Measurement of the t(t)over-barb(b)over-bar production cross section in the all-jet final state in pp collisions at root s=13 TeV

The CMS collaboration

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The CMS Collaboration , Eerola , P , Forthomme , L , Kirschenmann , H , Osterberg , K , Voutilainen , M , Garcia , F , Havukainen , J , Heikkilä , J K , Jårvinen , T , Kim , M S , Kinnunen , R , Lampen , T , Lassila-Perini , K , Laurila , S , Lehti , S , Linden , T , Luukka , P , Mäenpää , T , Siikonen , H , Tuominen , E , Tuominiemi , J , Viinikainen , J , Pekkanen , J , Tuuva , T , Karimäki , V , Sirunyan , A M & Tumasyan , A 2020 , ' Measurement of the t(t)over-barb(b)over-bar production cross section in the all-jet final state in pp collisions at root s=13 TeV ' , Physics Letters B , vol. 803 , 135285 . https://doi.org/10.1016/j.physletb.2020.135285

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Measurement of the $t\bar{t}b\bar{b}$ production cross section in the all-jet final state in pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration [*]

CERN, Switzerland

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ABSTRACT

A measurement of the production cross section of top quark pairs in association with two b jets ($t\bar{t}b\bar{b}$) is presented using data collected in proton-proton collisions at $\sqrt{s} = 13$ TeV by the CMS detector at the LHC corresponding to an integrated luminosity of 35.9 fb^{-1}. The cross section is measured in the all-jet decay channel of the top quark pair by selecting events containing at least eight jets, of which at least two are identified as originating from the hadronization of b quarks. A combination of multivariate analysis techniques is used to reduce the large background from multijet events not containing a top quark pair, and to help discriminate between jets originating from top quark decays and other additional jets. The cross section is determined for the total phase space to be $5.5 \pm 0.3\,(\text{stat})^{+1.6}_{-1.3}\,(\text{syst})\,\text{pb}$ and also measured for two fiducial $t\bar{t}b\bar{b}$ definitions. The measured cross sections are found to be larger than theoretical predictions by a factor of 1.5–2.4, corresponding to 1–2 standard deviations.

1. Introduction

At the CERN LHC, top quark pairs are produced with copious amounts of additional jets, including those resulting from the hadronization of b quarks (b jets). Top quark pair production in association with a pair of b jets, $t\bar{t}b\bar{b}$, is challenging to model because of the very different energy scales for the b jets produced in association with the $t\bar{t}$ system and that of $t\bar{t}$ system [1], and because of the small but nonnegligible mass of the b quark. Improving the accuracy and the precision of perturbative calculations in quantum chromodynamics (QCD) for this process is crucial, since it represents an important background for numerous searches or other measurements at the LHC. In particular, $t\bar{t}$ production in association with a Higgs boson ($t\bar{t}H$), where the Higgs boson decays to $b\bar{b}$, suffers from an irreducible $t\bar{t}b\bar{b}$ background [2–7]. Searches for four top quark production ($t\bar{t}t\bar{t}$) are also affected by this background [8–10]. The two latter processes provide direct access to the top quark Yukawa coupling, a crucial parameter of the standard model [11,12]. An improved understanding of the $t\bar{t}b\bar{b}$ process would help reduce the uncertainty in such measurements.

Calculations of the production cross section of $t\bar{t}$ in association with jets have been performed at next-to-leading order (NLO) in QCD and matched with parton showers for up to two additional massless partons in the matrix element [13–15]. The $t\bar{t}b\bar{b}$ cross section at NLO, matched with parton showers, has also been calculated for massless b quarks (five-flavour scheme, 5FS) [16], and has recently become available for massive b quarks (four-flavour scheme, 4FS) [17–19]. A comparison of the measurements of the $t\bar{t}b\bar{b}$ cross section with such calculations provides valuable guidance to improve the different frameworks. The $t\bar{t}b\bar{b}$ cross section has been measured previously at $\sqrt{s} = 8$ and 13 TeV by the ATLAS and CMS Collaborations, in events containing one or two charged leptons [20–24].

This Letter focuses on the all-jet final state of the $t\bar{t}$ system, where each top quark decays into three jets, leading to a signature of four b jets and four light-quark jets for the $t\bar{t}b\bar{b}$ system. This final state is favoured by a large branching fraction and provides a complete reconstruction of top quarks, as opposed to other decay channels of the top quark pairs. Moreover, the main uncertainties affecting the sensitivity in this measurement are different than those affecting final states containing leptons, therefore providing complementary information. However, the all-jet channel also suffers from a large background from multijet production, as well as from the difficulty of identifying jets that originate from decaying top quarks. Multivariate analysis techniques are developed and implemented to mitigate these problems. The $t\bar{t}b\bar{b}$ cross section is measured using data collected by the CMS detector in pp collisions at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 35.9 fb^{-1} [25].

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

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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. 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 reside within the solenoid field. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and end detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of its coordinate system and kinematic variables, can be found in Ref. [26]. Samples of $\mathrm{t\bar{t}}$ events are simulated at NLO in QCD using POWHEG (v2) [27–30]. These samples include $\mathrm{t\bar{t}b\bar{b}}$ events, where the additional b jets are generated by the parton shower. Single top quark production in the t channel or in association with a W boson, and $\mathrm{t\bar{t}H}$ production are simulated at NLO with POWHEG [31–33]. Production of W or Z bosons in association with jets (V+jets), as well as QCD multijet events, are simulated at leading order (LO) with MADGRAPH5_aMC@NLO (v2.2.2) [14], and the MLM merging scheme [34]. The MADGRAPH5_aMC@NLO generator is used at NLO for simulating associated production of top quark pairs with W or Z bosons ($\mathrm{t\bar{t}V}$). Diboson processes (WW, WZ and ZZ) are simulated at LO using PYTHIA (v8.219) [35].

All simulated events are processed with PYTHIA for modelling of the parton showering, hadronization, and underlying event (UE). The NNPDF 3.0 [36] parton distribution functions (PDFs) are used throughout, at the same perturbative order as used by the event generators. The CUETP8M1 UE tune [37] is used for all processes except for the $\mathrm{t\bar{t}}$, $\mathrm{t\bar{t}H}$ and single top quark processes. For these, an updated version of the tune is used (CUETP8M2T4), in which an adjusted value of the strong coupling constant is used in the description of initial-state radiation [38]. Simulation of the CMS detector response is based on GEANT4 (v9.4) [39]. Additional pp interactions in the same or neighbouring bunch crossings (pileup) are simulated with PYTHIA and overlaid with hard-scattering events according to the pileup distribution measured in data.

The various simulated processes are normalized to state-of-the-art predictions for the production cross sections. The $\mathrm{t\bar{t}}$, V+jets, single top quark, and $\mathrm{W^+W^-}$ samples are normalized to next-to-NLO (NNLO) precision in QCD [40–43], while remaining processes such as $\mathrm{t\bar{t}V}$, $\mathrm{t\bar{t}H}$, and other diboson production are normalized to NLO in QCD [14,44].

3. Definitions of fiducial phase space

The $\mathrm{t\bar{t}b\bar{b}}$ production cross section is measured for three different phase space definitions. Two definitions for $\mathrm{t\bar{t}b\bar{b}}$ events in the fiducial phase space, matching the detector acceptance, are considered: one that is based exclusively on stable generated particles after hadronization (parton-independent), and one that also uses parton-level information after radiation emission (parton-based). The former facilitates comparisons with predictions from event generators, while the latter is closer to the approach taken by searches for $\mathrm{t\bar{t}H}$ production to define the contribution from the $\mathrm{t\bar{t}b\bar{b}}$ process. The cross section is reported for the total phase space by correcting the parton-based fiducial cross section by the experimental acceptance.

Particle-level jets are defined by clustering stable generated final-state particles, excluding neutrinos, using the anti-k_T algorithm [45,46] with a distance parameter of 0.4. These jets are defined unambiguously as b or c jets by rescaling the momenta of generated b and c hadrons to a negligible value, while preserving their direction, and including them in the clustering procedure [47]. A jet is labelled b jet if it is matched to at least one b hadron, and labelled c jet if matched with at least one c hadron and no b hadron.

Events in the generated $\mathrm{t\bar{t}}$ sample are divided into exclusive categories according to the flavour of the jets that do not originate from the decay of top quarks, which we refer to as “additional” jets. The b or c jets are considered to originate from a top quark if one of the clustered b or c hadrons features a top quark in its simulation history. Additional jets are required to have a transverse momentum $p_\mathrm{T} > 20$ GeV, and absolute pseudorapidity $|\eta| < 2.4$. No explicit requirement on the b hadron kinematic variables is used. Events are categorized as $\mathrm{t\bar{t}b\bar{b}}$ if they contain at least two additional b jets, which defines the total phase space for which the $\mathrm{t\bar{t}b\bar{b}}$ cross section is measured. Events with a single additional b jet are categorized as $\mathrm{t\bar{t}b}$ ($\mathrm{t\bar{t}2b}$) if that b jet is matched with exactly one (at least two) b hadron(s). The $\mathrm{t\bar{t}b}$ events correspond to $\mathrm{t\bar{t}b\bar{b}}$ events where one of the additional b jets fails the above kinematic requirements, while $\mathrm{t\bar{t}2b}$ events arise from collinear gluon splittings. If no b jets are present but at least one additional c jet is present the event is referred to as $\mathrm{t\bar{t}c\bar{c}}$; all remaining events are denoted $\mathrm{t\bar{t}jj}$.

For the parton-based definition of the $\mathrm{t\bar{t}b\bar{b}}$ fiducial phase space, at least eight jets with $p_\mathrm{T} > 20$ GeV and $|\eta| < 2.4$ must be present, of which at least six have $p_\mathrm{T} > 30$ GeV. At least four of these jets must be b jets, and at least two of those must not originate from top quarks. This last requirement is removed for the parton-independent fiducial definition, in order to be independent of the origin of the b jets, and thus of the simulated parton content. Some $\mathrm{t\bar{t}b\bar{b}}$ events in the total phase space failing the fiducial requirements may still be reconstructed and selected because of resolution effects, and are referred to as out-of-acceptance. They correspond to 16% of all reconstructed $\mathrm{t\bar{t}b\bar{b}}$ events.

