

CERN-EP-2023-014
2023/07/28

CMS-TOP-21-005

Evidence for four-top quark production in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

The production of four top quarks ($t\bar{t}t\bar{t}$) is studied with LHC proton-proton collision data samples collected by the CMS experiment at a center-of-mass energy of 13 TeV, and corresponding to integrated luminosities of up to 138 fb^{-1} . Events that have no leptons (all-hadronic), one lepton, or two opposite-sign leptons (where lepton refers only to prompt electrons or prompt muons) are considered. This is the first $t\bar{t}t\bar{t}$ measurement that includes the all-hadronic final state. The observed significance of the $t\bar{t}t\bar{t}$ signal in these final states of 3.9 standard deviations (1.5 expected) provides evidence for $t\bar{t}t\bar{t}$ production, with a measured cross section of $36^{+12}_{-11} \text{ fb}$. Combined with earlier CMS results in other final states, the signal significance is 4.0 standard deviations (3.2 expected). The combination returns an observed cross section of $17 \pm 4 \text{ (stat)} \pm 3 \text{ (syst)} \text{ fb}$, which is consistent with the standard model prediction.

We dedicate this publication to our friends and colleagues Meenakshi Narain and Stephen Wimpenny, who passed away unexpectedly while this paper was in preparation. This work would not have been possible without their guidance and contributions.

Published in Physics Letters B as doi:10.1016/j.physletb.2023.138076.

1 Introduction

The production of four top quarks ($t\bar{t}t\bar{t}$) is predicted to occur very rarely in the standard model (SM). In proton-proton (pp) collisions at $\sqrt{s} = 13$ TeV, the production cross section has been calculated to be $12.0^{+2.2}_{-2.5}$ fb at next-to-leading order (NLO) in quantum chromodynamics (QCD) and electroweak (EW) contributions [1–5]. Examples of the SM lowest order contributions to $t\bar{t}t\bar{t}$ production in pp collisions are shown in Fig. 1.

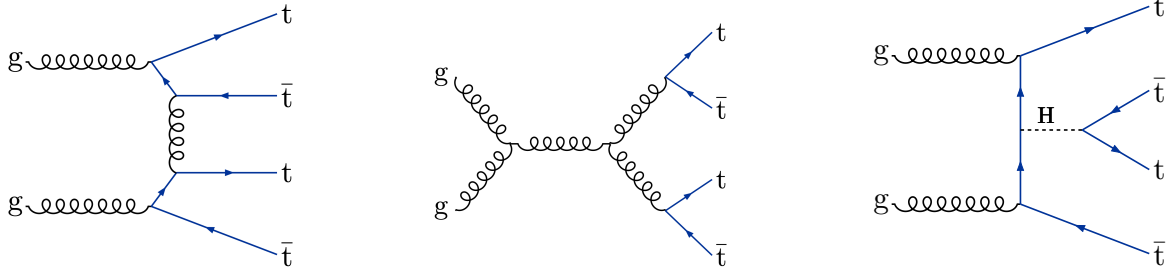


Figure 1: Examples of Feynman diagrams for $t\bar{t}t\bar{t}$ production at leading order in the SM.

Deviations from the predicted value occur in many proposed models of physics beyond the SM, such as supersymmetry [6, 7], composite models [8], top quark compositeness [9], two Higgs doublet models [10–12], and models with extra spatial dimensions [13, 14]. Measurements of $t\bar{t}t\bar{t}$ production can also be used to constrain the top quark Yukawa coupling, CP -related parameters, and effective field theory operators [15].

In the SM, the top quark dominantly decays to a bottom quark and a W boson. Each W boson decays to either leptons or quarks, so the $t\bar{t}t\bar{t}$ final state consists of four bottom quarks and up to four leptonic W boson decays. No analyses described or cited in this Letter attempt to explicitly identify τ lepton products and hence hereafter “lepton” will refer only to e and μ , whether produced directly in $W \rightarrow e/\mu + \nu$ decays or via $W \rightarrow \tau + \nu$ with $\tau \rightarrow e/\mu + 2\nu$.

The production of $t\bar{t}t\bar{t}$ has been searched for by both ATLAS [16–18] and CMS [19–22] at the CERN LHC. The ATLAS Collaboration has reported evidence for $t\bar{t}t\bar{t}$ production in final states with either two same-sign leptons or at least three leptons (referred to as “SSDL&ML”) [18], with an observed significance of 4.3 standard deviations (2.4 expected) and a measured production cross section of 24^{+7}_{-6} fb (assuming SM branching ratios). The significance observed in searches for $t\bar{t}t\bar{t}$ production by the CMS Collaboration in similar SSDL&ML final states is 2.6 standard deviations (2.7 expected), with a measured production cross section of $12.6^{+5.8}_{-5.2}$ fb, using data collected in 2016–2018 with an integrated luminosity of 138 fb^{-1} [21]. The CMS Collaboration has also reported an observed significance of 1.4 standard deviations and a measured production cross section of 13^{+11}_{-9} fb in final states with one lepton or two opposite-sign leptons, using data collected in 2016 with an integrated luminosity of 38 fb^{-1} [22].

