lawhorn, H.B. Newman, C. Pena, M. Spiropulu, J.R. Vlimant, 72  
 8 S. Xie, R.Y. Zhu 73  
 9 74

10 *California Institute of Technology, Pasadena, USA* 75  
 11 76

12 M.B. Andrews, T. Ferguson, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev, M. Weinberg 77  
 13 78

14 *Carnegie Mellon University, Pittsburgh, USA* 79  
 15 80

16 J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, S. Leontsinis, T. Mulholland, K. Stenson, 81  
 17 S.R. Wagner 82  
 18 83

19 *University of Colorado Boulder, Boulder, USA* 84  
 20 85

21 J. Alexander, J. Chaves, J. Chu, S. Dittmer, K. Mcdermott, N. Mirman, J.R. Patterson, A. Rinkevicius, A. Ryd, 86  
 22 L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek 87  
 23 88

24 *Cornell University, Ithaca, USA* 89  
 25 90

26 D. Winn 91  
 27 92

28 *Fairfield University, Fairfield, USA* 93  
 29 94

30 S. Abdullin, M. Albrow, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, 95  
 31 J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, A. Canepa, H.W.K. Cheung, F. Chlebana, 96  
 32 M. Cremonesi, J. Duarte, V.D. Elvira, I. Fisk, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, 97  
 33 S. Grünendahl, O. Gutsche, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, 98  
 34 M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, R. Lopes De Sá, 99  
 35 J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, P. Merkel, 100  
 36 S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, B. Schneider, 101  
 37 E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, 102  
 38 S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, 103  
 39 H.A. Weber, A. Whitbeck 104  
 40 105  
 41 106  
 42 107

43 *Fermi National Accelerator Laboratory, Batavia, USA* 108  
 44 109

45 D. Acosta, P. Avery, P. Bortignon, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, S. Das, R.D. Field, 110  
 46 I.K. Furic, J. Konigsberg, A. Korytov, K. Kotov, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, D. Rank, 111  
 47 L. Shchutska, D. Sperka, N. Terentyev, L. Thomas, J. Wang, S. Wang, J. Yelton 112  
 48 113

49 *University of Florida, Gainesville, USA* 114  
 50 115

51 S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez 116  
 52 117

53 *Florida International University, Miami, USA* 118  
 54 119

55 A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, T. Perry, H. Prosper, 120  
 56 A. Santra, R. Yohay 121  
 57 122

58 *Florida State University, Tallahassee, USA* 123  
 59 124

60 M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, T. Roy, F. Yumiceva 125  
 61 126

62 *Florida Institute of Technology, Melbourne, USA* 127  
 63 128  
 64 129  
 65 130

1 M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, O. Evdokimov, C.E. Gerber, 66  
 2 D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, I.D. Sandoval Gonzalez, M.B. Tonjes, H. Trauger, N. Varelas, 67  
 3 H. Wang, Z. Wu, J. Zhang 68  
 4

5 *University of Illinois at Chicago (UIC), Chicago, USA* 69  
 6 70

7 B. Bilki<sup>65</sup>, W. Clarida, K. Dilsiz<sup>66</sup>, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, 72  
 8 H. Mermerkaya<sup>67</sup>, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul<sup>68</sup>, Y. Onel, F. Ozok<sup>69</sup>, A. Penzo, 73  
 9 C. Snyder, E. Tiras, J. Wetzel, K. Yi 74  
 10 75

11 *The University of Iowa, Iowa City, USA* 76  
 12 77

13 B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, J. Roskes, 78  
 14 U. Sarica, M. Swartz, M. Xiao, C. You 79  
 15 80

16 *Johns Hopkins University, Baltimore, USA* 81  
 17 82

18 A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, J. Castle, S. Khalil, A. Kropivnitskaya, 83  
 19 D. Majumder, W. Mcbrayer, M. Murray, C. Royon, S. Sanders, R. Stringer, J.D. Tapia Takaki, Q. Wang 84  
 20 85

21 *The University of Kansas, Lawrence, USA* 86  
 22 87

23 A. Ivanov, K. Kaadze, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda 88  
 24 89

25 *Kansas State University, Manhattan, USA* 90  
 26 91

27 F. Rebassoo, D. Wright 92  
 28 93

29 *Lawrence Livermore National Laboratory, Livermore, USA* 94  
 30 95

31 C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, 96  
 32 R.G. Kellogg, J. Kunkle, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, S.C. Tonwar 97  
 33 98