4. Event reconstruction and selection

The particle-flow algorithm [48] aims to reconstruct and identify each particle in an event, with an optimized combination of information from the various elements of the CMS detector. The primary pp interaction vertex is taken to be the reconstructed vertex with the largest sum of the p_T^2 of the objects associated to that vertex, where the considered objects are those returned by a jet clustering algorithm [45,46] applied to the tracks assigned to the vertex, and the associated missing transverse momentum, taken as the negative vector sum of the p_T of those objects. The energy of photons is 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 p_T of muons is obtained from the curvature of the corresponding tracks. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for zero-suppression effects and for the response function of the calorimeters to hadronic showers. The energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies.

For each event, hadronic jets are clustered from the reconstructed particles using the anti-k_T algorithm with a distance parameter of 0.4. The jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be within 5 to 10% of the true momentum over the whole p_T spectrum and detector acceptance. Pileup interactions can contribute additional tracks and calorimetric energy depositions to the jet momentum. To mitigate this effect, tracks identified to be originating from pileup vertices are discarded and an offset correction is applied to correct for remaining contributions [47].

Jet energy corrections are derived from simulation to bring the average measured response of a jet to that of a particle-level jet. In situ measurements of the momentum balance in dijet, photon+jet, Z+jet, and multijet events are used to account for any residual differences in jet energy scale in data and simulation [49]. The data used for these measurements are independent of those used for the present Letter.

A combined secondary vertex b tagging algorithm (CSVv2) is used to identify jets originating from the hadronization of b quarks [50], with an efficiency for identifying b jets in simulated $\mathrm{t\bar{t}}$ events of about 65%. The misidentification probability is about 10 and 1% for c and light-flavour jets, respectively, where the latter refers to jets originating from the hadronization of u, d, s quarks or gluons. The distribution of the discriminator score for b and light-flavour jets in the simulation is calibrated to match the distribution measured in control samples of $\mathrm{t\bar{t}}$ events with exactly two leptons (electrons or muons) and two jets, and Z bosons produced in association with jets where the Z bosons decay to pairs of electrons or muons. The calibration is achieved by reweighting events using scale factors that are parameterized by the jet flavour, p_T, $|\eta|$, and b tagging discriminator score [50].

Data are collected using two triggers [51], both requiring at least six jets with $|\eta| < 2.4$. The first (second) trigger considers jets with $p_\mathrm{T} > 40$ (30) GeV, and requires that the jet scalar p_T sum, H_T, exceeds 450 (400) GeV and that at least one (two) of the jets is (are) b tagged. The efficiency of these triggers is measured in simulation, as well as in a data control sample collected using independent single-muon triggers. The trigger efficiency in simulation is corrected to match the efficiency observed in the data by reweighting events using scale factors defined as the ratio between the efficiencies in the data and simulation. For events satisfying the preselection criteria detailed below, the trigger efficiency is above 95%.

An offline preselection is applied to data and simulated events, by requiring the presence of at least six jets with $p_\mathrm{T} > 40$ GeV and $|\eta| < 2.4$, of which at least two are b tagged, and $H_\mathrm{T} > 500$ GeV. Additional jets in the events are considered if they satisfy the requirements $p_\mathrm{T} > 30$ GeV and $|\eta| < 2.4$. Events are vetoed if they contain electrons or muons with $p_\mathrm{T} > 15$ GeV and $|\eta| < 2.4$ that satisfy highly efficient identification criteria [52,53] and are isolated from hadronic activity. About 20% of the $\mathrm{t\bar{t}b\bar{b}}$ events in the fiducial phase space pass the offline selection.

5. Multivariate analysis

The final state considered in this analysis suffers from a large background from multijet production, as well as from the difficulty to identify which jets do not stem from top quark decays. To address these challenges and improve the sensitivity to the $\mathrm{t\bar{t}b\bar{b}}$ signal, several multivariate analysis tools have been employed.

The multijet background can be discriminated from $\mathrm{t\bar{t}}$ production by observing that the latter is expected to contain four light-quark jets from W boson decays per event, whereas the former is enriched in gluon jets. Gluon and quark jets are separated using a quark-gluon likelihood (QGL) variable, based on jet substructure observables [54,55]. Using the individual jet QGL values, the likelihood of an event to contain N_q light-quark jets and N_g gluon jets is defined as

$$L(N_\mathrm{q}, N_\mathrm{g}) = \sum_{\mathrm{perm}} \left(\prod_{k=i_1}^{i_{N_\mathrm{q}}} f_\mathrm{q}(\zeta_k) \right) \left(\prod_{m=i_{N_\mathrm{q}+1}}^{i_{N_\mathrm{q}+N_\mathrm{g}}} f_\mathrm{g}(\zeta_m) \right), \tag{1}$$

where the sums run over all possible assignments of N_q jets to quarks (indices k) and N_g jets to gluons (indices m), ζ_i is the QGL discriminant of the ith jet, and f_q and f_g are the probability densities for ζ_i under the hypothesis of (u, d, s, or c) quark or gluon origin, respectively. When computing $L(N_\mathrm{q}, N_\mathrm{g})$, b-tagged jets are not considered. Based on the event likelihoods with $N_\mathrm{q} = 4$ and $N_\mathrm{g} = 0$, as well as $N_\mathrm{q} = 0$ and $N_\mathrm{g} = 4$, the QGL ratio (QGLR) is defined as $\mathrm{QGLR} = L(4,0)/(L(4,0) + L(0,4))$. Other values for N_q and N_g have been tried but led to reduced discrimination between multijet and $\mathrm{t\bar{t}}$ production. We correct the modelling of the QGL in the simulation by reweighting each event based on the quark or gluon origin and the QGL value of all jets in the event, where the weights are measured using data samples enriched in Z+jets and dijet events [55]. After applying this correction, a good agreement is found between data and simulation.

To address the large combinatorial ambiguity in identifying the additional jets in the events, we have trained a boosted decision tree (BDT) using the TMVA package [56], henceforth referred to as the “permutation BDT”. In events with eight reconstructed jets, there are 28 ways to select six of those as originating from the all-jet decay of a top quark pair, and there are 90 ways to match those six jets to the six partons from the top quark decay chains. Some permutations are indistinguishable and are not considered, i.e. permutations of two jets assigned to a W boson decay are not considered, and neither are the permutations of three jets assigned to a t or $\mathrm{\bar{t}}$ decay. To reduce the large number of permutations, the least favoured ones are rejected using a χ^2 variable quantifying the compatibility of the invariant masses of the different jet pairings with those of the particles they should come from, defined as

$$\chi^2 = (m_{\mathrm{j_1,j_3,j_4}} - m_\mathrm{t})^2/\sigma_\mathrm{t}^2 + (m_{\mathrm{j_3,j_4}} - m_\mathrm{W})^2/\sigma_\mathrm{W}^2 + (m_{\mathrm{j_2,j_5,j_6}} - m_\mathrm{t})^2/\sigma_\mathrm{t}^2 + (m_{\mathrm{j_5,j_6}} - m_\mathrm{W})^2/\sigma_\mathrm{W}^2,$$

where $m_{(\ldots)}$ denotes the invariant mass of the given jets, and $\sigma_\mathrm{W} = 10.9$ GeV and $\sigma_\mathrm{t} = 17.8$ GeV are the experimental resolutions in the two- and three-jet invariant masses, respectively. The masses entering the equation are $m_\mathrm{t} = 172.3$ GeV and $m_\mathrm{W} = 80.2$ GeV, measured from the generated $\mathrm{t\bar{t}}$ system after reconstruction. The BDT is trained using simulated $\mathrm{t\bar{t}}$ events after applying the above preselection criteria, requiring the presence of at least seven jets, and reducing the number of permutations by requiring that $\chi^2 < 33.38$, corresponding to a p-value $P(\chi^2)$ of 10^{-6} for a χ^2 distribution with four degrees of freedom. Events for which no permutation satisfies this requirement are rejected. The correct jet-parton assignment is considered as a signal in the training, while all other distinguishable combinations are treated as background. Input variables used for the BDT include jet b tagging discriminator scores and kinematic quantities, such as invariant masses of pairs and triplets of jets, angular openings between jets, and the transverse momenta of jets. For each permutation, only quantities pertaining to the six jets assumed to originate from the top quarks are used in the training. The permutation yielding the highest BDT score is used for the rest of the analysis. For $\mathrm{t\bar{t}}$ events with eight jets where all six jets from the top quark decays have been selected, the permutation BDT identifies the correct permutation with about 60% efficiency.

As a further handle to reduce the multijet background, we have trained a second BDT to discriminate this background from inclusive $\mathrm{t\bar{t}}$+jets production. While supervised training of multivariate classifiers relies on samples of simulated events, the poor modelling of multijet production and the insufficient size of the available simulated samples limit the achievable discrimination power. A proposed method to alleviate these shortcomings is a classification without labels (CWoLa) [57]. In this weakly supervised approach, the classifier is trained using data, whereby one region in the data is treated as background and another independent region is treated as signal. In the limit of large training sample the resulting classifier converges to the optimal classifier to distinguish between signal and background, provided the two following conditions are fulfilled [57]. First, the relative rates of the actual signal and background processes should be different in the two regions. Second, the distributions of the variables entering the CWoLa classifier should be independent of the quantity used to define the two regions, for both the signal and background processes. The CWoLa BDT is trained using a sample of data with exactly seven jets, where two independent regions are defined by requiring that the QGLR is below or above 0.95. The first and second regions are expected to contain about 10 and 20% of $t\bar{t}$ events, respectively. Variables used for constructing the CWoLa BDT are kinematic quantities similar to those used in the permutation BDT, the output value of the permutation BDT, and the b tagging discriminator scores of the two jets identified by the permutation BDT as the b jets originating from the top quark decays. Only the six jets identified by the permutation BDT as coming from the top quark decays are used to define the CWoLa BDT input variables. The performance of the resulting classifier, measured in the region with at least eight jets, is found to be comparable to that of a supervised classifier trained using simulated samples.

6. Cross sections

To measure the $t\bar{t}b\bar{b}$ cross section we require, in addition to the preselection criteria, the presence of at least eight jets, and $P(\chi^2) > 10^{-6}$. The distributions in the QGLR and of the CWoLa BDT discriminants for selected events are shown in Fig. 1. The cross section is extracted from a binned maximum likelihood fit to a two-dimensional distribution (referred to as 2DCSV) constructed using the largest and second-largest b tagging discriminator scores among the jets determined to be additional jets by the permutation BDT. In order to increase the signal purity and the precision in the measurement, we define a signal region (SR) by requiring that the CWoLa BDT score be above 0.5, and the QGLR be above 0.8. These thresholds are optimized to obtain the best expected precision in the cross section. About 20% of the $t\bar{t}b\bar{b}$ signal that passes the offline preselection is selected into the SR.

The multijet background is also estimated from data. Three independent control regions (CRs), orthogonal to the SR, are defined by inverting the requirements on the CWoLa BDT and the QGLR: the CR1 (BDT > 0.5, QGLR < 0.8), the CR2 (BDT < 0.5, QGLR < 0.8), and the CR3 (BDT < 0.5, QGLR > 0.8). For multijet production, the CWoLa BDT score and the QGLR are nearly independent, so that in each bin i of the 2DCSV distribution the number of multijet events in the SR, N_i^{SR}, can be estimated from the number of multijet events in the CRs as

$$N_i^{\text{SR}} = N_i^{\text{CR3}} \frac{N_i^{\text{CR1}}}{N_i^{\text{CR2}}}. \tag{2}$$

This relationship is a consequence of the choice of variables entering the CWoLa BDT, which were required to be independent of the QGLR in order to satisfy the hypotheses of the CWoLa method. In order to properly take into account the small but non-negligible signal contribution in the CRs, the fit to extract the cross section is performed in all four regions, with the multijet rates N_i^{CR1}, N_i^{CR2}, and N_i^{CR3} free to vary in the fit. The assumption of Eq. (2) on which this estimation relies is confirmed using the simulation. In addition, we verify that Eq. (2) is also satisfied in the data for kinematic distributions, such as the invariant mass of the reconstructed W bosons and top quarks, where for each bin of these distributions the multijet yields are estimated by taking the difference between the observed yields in data and the predicted yields of all simulated processes. Finally, we validate Eq. (2) using alternative definitions of the four regions in the plane formed by the QGLR and the CWoLa BDT, excluding the SR as defined above. The outcome of goodness-of-fit tests of the 2DCSV distribution was also positive for each of the alternative region definitions.

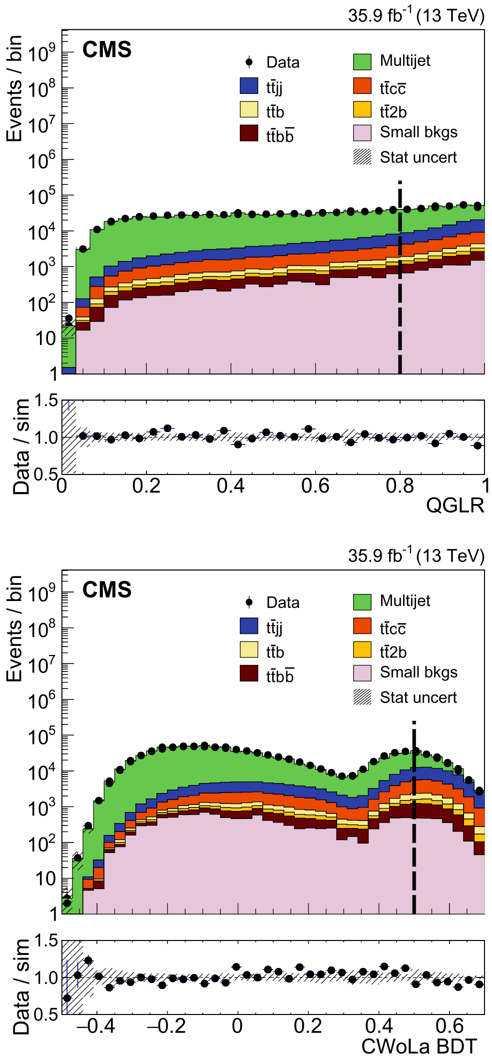

Fig. 1. Distributions in the QGLR (upper) and the CWoLa BDT discriminants (lower). Both are after preselection, requiring $P(\chi^2) > 10^{-6}$ and at least eight selected jets. All the contributions are based on simulation. The multijet contribution is scaled to match the total yields in data, after the other processes including the $t\bar{t}b\bar{b}$ signal have been normalized to their corresponding theoretical cross sections. This choice takes into account only the effect of the shape variation from the multijet background. The small backgrounds include $t\bar{t}V$, $t\bar{t}H$, single top quark, V+jets, and diboson production. The lower panels show the ratio between the observed data and the predictions. The dashed lines indicate the boundaries between the signal and control regions defined in Section 6. Hatched bands indicate the statistical uncertainty in the predictions without considering the systematic sources, dominated by the uncertainties in the simulated multijet background. Underflow and overflow events were added to the first and last bins, respectively.

The data are fitted using a profiled maximum likelihood technique, where the likelihood is built as a product of independent Poisson likelihoods, defined for each bin i of the 2DCSV distributions in the four event regions using the following expression for the number of events in bin i:

$$\mathcal{N}_i = \mu\, \mathcal{T}_i^{\text{sig}}(\vec{\theta}) + \sum_{k \text{ in sim bkg}} \mathcal{T}_i^{k}(\vec{\theta}) + N_i, \tag{3}$$

where μ is a signal strength parameter, defined by the ratio of observed to expected signal, $\mathcal{T}_i^k$ is the expected yield for process k

in bin i, "sig" includes the contributions from $\mathrm{t\bar{t}b\bar{b}}$, $\mathrm{t\bar{t}2b}$, and $\mathrm{t\bar{t}b}$, and $\vec{\theta}$ is a vector of nuisance parameters affecting the predicted yields of the various processes introduced to model the systematic uncertainties described in the next section. The parameters N_i are used to estimate the multijet background from the combined fit of the four regions; they are free parameters in the CRs and are given by Eq. (2) in the SR. The likelihood also features constraint terms for each of the nuisance parameters considered in the fit. Different templates are constructed from $\mathrm{t\bar{t}b\bar{b}}$ events matching the fiducial requirements and from events failing these requirements. For the fiducial $\mathrm{t\bar{t}b\bar{b}}$ templates, the effect of nuisance parameters corresponding to theoretical uncertainties is normalized such that the $\mathrm{t\bar{t}b\bar{b}}$ cross section in the fiducial phase space is preserved, i.e. only shape variations within that phase space and their impact on the reconstruction efficiency are taken into account. No such requirement is made for the other templates. The uncertainty in the measured cross section is obtained by profiling the nuisance parameters. As described in the next section, some uncertainties are not profiled and are added in quadrature with the uncertainty obtained from the fit. The fit is repeated for each of the two fiducial phase-space definitions for $\mathrm{t\bar{t}b\bar{b}}$ events described in Section 3, leading to different in- and out-of-acceptance $\mathrm{t\bar{t}b\bar{b}}$ templates. The total $\mathrm{t\bar{t}b\bar{b}}$ cross section is obtained by dividing the cross section for the parton-based fiducial phase space by the acceptance, estimated using POWHEG+PYTHIA to be $(29.4 \pm 1.8)\%$. Uncertainties affecting this acceptance correction are detailed in the next section.

7. Systematic uncertainties

Several sources of systematic uncertainties affecting the predictions for the signal and background processes entering the analysis are considered. These uncertainties may affect the normalization of the templates entering the fit, or may alter both their shape and their normalization. The migration of events between the four regions is taken into account when relevant. Experimental sources of uncertainties are taken to be fully correlated for all signal and background distributions estimated using the simulation, while only a subset of theoretical uncertainties are correlated among the $\mathrm{t\bar{t}}$+jets components.

The modelling of the shape of the b tagging discriminator in the simulation represents an important source of systematic uncertainty. Several uncertainties in the calibration of the b tagging discriminator distribution are propagated independently to the shape and normalization of the 2DCSV templates. These are related to the uncertainty in the contamination by light- (heavy-) flavour jets in the control samples used for the measurement of heavy- (light-) jet correction factors, as well as to the statistical uncertainty in these measurements [50]. Since no dedicated measurement is performed for c jets, the uncertainty in the shape of the b tagging discriminator distribution for c jets is conservatively taken to be twice the relative uncertainty considered for b jets. In total, six different nuisance parameters are introduced to estimate the uncertainty arising from b tagging.

We evaluate the effect of the uncertainty in the jet energy scale (JES) and jet energy resolution (JER) by shifting the jet four-momenta using correction factors that depend on jet p_{T} and $|\eta|$ for the JES, and jet $|\eta|$ for the JER [49]. The calibration of the JES is affected by several sources of uncertainty, which are propagated independently to the measurement. The uncertainty in the JES is also propagated to the b tagging calibration, and the resulting effect on the distribution of the b tagging discriminators is taken to be correlated with the effect on the jet momenta.

Uncertainties pertaining to the QGL are estimated conservatively by removing or doubling the scale factors applied to correct the distribution of the QGL in the simulation [55]. The uncertainty in the integrated luminosity is evaluated to be 2.5% [25]. Uncertainties in the trigger efficiency are estimated by varying the trigger scale factors by their uncertainty, as determined from the efficiency measurements in data and simulation. The uncertainty in the modelling of pileup is estimated by reweighting simulated events to yield different distributions of the expected number of pileup interactions, obtained by varying the total inelastic pp cross section by 4.6% [58]. We take into account the limited size of the simulated samples by varying independently the predicted yields in every bin by their statistical uncertainties.