34 *University of Maryland, College Park, USA* 99  
 35 100

36 D. Abercrombie, B. Allen, V. Azzolini, R. Barbieri, A. Baty, R. Bi, K. Bierwagen, S. Brandt, W. Busza, 101  
 37 I.A. Cali, M. D'Alfonso, Z. Demiralgi, G. Gomez Ceballos, M. Goncharov, D. Hsu, Y. Iiyama, G.M. Innocenti, 102  
 38 M. Klute, D. Kovalskyi, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, B. Maier, A.C. Marini, C. Mcginn, 103  
 39 C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephans, 104  
 40 K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch 105  
 41 106  
 42 107

43 *Massachusetts Institute of Technology, Cambridge, USA* 108  
 44 109

45 A.C. Benvenuti, R.M. Chatterjee, A. Evans, P. Hansen, S. Kalafut, S.C. Kao, Y. Kubota, Z. Lesko, J. Mans, 110  
 46 S. Nourbakhsh, N. Ruckstuhl, R. Rusack, N. Tambe, J. Turkewitz 111  
 47 112

48 *University of Minnesota, Minneapolis, USA* 113  
 49 114

50 J.G. Acosta, S. Oliveros 115  
 51 116

52 *University of Mississippi, Oxford, USA* 117  
 53 118

54 E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, 119  
 55 J. Monroy, J.E. Siado, G.R. Snow, B. Stieger 120  
 56 121

57 *University of Nebraska-Lincoln, Lincoln, USA* 122  
 58 123

59 M. Alyari, J. Dolen, A. Godshalk, C. Harrington, I. Iashvili, A. Kharchilava, A. Parker, S. Rappoccio, 124  
 60 B. Roozbahani 125  
 61 126

62 *State University of New York at Buffalo, Buffalo, USA* 127  
 63 128  
 64 129  
 65 130

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

3  
4 *Northeastern University, Boston, USA*

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

7  
8  
9 *Northwestern University, Evanston, USA*

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

13  
14  
15 *University of Notre Dame, Notre Dame, USA*

16  
17 J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, B. Liu, W. Luo,  
18 D. Pugh, B.L. Winer, H.W. Wulsin

19  
20 *The Ohio State University, Columbus, USA*

21  
22 A. Benaglia, S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, D. Lange, J. Luo, D. Marlow,  
23 K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, A. Svyatkovskiy, C. Tully

24  
25 *Princeton University, Princeton, USA*

26  
27 S. Malik, S. Norberg

28  
29 *University of Puerto Rico, Mayaguez, USA*

30  
31 A. Barker, V.E. Barnes, S. Folgueras, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, A. Khatiwada, D.H. Miller,  
32 N. Neumeister, J.F. Schulte, J. Sun, F. Wang, W. Xie

33  
34 *Purdue University, West Lafayette, USA*

35  
36 T. Cheng, N. Parashar, J. Stupak

37  
38 *Purdue University Northwest, Hammond, USA*

39  
40 A. Adair, B. Akgun, Z. Chen, K.M. Ecklund, F.J.M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup,  
41 B.P. Padley, J. Roberts, J. Rorie, Z. Tu, J. Zabel

42  
43 *Rice University, Houston, USA*

44  
45 B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han,  
46 O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, M. Verzetti

47  
48 *University of Rochester, Rochester, USA*

49  
50 R. Ciesielski, K. Goulios, C. Mesropian

51  
52 *The Rockefeller University, New York, USA*

53  
54 A. Agapitos, J.P. Chou, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan,  
55 R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur,  
56 S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

57  
58 *Rutgers, The State University of New Jersey, Piscataway, USA*

59  
60 M. Foerster, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

61  
62 *University of Tennessee, Knoxville, USA*

63  
64  
65

66  
67  
68  
69  
70  
71  
72  
73  
74  
75  
76  
77  
78  
79  
80  
81  
82  
83  
84  
85  
86  
87  
88  
89  
90  
91  
92  
93  
94  
95  
96  
97  
98  
99  
100  
101  
102  
103  
104  
105  
106  
107  
108  
109  
110  
111  
112  
113  
114  
115  
116  
117  
118  
119  
120  
121  
122  
123  
124  
125  
126  
127  
128  
129  
130

O. Bouhali<sup>70</sup>, A. Castaneda Hernandez<sup>70</sup>, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon<sup>71</sup>, 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. Duderø, 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. Klabbbers, 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

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

<sup>2</sup> Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.