Theoretical uncertainties in the modelling of the $\mathrm{t\bar{t}}$+jets process enter this analysis both through the efficiency to reconstruct and select $\mathrm{t\bar{t}b\bar{b}}$ events, and through the contamination from $\mathrm{t\bar{t}c\bar{c}}$ and $\mathrm{t\bar{t}jj}$ backgrounds. The uncertainties in the renormalization and factorization scales (μ_{R} and μ_{F}, respectively) are estimated by varying both scales independently by a factor of two up or down in the event generation, omitting the two cases where the scales are varied in opposite directions, and taking the envelope of the six resulting variations. Likewise, the uncertainties related to the choice of the scale in the parton shower is evaluated by varying the scale in the initial-state shower by factors of 0.5 and 2, and the scale in the final-state shower by factors of $\sqrt{2}$ and $1/\sqrt{2}$. Propagation of the uncertainties associated with the PDFs, as well as with the value of the strong coupling in the PDFs, has been achieved by reweighting generated events using variations of the NNPDF 3.0 set [36]. The impact of the choice of the matching scale $h_{\mathrm{damp}} = 1.58 m_{\mathrm{t}}$ between the matrix-element generator and the parton shower in POWHEG is evaluated using simulated samples generated with different choices of $h_{\mathrm{damp}} = m_{\mathrm{t}}$ and $2.24 m_{\mathrm{t}}$ [38]. We evaluate the uncertainty related to the UE tune by varying the tune parameters according to their uncertainties. The uncertainty from the modelling of colour reconnection in the final state is evaluated by considering four alternatives to the PYTHIA default, which is based on multiple-parton interactions (MPI) with early resonance decays (ERD) switched off. These alternatives are an MPI-based scheme with ERD switched on, a QCD-inspired scheme [59], and a gluon-move scheme with ERD either off or on [60]. All the alternative models were tuned to LHC data [61]. It has been verified that the selection efficiency obtained from the nominal $\mathrm{t\bar{t}}$ simulation, in which additional b jets are generated by the parton shower, is in agreement within estimated modelling uncertainties with that obtained using a sample of $\mathrm{t\bar{t}b\bar{b}}$ events generated at NLO in QCD with massive b quarks (4FS) [19]. Since the spectrum of the top quark p_{T} is known to be softer in the data than in the simulation, we evaluate the effect of this mismodelling by reweighting the generated events to match the top quark p_{T} distribution measured in data [62]. The latter two uncertainties are not evaluated using profiled nuisance parameters, but by repeating the measurement using varied signal and background predictions. The differences in the measured cross sections are taken as the corresponding uncertainties and are added in quadrature with the uncertainty obtained from the profile likelihood. Uncertainties related to the μ_{R} and μ_{F} scales, the parton shower scale, and the h_{damp} choice are taken to be uncorrelated for the $\mathrm{t\bar{t}b\bar{b}}$, $\mathrm{t\bar{t}b}$, $\mathrm{t\bar{t}2b}$, $\mathrm{t\bar{t}c\bar{c}}$ and $\mathrm{t\bar{t}jj}$ templates, while the other modelling uncertainties are taken to be correlated for all $\mathrm{t\bar{t}}$ events. In addition to the aforementioned modelling uncertainties, we assign an uncertainty of 50% to the normalization of the $\mathrm{t\bar{t}c\bar{c}}$ background to cover the lack of precise measurements of this process. The results are stable when doubling that uncertainty.

Compared to $\mathrm{t\bar{t}}$+jets and multijet production, the contribution of other background processes such as $\mathrm{t\bar{t}V}$, $\mathrm{t\bar{t}H}$, V+jets, diboson, and single top quark production is small. We assign uncertainties to their predicted rates based on the PDF and $\mu_{\mathrm{R}}/\mu_{\mathrm{F}}$ scale uncertainties in their theoretical cross sections.

Table 1 summarizes the contributions of the various sources of systematic uncertainties to the total uncertainty in the cross

Table 1
The considered sources of systematic uncertainties and their respective contributions to the total systematic uncertainty in the measured $\mathrm{t\bar{t}b\bar{b}}$ cross section for the two defined $\mathrm{t\bar{t}b\bar{b}}$ fiducial phase spaces. The upper (lower) portion of the table lists uncertainties related to the experimental conditions (theoretical modelling). The numbers are obtained by taking the difference in quadrature of the profile likelihood width when fixing nuisance parameters corresponding to a given source of uncertainty and leaving the others free to vary.

Source	Fiducial, parton-independent (%)	Fiducial, parton-based (%)
Simulated sample size	$^{+15}_{-11}$	$^{+15}_{-11}$
Quark-gluon likelihood	$^{+13}_{-8}$	$^{+13}_{-8}$
b tagging of b quark	± 10	± 10
JES and JER	$^{+5.1}_{-5.2}$	$^{+5.0}_{-5.4}$
Integrated luminosity	$^{+2.8}_{-2.2}$	$^{+2.4}_{-2.2}$
Trigger efficiency	$^{+2.6}_{-2.1}$	$^{+2.5}_{-2.2}$
Pileup	$^{+2.3}_{-2.0}$	$^{+2.2}_{-1.9}$
μ_R and μ_F scales	$^{+13}_{-9}$	$^{+13}_{-9}$
Parton shower scale	$^{+11}_{-8}$	$^{+11}_{-8}$
UE tune	$^{+9.0}_{-5.3}$	$^{+9.0}_{-5.2}$
Colour reconnection	± 7.2	± 7.1
Shower matching (h_damp)	$^{+4.3}_{-2.8}$	$^{+3.8}_{-2.7}$
$\mathrm{t\bar{t}c\bar{c}}$ normalization	$^{+3.2}_{-4.4}$	$^{+2.9}_{-4.5}$
Modelling of p_T of top quark	± 2.5	± 2.4
PDFs	$^{+2.2}_{-2.0}$	$^{+2.2}_{-2.0}$
Total	$^{+28}_{-23}$	$^{+28}_{-23}$

sections measured in the fiducial phase space. The theoretical uncertainty in the acceptance from the various sources listed above is estimated to be 6%, and is added in quadrature with the uncertainty in the parton-based fiducial cross section to yield the systematic uncertainty in the total $\mathrm{t\bar{t}b\bar{b}}$ cross section.

8. Results

The result of the maximum likelihood fit described in Section 6 is shown in Fig. 2 for the 2DCSV distributions in the four analysis regions. The contribution from multijet production nearly matches the differences between the yields in data and from the other processes in the CR1, CR2, and CR3 because it is estimated from the data in the four regions according to the method described in the previous section. The measured cross section for the two $\mathrm{t\bar{t}b\bar{b}}$ definitions in the fiducial phase space, as well as for the total phase space introduced in Section 3, are given in Table 2. The measurement uncertainty is dominated by the systematic effects from the simulation sample sizes, QGL corrections, and μ_R and μ_F dependences on changes in scale.

Because of the large overlap between the two definitions of the $\mathrm{t\bar{t}b\bar{b}}$ fiducial phase space, the measured cross sections are numerically equal at the quoted precision. The measurements are compared with NLO predictions from POWHEG for inclusive $\mathrm{t\bar{t}}$ production interfaced with either PYTHIA or HERWIG++ (v2.7.1) [63], using the EE5C UE tune [64] for the latter. Predictions from MADGRAPH5_aMC@NLO at NLO interfaced with PYTHIA for $\mathrm{t\bar{t}}$ production with up to two extra massless partons (5FS) merged using the FxFx scheme [15], and for $\mathrm{t\bar{t}b\bar{b}}$ production with massive b quarks (4FS), are also compared with the measurements. The predicted cross sections are not rescaled by any NLO to NNLO K-factor, which for inclusive $\mathrm{t\bar{t}}$ production amounts to 1.1–1.15 [40]. Measured and predicted cross sections are shown in Fig. 3. The predictions underestimate the measured cross section by a factor of 1.5–2.4, corresponding to differences of 1–2 standard deviations. This is consistent with the results from Refs. [20–24].

9. Summary

The first measurement of the $\mathrm{t\bar{t}b\bar{b}}$ cross section in the all-jet final state was presented, using 35.9 fb^{-1} of data collected in pp collisions at $\sqrt{s} = 13$ TeV. The cross section is first measured in a fiducial region of particle-level phase space by defining two categories of $\mathrm{t\bar{t}b\bar{b}}$ events, and subsequently this result is corrected to the total phase space. One of the defined fiducial regions corresponds to ignoring parton-level information, while the other uses parton-level information to identify the particle-level jets that do not originate from the decay of top quarks. For both definitions, the cross section is measured to be $1.6 \pm 0.1\,(\mathrm{stat})^{+0.5}_{-0.4}\,(\mathrm{syst})\,\mathrm{pb}$. The cross section in the total phase space is obtained by correcting this measurement for the experimental acceptance on the jets originating from the top quarks, which yields $5.5 \pm 0.3\,(\mathrm{stat})^{+1.6}_{-1.3}\,(\mathrm{syst})\,\mathrm{pb}$. This measurement provides valuable input to studies of the $\mathrm{t\bar{t}H}$ process, where the Higgs boson decays into a pair of b quarks, and for which the normalization and modelling of the $\mathrm{t\bar{t}b\bar{b}}$ process represent a leading source of systematic uncertainty. Furthermore, these results represent a stringent test of perturbative quantum chromodynamics at the LHC. Predictions from several generators are compared with measurements and found to be smaller than the measured values by a factor of 1.5–2.4, corresponding to 1–2 standard deviations. This is consistent with previous results for the $\mathrm{t\bar{t}b\bar{b}}$ cross section and calls for further experimental and theoretical studies of the associated production of top quark pairs and b jets.

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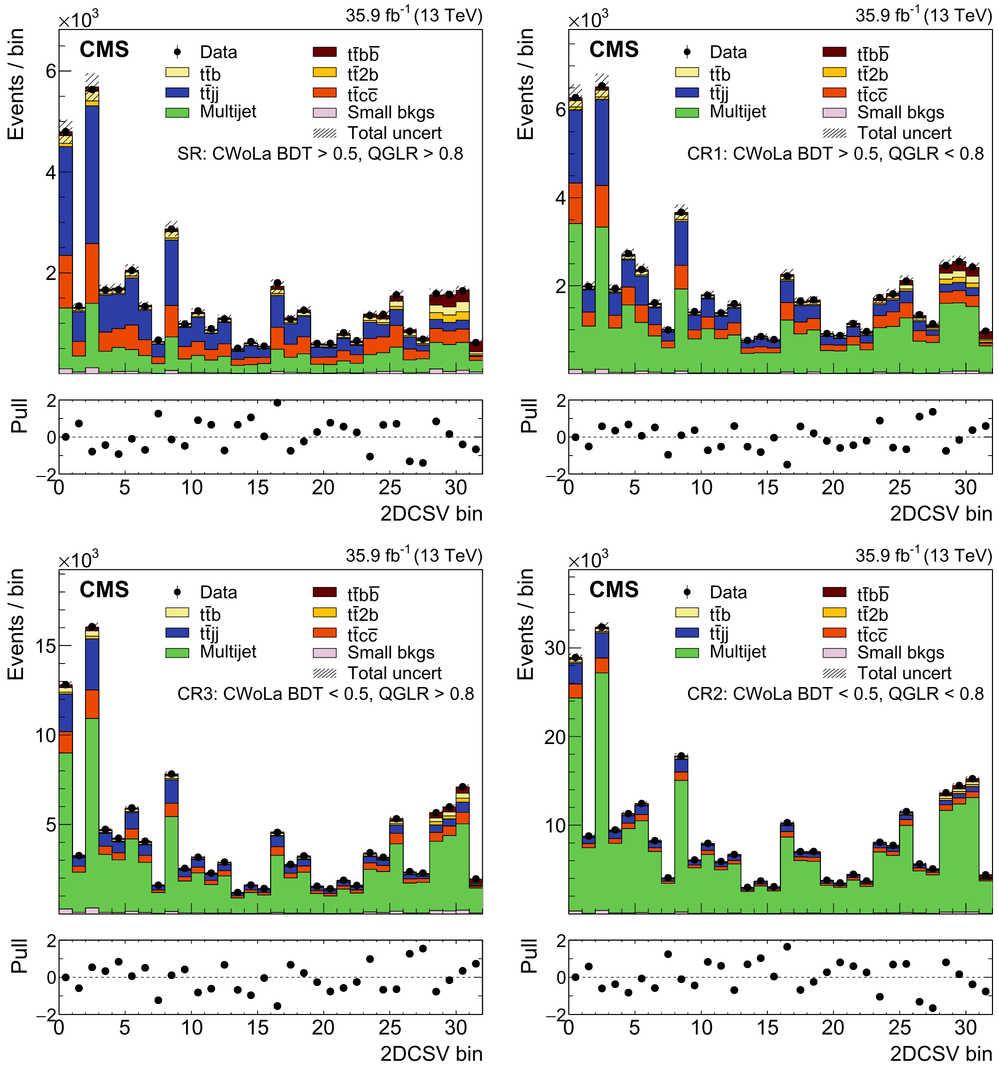

Fig. 2. Distribution in the 2DCSV in the SR (upper left), CR1 (upper right), CR2 (lower right), and CR3 (lower left) regions. For clarity, the two-dimensional distribution with largest and next-to-largest b tagging discriminant scores for the additional jets have been unrolled to one dimension, and the resulting bins ordered according to increasing values of the ratio between expected signal and background yields in each bin of the SR. The small backgrounds include tt̄V, tt̄H, single top quark, V+jets, and diboson production. Hatched bands correspond to uncertainties. The bottom panels show the pull distribution. The pull is defined as the bin by bin difference between data and predicted yields after the fit, divided by the uncertainties accounted for correlations between data and predictions after the fit.

Table 2
Measured and predicted cross sections for the different definitions of the tt̄bb̄ phase space considered in this analysis. For measurements, the first uncertainty is statistical, while the second one is from the systematic sources. The uncertainties in the predicted cross sections include the statistical uncertainty, the PDF uncertainties, and the μ_R and μ_F dependences on changes in scale. The uncertainties in scale for parton showers are not included, and amount to about 15% for POWHEG+PYTHIA. Unless specified otherwise, PYTHIA is used for the modelling the parton shower, hadronization, and the underlying event.

	Fiducial, parton-independent (pb)	Fiducial, parton-based (pb)	Total (pb)
Measurement	$1.6 \pm 0.1^{+0.5}_{-0.4}$	$1.6 \pm 0.1^{+0.5}_{-0.4}$	$5.5 \pm 0.3^{+1.6}_{-1.3}$
POWHEG (tt̄)	1.1 ± 0.2	1.0 ± 0.2	3.5 ± 0.6
POWHEG (tt̄) + HERWIG++	0.8 ± 0.2	0.8 ± 0.2	3.0 ± 0.5
MADGRAPH5_aMC@NLO (4FS tt̄bb̄)	0.8 ± 0.2	0.8 ± 0.2	2.3 ± 0.7
MADGRAPH5_aMC@NLO (5FS tt̄+jets, FxFx)	1.0 ± 0.1	1.0 ± 0.1	3.6 ± 0.3

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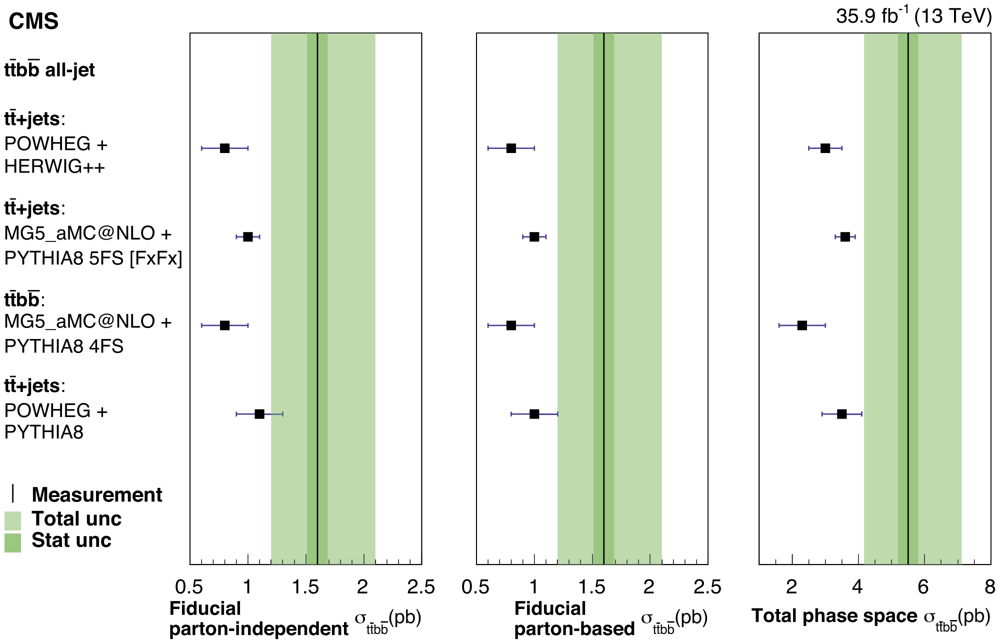

Fig. 3. Comparison of the measured $\mathrm{t\bar{t}b\bar{b}}$ production cross sections (vertical lines) with predictions from several Monte Carlo generators (squares), for three definitions of our $\mathrm{t\bar{t}b\bar{b}}$ regions of phase space: fiducial parton-independent (left), fiducial parton-based (middle), total (right). The dark (light) shaded bands show the statistical (total) uncertainties in the measured value. Uncertainty intervals in the theoretical cross sections include the statistical uncertainty as well as the uncertainties in the PDFs and the μ_{R} and μ_{F} scales.

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The CMS Collaboration

A.M. Sirunyan[†], A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, F. Ambrogi, T. Bergauer, J. Brandstetter, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth[1], M. Jeitler[1], N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, J. Schieck[1], R. Schöfbeck, M. Spanring, D. Spitzbart, W. Waltenberger, C.-E. Wulz[1], M. Zarucki

Institut für Hochenergiephysik, Wien, Austria

V. Drugakov, V. Mossolov, J. Suarez Gonzalez

Institute for Nuclear Problems, Minsk, Belarus

M.R. Darwish, E.A. De Wolf, D. Di Croce, X. Janssen, A. Lelek, M. Pieters, H. Rejeb Sfar, H. Van Haevermaet, P. Van Mechelen, S. Van Putte, N. Van Remortel

Universiteit Antwerpen, Antwerpen, Belgium

F. Blekman, E.S. Bols, S.S. Chhibra, J. D'Hondt, J. De Clercq, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders

Vrije Universiteit Brussel, Brussel, Belgium

D. Beghin, B. Bilin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, L. Favart, A. Grebenyuk, A.K. Kalsi, A. Popov, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom

Université Libre de Bruxelles, Bruxelles, Belgium

T. Cornelis, D. Dobur, I. Khvastunov[2], M. Niedziela, C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

Ghent University, Ghent, Belgium

O. Bondu, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, A. Giammanco, V. Lemaitre, A. Magitteri, J. Prisciandaro, A. Saggio, M. Vidal Marono, P. Vischia, J. Zobec

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

F.L. Alves, G.A. Alves, G. Correia Silva, C. Hensel, A. Moraes, P. Rebello Teles

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato[3], E. Coelho, E.M. Da Costa, G.G. Da Silveira[4], D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, J. Martins[5], D. Matos Figueiredo, M. Medina Jaime[6], M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote[3], F. Torres Da Silva De Araujo, A. Vilela Pereira

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

C.A. Bernardes[a], L. Calligaris[a], T.R. Fernandez Perez Tomei[a], E.M. Gregores[b], D.S. Lemos, P.G. Mercadante[b], S.F. Novaes[a], Sandra S. Padula[a]

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

A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

M. Bonchev, A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov

University of Sofia, Sofia, Bulgaria

W. Fang[7], X. Gao[7], L. Yuan

Beihang University, Beijing, China

M. Ahmad, G.M. Chen, H.S. Chen, M. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, S.M. Shaheen[8], A. Spiezia, J. Tao, E. Yazgan, H. Zhang, S. Zhang[8], J. Zhao

Institute of High Energy Physics, Beijing, China

A. Agapitos, Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang, Q. Wang

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

Z. Hu, Y. Wang

Tsinghua University, Beijing, China

M. Xiao

Zhejiang University, Hangzhou, China

C. Avila, A. Cabrera, C. Florez, C.F. González Hernández, M.A. Segura Delgado

Universidad de Los Andes, Bogota, Colombia

J. Mejia Guisao, J.D. Ruiz Alvarez, C.A. Salazar González, N. Vanegas Arbelaez

Universidad de Antioquia, Medellin, Colombia

D. Giljanović, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

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

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, S. Ceci, D. Ferencek, K. Kadija, B. Mesic, M. Roguljic, A. Starodumov[9], T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

M.W. Ather, A. Attikis, E. Erodotou, A. Ioannou, M. Kolosova, S. Konstantinou, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, D. Tsiakkouri

University of Cyprus, Nicosia, Cyprus

M. Finger[10], M. Finger Jr.[10], A. Kveton, J. Tomsa

Charles University, Prague, Czech Republic

E. Ayala

Escuela Politecnica Nacional, Quito, Ecuador

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

H. Abdalla[11], E. Salama[12,13]

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

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, L. Forthomme, H. Kirschenmann, K. Osterberg, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

F. Garcia, J. Havukainen, J.K. Heikkilä, T. Järvinen, V. Karimäki, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, H. Siikonen, E. Tuominen, J. Tuominiemi

Helsinki Institute of Physics, Helsinki, Finland

T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[14], M. Titov

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

S. Ahuja, C. Amendola, F. Beaudette, P. Busson, C. Charlot, B. Diab, G. Falmagne, R. Granier de Cassagnac, I. Kucher, A. Lobanov, C. Martin Perez, M. Nguyen, C. Ochando, P. Paganini, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A. Zabi, A. Zghiche

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, France

J.-L. Agram[15], J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte[15], J.-C. Fontaine[15], D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France

S. Gadrat

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

S. Beauceron, C. Bernet, G. Boudoul, C. Camen, A. Carle, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, Sa. Jain, F. Lagarde, I.B. Laktineh, H. Lattaud, A. Lesauvage, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, L. Torterotot, G. Touquet, M. Vander Donckt, S. Viret