<sup>3</sup> Also at Universidade Estadual de Campinas, Campinas, Brazil.

<sup>4</sup> Also at Universidade Federal de Pelotas, Pelotas, Brazil.

<sup>5</sup> Also at Université Libre de Bruxelles, Bruxelles, Belgium.

<sup>6</sup> Also at Joint Institute for Nuclear Research, Dubna, Russia.

<sup>7</sup> Also at Helwan University, Cairo, Egypt.

<sup>8</sup> Now at Zewail City of Science and Technology, Zewail, Egypt.

<sup>9</sup> Now at Fayoum University, El-Fayoum, Egypt.

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

<sup>11</sup> Now at Ain Shams University, Cairo, Egypt.

<sup>12</sup> Also at Université de Haute Alsace, Mulhouse, France.

<sup>13</sup> Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

<sup>14</sup> Also at Tbilisi State University, Tbilisi, Georgia.

<sup>15</sup> Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

<sup>16</sup> Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.

<sup>17</sup> Also at University of Hamburg, Hamburg, Germany.

<sup>18</sup> Also at Brandenburg University of Technology, Cottbus, Germany.

<sup>19</sup> Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

<sup>20</sup> Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.

<sup>21</sup> Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.

<sup>22</sup> Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India.

<sup>23</sup> Also at Institute of Physics, Bhubaneswar, India.

<sup>24</sup> Also at University of Visva-Bharati, Santiniketan, India.

<sup>25</sup> Also at University of Ruhuna, Matara, Sri Lanka.

<sup>26</sup> Also at Isfahan University of Technology, Isfahan, Iran.

<sup>27</sup> Also at Yazd University, Yazd, Iran.

<sup>28</sup> Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.

<sup>29</sup> Also at Università degli Studi di Siena, Siena, Italy.

<sup>30</sup> Also at Purdue University, West Lafayette, USA.

<sup>31</sup> Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.

<sup>32</sup> Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.

<sup>33</sup> Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.

<sup>34</sup> Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.

<sup>35</sup> Also at Institute for Nuclear Research, Moscow, Russia.

1	36	Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.	66
2	37	Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.	67
3	38	Also at University of Florida, Gainesville, USA.	68
4	39	Also at P.N. Lebedev Physical Institute, Moscow, Russia.	69
5	40	Also at California Institute of Technology, Pasadena, USA.	70
6	41	Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.	71
7	42	Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.	72
8	43	Also at INFN Sezione di Roma; Sapienza Università di Roma, Rome, Italy.	73
9	44	Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.	74
10	45	Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.	75
11	46	Also at National and Kapodistrian University of Athens, Athens, Greece.	76
12	47	Also at Riga Technical University, Riga, Latvia.	77
13	48	Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.	78
14	49	Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.	79
15	50	Also at Gaziosmanpasa University, Tokat, Turkey.	80
16	51	Also at Istanbul Aydin University, Istanbul, Turkey.	81
17	52	Also at Mersin University, Mersin, Turkey.	82
18	53	Also at Cag University, Mersin, Turkey.	83
19	54	Also at Piri Reis University, Istanbul, Turkey.	84
20	55	Also at Adiyaman University, Adiyaman, Turkey.	85
21	56	Also at Izmir Institute of Technology, Izmir, Turkey.	86
22	57	Also at Necmettin Erbakan University, Konya, Turkey.	87
23	58	Also at Marmara University, Istanbul, Turkey.	88
24	59	Also at Kafkas University, Kars, Turkey.	89
25	60	Also at Istanbul Bilgi University, Istanbul, Turkey.	90
26	61	Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.	91
27	62	Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.	92
28	63	Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.	93
29	64	Also at Utah Valley University, Orem, USA.	94
30	65	Also at BEYKENT UNIVERSITY, Istanbul, Turkey.	95
31	66	Also at Bingol University, Bingol, Turkey.	96
32	67	Also at Erzincan University, Erzincan, Turkey.	97
33	68	Also at Sinop University, Sinop, Turkey.	98
34	69	Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.	99
35	70	Also at Texas A&M University at Qatar, Doha, Qatar.	100
36	71	Also at Kyungpook National University, Daegu, Korea.	101
37			102
38			103
39			104
40			105
41			106
42			107
43			108
44			109
45			110
46			111
47			112
48			113
49			114
50			115
51			116
52			117
53			118
54			119
55			120
56			121
57			122
58			123
59			124
60			125
61			126
62			127
63			128
64			129
65			130