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

G. Adamov

Georgian Technical University, Tbilisi, Georgia

Z. Tsamalaidze[10]

Tbilisi State University, Tbilisi, Georgia

C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, D. Meuser, A. Pauls, M. Preuten, M.P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer

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

A. Albert, M. Erdmann, B. Fischer, S. Ghosh, T. Hebbeker, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, G. Mocellin, S. Mondal, S. Mukherjee, D. Noll, A. Novak, T. Pook, A. Pozdnyakov, T. Quast, M. Radziej, Y. Rath, H. Reithler, M. Rieger, J. Roemer, A. Schmidt, S.C. Schuler, A. Sharma, S. Wiedenbeck, S. Zaleski

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

G. Flügge, W. Haj Ahmad [16], O. Hlushchenko, T. Kress, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl [17]

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

M. Aldaya Martin, P. Asmuss, I. Babounikau, H. Bakhshiansohi, K. Beernaert, O. Behnke, A. Bermúdez Martínez, D. Bertsche, A.A. Bin Anuar, K. Borras [18], V. Botta, A. Campbell, A. Cardini, P. Connor, S. Consuegra Rodríguez, C. Contreras-Campana, V. Danilov, A. De Wit, M.M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, D. Eckstein, T. Eichhorn, A. Elwood, E. Eren, E. Gallo [19], A. Geiser, A. Grohsjean, M. Guthoff, M. Haranko, A. Harb, A. Jafari, N.Z. Jomhari, H. Jung, A. Kasem [18], M. Kasemann, H. Kaveh, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Leonard, J. Lidrych, K. Lipka, W. Lohmann [20], R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, G. Mittag, J. Mnich, A. Mussgiller, V. Myronenko, D. Pérez Adán, S.K. Pflitsch, D. Pitzl, A. Raspereza, A. Saibel, M. Savitskyi, V. Scheurer, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, H. Tholen, O. Turkot, A. Vagnerini, M. Van De Klundert, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev, R. Zlebcik

Deutsches Elektronen-Synchrotron, Hamburg, Germany

R. Aggleton, S. Bein, L. Benato, A. Benecke, V. Blobel, T. Dreyer, A. Ebrahimi, F. Feindt, A. Fröhlich, C. Garbers, E. Garutti, D. Gonzalez, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, T. Lange, A. Malara, J. Multhaup, C.E.N. Niemeyer, A. Perieanu, A. Reimers, O. Rieger, C. Scharf, P. Schleper, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, B. Vormwald, I. Zoi

University of Hamburg, Hamburg, Germany

M. Akbiyik, C. Barth, M. Baselga, S. Baur, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, M. Giffels, P. Goldenzweig, A. Gottmann, M.A. Harrendorf, F. Hartmann [17], U. Husemann, S. Kudella, S. Mitra, M.U. Mozer, D. Müller, Th. Müller, M. Musich, A. Nürnberg, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, H.J. Simonis, R. Ulrich, M. Wassmer, M. Weber, C. Wöhrmann, R. Wolf

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

G. Anagnostou, P. Asenov, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki

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

M. Diamantopoulou, G. Karathanasis, P. Kontaxakis, A. Manousakis-katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, A. Stakia, K. Theofilatos, K. Vellidis, E. Vourliotis

National and Kapodistrian University of Athens, Athens, Greece

G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

National Technical University of Athens, Athens, Greece

I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, K. Manitara, N. Manthos, I. Papadopoulos, J. Strologas, F.A. Triantis, D. Tsitsonis

University of Ioánnina, Ioánnina, Greece

M. Bartók[21], R. Chudasama, M. Csanad, P. Major, K. Mandal, A. Mehta, M.I. Nagy, G. Pasztor, O. Surányi, G.I. Veres

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

G. Bencze, C. Hajdu, D. Horvath[22], F. Sikler, T.Á. Vámi, V. Veszpremi, G. Vesztergombi[†]

Wigner Research Centre for Physics, Budapest, Hungary

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

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

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

Institute of Physics, University of Debrecen, Debrecen, Hungary

T. Csorgo, W.J. Metzger, F. Nemes, T. Novak

Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary

S. Choudhury, J.R. Komaragiri, P.C. Tiwari

Indian Institute of Science (IISc), Bangalore, India

S. Bahinipati[23], C. Kar, G. Kole, P. Mal, V.K. Muraleedharan Nair Bindhu, A. Nayak[24], D.K. Sahoo[23], S.K. Swain

National Institute of Science Education and Research, HBNI, Bhubaneswar, India

S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, M. Kaur, S. Kaur, P. Kumari, M. Lohan, M. Meena, K. Sandeep, S. Sharma, J.B. Singh, A.K. Virdi, G. Walia

Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India

R. Bhardwaj[25], M. Bharti[25], R. Bhattacharya, S. Bhattacharya, U. Bhawandeep[25], D. Bhowmik, S. Dutta, S. Ghosh, M. Maity[26], K. Mondal, S. Nandan, A. Purohit, P.K. Rout, G. Saha, S. Sarkar, T. Sarkar[26], M. Sharan, B. Singh[25], S. Thakur[25]

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

P.K. Behera, P. Kalbhor, A. Muhammad, P.R. Pujahari, A. Sharma, A.K. Sikdar

Indian Institute of Technology Madras, Madras, India

D. Dutta, V. Jha, V. Kumar, D.K. Mishra, P.K. Netrakanti, L.M. Pant, P. Shukla

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, Ravindra Kumar Verma

Tata Institute of Fundamental Research-A, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, N. Sahoo, S. Sawant

Tata Institute of Fundamental Research-B, Mumbai, India

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

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

S. Chenarani[27], E. Eskandari Tadavani, S.M. Etesami[27], M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi

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

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia[a,b], R. Aly[a,b,28], C. Calabria[a,b], A. Colaleo[a], D. Creanza[a,c], L. Cristella[a,b], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,b], L. Fiore[a], A. Gelmi[a,b], G. Iaselli[a,c], M. Ince[a,b], S. Lezki[a,b], G. Maggi[a,c], M. Maggi[a], G. Miniello[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a], A. Ranieri[a], G. Selvaggi[a,b], L. Silvestris[a], R. Venditti[a], P. Verwilligen[a]

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

G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], L. Borgonovi[a,b], S. Braibant-Giacomelli[a,b], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], C. Ciocca[a], G. Codispoti[a,b], M. Cuffiani[a,b], G.M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], E. Fontanesi[a,b], P. Giacomelli[a], C. Grandi[a], L. Guiducci[a,b], F. Iemmi[a,b], S. Lo Meo[a,29], S. Marcellini[a], G. Masetti[a], F.L. Navarria[a,b], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], T. Rovelli[a,b], G.P. Siroli[a,b], N. Tosi[a]

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

S. Albergo[a,b,30], S. Costa[a,b], A. Di Mattia[a], R. Potenza[a,b], A. Tricomi[a,b,30], C. Tuve[a,b]

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

G. Barbagli[a], A. Cassese, R. Ceccarelli, K. Chatterjee[a,b], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], G. Latino[a,b], P. Lenzi[a,b], M. Meschini[a], S. Paoletti[a], G. Sguazzoni[a], L. Viliani[a]

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

L. Benussi, S. Bianco, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

M. Bozzo[a,b], F. Ferro[a], R. Mulargia[a,b], E. Robutti[a], S. Tosi[a,b]

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

A. Benaglia[a], A. Beschi[a,b], F. Brivio[a,b], V. Ciriolo[a,b,17], S. Di Guida[a,b,17], M.E. Dinardo[a,b], P. Dini[a], S. Gennai[a], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a,b], M. Malberti[a], S. Malvezzi[a], D. Menasce[a], F. Monti[a,b], L. Moroni[a], G. Ortona[a,b], M. Paganoni[a,b], D. Pedrini[a], S. Ragazzi[a,b], T. Tabarelli de Fatis[a,b], D. Zuolo[a,b]

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

S. Buontempo[a], N. Cavallo[a,c], A. De Iorio[a,b], A. Di Crescenzo[a,b], F. Fabozzi[a,c], F. Fienga[a], G. Galati[a], A.O.M. Iorio[a,b], L. Lista[a,b], S. Meola[a,d,17], P. Paolucci[a,17], B. Rossi[a], C. Sciacca[a,b], E. Voevodina[a,b]

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

P. Azzi[a], N. Bacchetta[a], D. Bisello[a,b], A. Boletti[a,b], A. Bragagnolo[a,b], R. Carlin[a,b], P. Checchia[a], P. De Castro Manzano[a], T. Dorigo[a], U. Dosselli[a], F. Gasparini[a,b], U. Gasparini[a,b], A. Gozzelino[a], S.Y. Hoh[a,b], P. Lujan[a], M. Margoni[a,b], A.T. Meneguzzo[a,b], J. Pazzini[a,b], M. Presilla[b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], A. Tiko[a], M. Tosi[a,b], M. Zanetti[a,b], P. Zotto[a,b], G. Zumerle[a,b]

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

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

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

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

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

K. Androsov[a], P. Azzurri[a], G. Bagliesi[a], V. Bertacchi[a,c], L. Bianchini[a], T. Boccali[a], R. Castaldi[a], M.A. Ciocci[a,b], R. Dell'Orso[a], G. Fedi[a], L. Giannini[a,c], A. Giassi[a], M.T. Grippo[a], F. Ligabue[a,c], E. Manca[a,c], G. Mandorli[a,c], A. Messineo[a,b], F. Palla[a], A. Rizzi[a,b], G. Rolandi[31], S. Roy Chowdhury, A. Scribano[a], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], N. Turini, A. Venturi[a], P.G. Verdini[a]

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

F. Cavallari[a], M. Cipriani[a,b], D. Del Re[a,b], E. Di Marco[a,b], M. Diemoz[a], E. Longo[a,b], B. Marzocchi[a,b], P. Meridiani[a], G. Organtini[a,b], F. Pandolfi[a], R. Paramatti[a,b], C. Quaranta[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], L. Soffi[a,b]

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

N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a], R. Bellan[a,b], A. Bellora, C. Biino[a], A. Cappati[a,b], N. Cartiglia[a], S. Cometti[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], B. Kiani[a,b], C. Mariotti[a], S. Maselli[a], E. Migliore[a,b], V. Monaco[a,b], E. Monteil[a,b], M. Monteno[a], M.M. Obertino[a,b], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], G.L. Pinna Angioni[a,b], A. Romero[a,b], M. Ruspa[a,c], R. Salvatico[a,b], V. Sola[a], A. Solano[a,b], D. Soldi[a,b], A. Staiano[a]

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

S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], A. Da Rold[a,b], G. Della Ricca[a,b], F. Vazzoler[a,b], A. Zanetti[a]

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

B. Kim, D.H. Kim, G.N. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, S. Sekmen, D.C. Son, Y.C. Yang

Kyungpook National University, Daegu, Republic of Korea

H. Kim, D.H. Moon, G. Oh

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

B. Francois, T.J. Kim, J. Park

Hanyang University, Seoul, Republic of Korea

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

Korea University, Seoul, Republic of Korea

J. Goh

Kyung Hee University, Department of Physics, Republic of Korea

H.S. Kim

Sejong University, Seoul, Republic of Korea

J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, H. Lee, K. Lee, S. Lee, K. Nam, M. Oh, S.B. Oh, B.C. Radburn-Smith, U.K. Yang, H.D. Yoo, I. Yoon, G.B. Yu

Seoul National University, Seoul, Republic of Korea

D. Jeon, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park, I.J. Watson

University of Seoul, Seoul, Republic of Korea

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

Sungkyunkwan University, Suwon, Republic of Korea

V. Veckalns[32]

Riga Technical University, Riga, Latvia

V. Dudenas, A. Juodagalvis, G. Tamulaitis, J. Vaitkus

Vilnius University, Vilnius, Lithuania

Z.A. Ibrahim, F. Mohamad Idris[33], W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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

J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada, L. Valencia Palomo

Universidad de Sonora (UNISON), Hermosillo, Mexico

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz[34], R. Lopez-Fernandez, A. Sanchez-Hernandez

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

S. Carrillo Moreno, C. Oropeza Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

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

J. Mijuskovic, N. Raicevic

University of Montenegro, Podgorica, Montenegro

D. Krofcheck

University of Auckland, Auckland, New Zealand

S. Bheesette, P.H. Butler

University of Canterbury, Christchurch, New Zealand

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

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

V. Avati, L. Grzanka, M. Malawski

AGH University of Science and Technology, Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland

H. Bialkowska, M. Bluj, B. Boimska, M. Górski, M. Kazana, M. Szleper, P. Zalewski

National Centre for Nuclear Research, Swierk, Poland

K. Bunkowski, A. Byszuk[35], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, M. Walczak

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

M. Araujo, P. Bargassa, D. Bastos, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, J. Seixas, K. Shchelina, G. Strong, O. Toldaiev, J. Varela

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

V. Alexakhin, P. Bunin, Y. Ershov, I. Golutvin, A. Kamenev, V. Karjavine, I. Kashunin, G. Kozlov, A. Lanev, A. Malakhov, V. Matveev[36,37], V.V. Mitsyn, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, O. Teryaev, N. Voytishin, B.S. Yuldashev[38], A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

L. Chtchipounov, V. Golovtcov, Y. Ivanov, V. Kim[39], E. Kuznetsova[40], P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, A. Vorobyev

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

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

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, A. Nikitenko[41], V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepennov, M. Toms, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia

T. Aushev

Moscow Institute of Physics and Technology, Moscow, Russia

O. Bychkova, R. Chistov[42], M. Danilov[42], S. Polikarpov[42], E. Tarkovskii

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

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin[43], L. Dudko, V. Klyukhin, N. Korneeva, I. Lokhtin, S. Obraztsov, M. Perfilov, V. Savrin, P. Volkov

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

A. Barnyakov[44], V. Blinov[44], T. Dimova[44], L. Kardapoltsev[44], Y. Skovpen[44]

Novosibirsk State University (NSU), Novosibirsk, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia

A. Babaev, A. Iuzhakov, V. Okhotnikov

National Research Tomsk Polytechnic University, Tomsk, Russia

V. Borchsh, V. Ivanchenko, E. Tcherniaev

Tomsk State University, Tomsk, Russia

P. Adzic[45], P. Cirkovic, D. Devetak, M. Dordevic, P. Milenovic, J. Milosevic, M. Stojanovic

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

M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, J.A. Brochero Cifuentes, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, Á. Navarro Tobar, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M.S. Soares, A. Triossi, C. Willmott

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

C. Albajar, J.F. de Trocóniz, R. Reyes-Almanza

Universidad Autónoma de Madrid, Madrid, Spain

B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, V. Rodríguez Bouza, S. Sanchez Cruz

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain

I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, A. García Alonso, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Russo[46], L. Scodellaro, N. Trevisani, I. Vila, J.M. Vizan Garcia

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

K. Malagalage

University of Colombo, Colombo, Sri Lanka

W.G.D. Dharmaratna, N. Wickramage

University of Ruhuna, Department of Physics, Matara, Sri Lanka

D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, J. Baechler, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, P. Bortignon, E. Bossini, C. Botta, E. Brondolin, T. Camporesi, A. Caratelli, G. Cerminara, E. Chapon, G. Cucciati, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, O. Davignon, A. De Roeck, N. Deelen, M. Deile, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita[47], D. Fasanella, S. Fiorendi, G. Franzoni, J. Fulcher, W. Funk, S. Giani, D. Gigi, A. Gilbert, K. Gill, F. Glege, M. Gruchala, M. Guilbaud, D. Gulhan, J. Hegeman, C. Heidegger, Y. Iiyama, V. Innocente, P. Janot, O. Karacheban[20], J. Kaspar, J. Kieseler, M. Krammer[1], N. Kratochwil, C. Lange, P. Lecoq, C. Lourenço, L. Malgeri, M. Mannelli, A. Massironi, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, J. Ngadiuba, J. Niedziela, S. Nourbakhsh, S. Orfanelli, L. Orsini, F. Pantaleo[17], L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabady, A. Racz, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas[48], J. Steggemann, S. Summers, V.R. Tavolaro, D. Treille, A. Tsirou, A. Vartak, M. Verzetti, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

L. Caminada[49], K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

Paul Scherrer Institut, Villigen, Switzerland

M. Backhaus, P. Berger, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T.A. Gómez Espinosa, C. Grab, D. Hits, T. Klijnsma, W. Lustermann, R.A. Manzoni, M. Marionneau, M.T. Meinhard, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pauss, G. Perrin, L. Perrozzi, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland

T.K. Aarrestad, C. Amsler[50], D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, B. Kilminster, S. Leontsinis, V.M. Mikuni, I. Neutelings, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, S. Wertz, A. Zucchetta

Universität Zürich, Zurich, Switzerland

T.H. Doan, C.M. Kuo, W. Lin, A. Roy, S.S. Yu

National Central University, Chung-Li, Taiwan

P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas, N. Suwonjandee

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

A. Bat, F. Boran, A. Celik[51], S. Damarseckin[52], Z.S. Demiroglu, F. Dolek, C. Dozen, I. Dumanoglu, E. Eskut, G. Gokbulut, Emine Gurpinar Guler[53], Y. Guler, I. Hos[54], C. Isik, E.E. Kangal[55], O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir[56], S. Ozturk[57], A.E. Simsek, D. Sunar Cerci[58], U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

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

B. Isildak[59], G. Karapinar[60], M. Yalvac

Middle East Technical University, Physics Department, Ankara, Turkey

I.O. Atakisi, E. Gülmez, M. Kaya[61], O. Kaya[62], Ö. Özçelik, S. Tekten, E.A. Yetkin[63]

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak, Y. Komurcu, S. Sen[64]

Istanbul Technical University, Istanbul, Turkey

B. Kaynak, S. Ozkorucuklu

Istanbul University, Istanbul, Turkey

B. Grynyov

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

L. Levchuk

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

F. Ball, E. Bhal, S. Bologna, J.J. Brooke, D. Burns[65], E. Clement, D. Cussans, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, S. Paramesvaran, B. Penning, T. Sakuma, S. Seif El Nasr-Storey, V.J. Smith, J. Taylor, A. Titterton

University of Bristol, Bristol, United Kingdom

K.W. Bell, A. Belyaev[66], C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, Gurpreet Singh Chahal [67], D. Colling, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, P. Everaerts, G. Hall, G. Iles, T. James, M. Komm, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, V. Milosevic, J. Nash [68], V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, M. Stoye, T. Strebler, A. Tapper, K. Uchida, T. Virdee [17], N. Wardle, D. Winterbottom, J. Wright, A.G. Zecchinelli, S.C. Zenz

Imperial College, London, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, A. Morton, I.D. Reid, L. Teodorescu, S. Zahid

Brunel University, Uxbridge, United Kingdom

K. Call, B. Caraway, J. Dittmann, K. Hatakeyama, C. Madrid, B. McMaster, N. Pastika, C. Smith

Baylor University, Waco, USA

R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

Catholic University of America, Washington, DC, USA

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

The University of Alabama, Tuscaloosa, USA

D. Arcaro, Z. Demiragli, D. Gastler, S. Girgis, D. Pinna, C. Richardson, J. Rohlf, D. Sperka, I. Suarez, L. Sulak, D. Zou

Boston University, Boston, USA

G. Benelli, B. Burkle, X. Coubez [18], D. Cutts, Y.t. Duh, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan [69], K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, S. Sagir [70], R. Syarif, E. Usai, D. Yu, W. Zhang

Brown University, Providence, USA

R. Band, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, F. Jensen, W. Ko, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, M. Shi, D. Taylor, K. Tos, M. Tripathi, Z. Wang, F. Zhang

University of California, Davis, Davis, USA

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, W.A. Nash, S. Regnard, D. Saltzberg, C. Schnaible, B. Stone, V. Valuev

University of California, Los Angeles, USA

K. Burt, Y. Chen, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, E. Kennedy, O.R. Long, M. Olmedo Negrete, M.I. Paneva, W. Si, L. Wang, S. Wimpenny, B.R. Yates, Y. Zhang

University of California, Riverside, Riverside, USA

J.G. Branson, P. Chang, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, D. Klein, V. Krutelyov, J. Letts, M. Masciovecchio, S. May, S. Padhi, M. Pieri, V. Sharma, M. Tadel, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, San Diego, La Jolla, USA

N. Amin, R. Bhandari, C. Campagnari, M. Citron, V. Dutta, M. Franco Sevilla, L. Gouskos, J. Incandela, B. Marsh, H. Mei, A. Ovcharova, H. Qu, J. Richman, U. Sarica, D. Stuart, S. Wang

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

D. Anderson, A. Bornheim, O. Cerri, I. Dutta, J.M. Lawhorn, N. Lu, J. Mao, H.B. Newman, T.Q. Nguyen, J. Pata, M. Spiropulu, J.R. Vlimant, S. Xie, Z. Zhang, R.Y. Zhu

California Institute of Technology, Pasadena, USA

M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, W.T. Ford, A. Johnson, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

University of Colorado Boulder, Boulder, USA

J. Alexander, J. Chaves, Y. Cheng, J. Chu, A. Datta, A. Frankenthal, K. Mcdermott, J.R. Patterson, D. Quach, A. Rinkevicius [71], A. Ryd, S.M. Tan, Z. Tao, J. Thom, P. Wittich, M. Zientek

Cornell University, Ithaca, USA

S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, Allison Reinsvold Hall, J. Hanlon, R.M. Harris, S. Hasegawa, R. Heller, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, J. Lewis, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, V. Papadimitriou, K. Pedro, C. Pena, G. Rakness, F. Ravera, L. Ristori, B. Schneider, E. Sexton-Kennedy, N. Smith, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, R. Vidal, M. Wang, H.A. Weber

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, D. Bourilkov, A. Brinkerhoff, L. Cadamuro, A. Carnes, V. Cherepanov, D. Curry, F. Errico, R.D. Field, S.V. Gleyzer, B.M. Joshi, M. Kim, J. Konigsberg, A. Korytov, K.H. Lo, P. Ma, K. Matchev, N. Menendez, G. Mitselmakher, D. Rosenzweig, K. Shi, J. Wang, S. Wang, X. Zuo

University of Florida, Gainesville, USA

Y.R. Joshi

Florida International University, Miami, USA

T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, R. Khurana, T. Kolberg, G. Martinez, T. Perry, H. Prosper, C. Schiber, R. Yohay, J. Zhang

Florida State University, Tallahassee, USA

M.M. Baarmand, M. Hohlmann, D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, C. Mills, T. Roy, M.B. Tonjes, N. Varelas, J. Viinikainen, H. Wang, X. Wang, Z. Wu

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

M. Alhusseini, B. Bilki [53], W. Clarida, K. Dilsiz [72], S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili [73], A. Moeller, J. Nachtman, H. Ogul [74], Y. Onel, F. Ozok [75], A. Penzo, C. Snyder, E. Tiras, J. Wetzel

The University of Iowa, Iowa City, USA

B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, W.T. Hung, P. Maksimovic, J. Roskes, M. Swartz

Johns Hopkins University, Baltimore, USA

C. Baldenegro Barrera, P. Baringer, A. Bean, S. Boren, J. Bowen, A. Bylinkin, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, C. Lindsey, D. Majumder, W. Mcbrayer, N. Minafra, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang, J. Williams, G. Wilson

The University of Kansas, Lawrence, USA

S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi

Kansas State University, Manhattan, USA

F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, S. Nabili, F. Ricci-Tam, M. Seidel, Y.H. Shin, A. Skuja, S.C. Tonwar, K. Wong

University of Maryland, College Park, USA

D. Abercrombie, B. Allen, A. Baty, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, M. Klute, D. Kovalskyi, Y.-J. Lee, P.D. Luckey, B. Maier, A.C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

Massachusetts Institute of Technology, Cambridge, USA

A.C. Benvenuti[†], R.M. Chatterjee, A. Evans, S. Guts, P. Hansen, J. Hiltbrand, Y. Kubota, Z. Lesko, J. Mans, R. Rusack, M.A. Wadud

University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

K. Bloom, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J.E. Siado, G.R. Snow[†], B. Stieger, W. Tabb

University of Nebraska-Lincoln, Lincoln, USA

G. Agarwal, C. Harrington, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, A. Parker, J. Pekkanen, S. Rappoccio, B. Roozbahani

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, G. Madigan, D.M. Morse, T. Orimoto, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northeastern University, Boston, USA

S. Bhattacharya, J. Bueghly, T. Gunter, K.A. Hahn, N. Odell, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

Northwestern University, Evanston, USA

R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, K. Lannon, W. Li, N. Loukas, N. Marinelli, I. Mcalister, F. Meng, C. Mueller, Y. Musienko[36], M. Planer, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

University of Notre Dame, Notre Dame, USA

J. Alimena, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, C. Hill, W. Ji, A. Lefeld, T.Y. Ling, B.L. Winer

The Ohio State University, Columbus, USA

S. Cooperstein, G. Dezoort, P. Elmer, J. Hardenbrook, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, S. Kwan, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, J. Salfeld-Nebgen, D. Stickland, C. Tully, Z. Wang

Princeton University, Princeton, USA

S. Malik, S. Norberg

University of Puerto Rico, Mayaguez, USA

A. Barker, V.E. Barnes, S. Das, L. Gutay, M. Jones, A.W. Jung, A. Khatiwada, B. Mahakud, D.H. Miller, G. Negro, N. Neumeister, C.C. Peng, S. Piperov, H. Qiu, J.F. Schulte, J. Sun, F. Wang, R. Xiao, W. Xie

Purdue University, West Lafayette, USA

T. Cheng, J. Dolen, N. Parashar

Purdue University Northwest, Hammond, USA

U. Behrens, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, Arun Kumar, W. Li, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, W. Shi, A.G. Stahl Leiton, Z. Tu, A. Zhang

Rice University, Houston, USA

A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, E. Ranken, P. Tan, R. Taus

University of Rochester, Rochester, USA

B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, S. Kyriacou, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S. Thomas

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

H. Acharya, A.G. Delannoy, G. Riley, S. Spanier

University of Tennessee, Knoxville, USA

O. Bouhali[76], M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[77], S. Luo, D. Marley, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov

Texas A&M University, College Station, USA

N. Akchurin, J. Damgov, F. De Guio, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang, A. Whitbeck

Texas Tech University, Lubbock, USA

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij

Vanderbilt University, Nashville, USA

M.W. Arenton, P. Barria, B. Cox, G. Cummings, R. Hirosky, M. Joyce, A. Ledovskoy, C. Neu, B. Tannenwald, Y. Wang, E. Wolfe, F. Xia

University of Virginia, Charlottesville, USA

R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa

Wayne State University, Detroit, USA

T. Bose, J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, I. De Bruyn, L. Dodd, F. Fiori, C. Galloni, B. Gomber[78], H. He, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, A. Loeliger, K. Long,

R. Loveless, J. Madhusudanan Sreekala, T. Ruggles, A. Savin, V. Sharma, W.H. Smith, D. Teague, S. Trembath-reichert, N. Woods

University of Wisconsin - Madison, Madison, WI, USA

[†] Deceased.
[1] Also at Vienna University of Technology, Vienna, Austria.
[2] Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.
[3] Also at Universidade Estadual de Campinas, Campinas, Brazil.
[4] Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.
[5] Also at UFMS, Nova Andradina, Brazil.
[6] Also at Universidade Federal de Pelotas, Pelotas, Brazil.
[7] Also at Université Libre de Bruxelles, Bruxelles, Belgium.
[8] Also at University of Chinese Academy of Sciences, Beijing, China.
[9] Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia.
[10] Also at Joint Institute for Nuclear Research, Dubna, Russia.
[11] Also at Cairo University, Cairo, Egypt.
[12] Also at British University in Egypt, Cairo, Egypt.
[13] Now at Ain Shams University, Cairo, Egypt.
[14] Also at Purdue University, West Lafayette, USA.
[15] Also at Université de Haute Alsace, Mulhouse, France.
[16] Also at Erzincan Binali Yildirim University, Erzincan, Turkey.
[17] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[18] Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[19] Also at University of Hamburg, Hamburg, Germany.
[20] Also at Brandenburg University of Technology, Cottbus, Germany.
[21] Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
[22] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[23] Also at IIT Bhubaneswar, Bhubaneswar, India.
[24] Also at Institute of Physics, Bhubaneswar, India.
[25] Also at Shoolini University, Solan, India.
[26] Also at University of Visva-Bharati, Santiniketan, India.
[27] Also at Isfahan University of Technology, Isfahan, Iran.
[28] Now at INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy.
[29] Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.
[30] Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.
[31] Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy.
[32] Also at Riga Technical University, Riga, Latvia.
[33] Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
[34] Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
[35] Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
[36] Also at Institute for Nuclear Research, Moscow, Russia.
[37] Now at National Research Nuclear University ’Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia.
[38] Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.
[39] Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
[40] Also at University of Florida, Gainesville, USA.
[41] Also at Imperial College, London, United Kingdom.
[42] Also at P.N. Lebedev Physical Institute, Moscow, Russia.
[43] Also at California Institute of Technology, Pasadena, USA.
[44] Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
[45] Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
[46] Also at Università degli Studi di Siena, Siena, Italy.
[47] Also at INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy.
[48] Also at National and Kapodistrian University of Athens, Athens, Greece.
[49] Also at Universität Zürich, Zurich, Switzerland.
[50] Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
[51] Also at Burdur Mehmet Akif Ersoy University, BURDUR, Turkey.
[52] Also at Şırnak University, Sirnak, Turkey.
[53] Also at Beykent University, Istanbul, Turkey.
[54] Also at Istanbul Aydin University, Istanbul, Turkey.
[55] Also at Mersin University, Mersin, Turkey.
[56] Also at Piri Reis University, Istanbul, Turkey.
[57] Also at Gaziosmanpasa University, Tokat, Turkey.
[58] Also at Adiyaman University, Adiyaman, Turkey.
[59] Also at Ozyegin University, Istanbul, Turkey.
[60] Also at Izmir Institute of Technology, Izmir, Turkey.
[61] Also at Marmara University, Istanbul, Turkey.
[62] Also at Kafkas University, Kars, Turkey.
[63] Also at Istanbul Bilgi University, Istanbul, Turkey.
[64] Also at Hacettepe University, Ankara, Turkey.

[65] Also at Vrije Universiteit Brussel, Brussel, Belgium.
[66] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[67] Also at IPPP Durham University, Durham, United Kingdom.
[68] Also at Monash University, Faculty of Science, Clayton, Australia.
[69] Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA.
[70] Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
[71] Also at Vilnius University, Vilnius, Lithuania.
[72] Also at Bingol University, Bingol, Turkey.
[73] Also at Georgian Technical University, Tbilisi, Georgia.
[74] Also at Sinop University, Sinop, Turkey.
[75] Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
[76] Also at Texas A&M University at Qatar, Doha, Qatar.
[77] Also at Kyungpook National University, Daegu, Republic of Korea.
[78] Also at University of Hyderabad, Hyderabad, India.