In this Letter, we present a search by the CMS Collaboration for the production of $t\bar{t}t\bar{t}$ in final states with zero leptons (all-hadronic), one lepton (single-lepton), or two opposite-sign leptons (referred to as “opposite-sign dileptons” or “OSDL”). The search uses data samples of pp collision data collected in 2016–2018 at $\sqrt{s} = 13$ TeV, with integrated luminosities of up to 138 fb^{-1} [23–25]. To discriminate the $t\bar{t}t\bar{t}$ signal events from the dominant background of $t\bar{t}$ production we take advantage of the higher multiplicity of jets, particularly those produced by the hadronization of b quarks. Events are required to have at least three candidate b jets in the single-lepton and all-hadronic final states, and at least two candidate b jets in the OSDL final state.

The all-hadronic final state was not used in previous measurements because of the difficulty of modeling the QCD multijet background in the relevant kinematic regions. Utilizing this channel for the first time is made possible by a novel background estimation strategy that uses a deep neural network (DNN) to estimate background distributions from data in control regions (CRs). The analyses of channels with leptons in the final state improve upon previous results by taking advantage of the increased integrated luminosity, upgraded detectors, and improved algorithms for the identification of bottom and top quarks. The results are combined with the previous SSdL&ML CMS results [21], which are also based on the 2016–2018 data set but use non-overlapping data regions (including CRs) to ensure statistical independence. Tabulated results are provided in the HEPData record for this analysis [26].

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid providing a magnetic field of 3.8 T, and enclosing a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A two-level trigger system reduces the rate of events retained for further processing to around 1 kHz. The first-level trigger is composed of custom hardware processors, using information from the calorimeters and muon detectors [27]. The software-based high-level trigger [28] uses the full event information. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [29].

3 Simulated event samples

Signal and background processes are modeled using several Monte Carlo event generators. Multiple simulated minimum bias interactions within the same or nearby bunch crossings (pileup) are superimposed on the hard scattering process with the multiplicity distribution matched to the data. Signal events are generated using the MADGRAPH5_aMC@NLO generator [1] versions 2.2.2 (2016) and 2.4.2 (2017–2018) in a tree-level approximation, with emission of up to two additional partons in matrix element calculations. Inclusive $t\bar{t}$ production is generated at NLO precision using POWHEG v2 [30–32]. Smaller contributions from $t\bar{t}$ production in association with one or two bosons (H, W, Z, WH, ZH, WW, WZ, ZZ), W and Z production, triple top quark production ($t\bar{t}t$, $t\bar{t}tW$), single top quark (tW) production, and Drell–Yan processes constitute the remaining backgrounds, particularly where additional hadronic jets are produced by QCD radiation [21]. Single top and $t\bar{t} + H$ processes are simulated using POWHEG at NLO, while the other smaller contributions are simulated using MADGRAPH5_aMC@NLO versions 2.2.2 (2016) and 2.4.2 (2017–2018) at leading order (LO).

Fragmentation and parton showering are modeled by PYTHIA 8 [33] versions 8.212 (2016) and 8.230 (2017–2018). For samples generated with LO (NLO) precision, the MLM [34] (FxFx [35]) matrix element to parton shower matching scheme is used. For the 2016 simulation, the underlying event tunes CUETP8M1 [36] and CUETP8M2T4 [37] are applied to Drell–Yan and $t\bar{t}$ production in association with two bosons, respectively. The tune CP5 [38] is applied to the remaining processes in the 2016 simulation and all processes in the 2017–2018 simulation. Simulations for the 2016 data-taking conditions are generated using the NNPDF3.0 [39] parton distribution functions (PDFs) with either LO or NLO accuracy, while for 2017–2018 samples

NNPDF3.1 [40] at next-to-NLO (NNLO) accuracy is used.

Cross sections at NLO and NNLO are used to normalize the simulated background samples. Events in the $t\bar{t}$ sample with one or more additional b jets from initial- or final-state radiation are reweighted to match corresponding cross sections measured by the CMS experiment: Ref. [41] is used for the SL analysis and Ref. [42] for the OSDL analysis. The detector response is simulated using GEANT4 [43]. In the single-lepton and OSDL final states, the contributions from all background processes are estimated using simulation. In the all-hadronic final state, CRs in data are used to estimate the dominant multijet and $t\bar{t}$ backgrounds.

4 Event reconstruction and data samples

A particle-flow algorithm [44] is used to reconstruct and identify each particle in an event, with an optimized combination of information from various CMS subdetectors. The objects identified by the algorithm comprise candidate electrons, muons, photons, and charged or neutral hadrons. Muon and electron candidates are restricted to the ranges $|\eta| < 2.4$ and $|\eta| < 2.5$, respectively [45–47], and are required to be isolated from other objects [45, 47, 48]. Jets are reconstructed from particle flow objects using the anti- k_T algorithm [49, 50] with distance parameters of 0.4 (AK4) and 0.8 (AK8). Residual differences in the jet energy scale and resolution between data and simulation are corrected [51]. Charged particles identified as originating from pileup are discarded, and the measured energy is corrected to remove the estimated contribution from neutral pileup particles [52, 53]. The H_T in an event is then defined as the scalar p_T sum of all AK4 jets with $p_T > 30$ GeV and $|\eta| < 2.5$.

The DEEPCSV [54] and DEEPJET algorithms [55] are used to discriminate (b tag) AK4 jets produced by the hadronization of bottom quarks from those produced by gluon and lighter quark hadronization. A misidentification probability of 1% and efficiencies of approximately 68% for DEEPCSV and 75% for DEEPJET are measured in simulated $t\bar{t}$ events [56].

Hadronic top quark decays with a small or moderate Lorentz boost will typically produce three separate AK4 jets. These decays are referred to as “resolved” and are identified using multivariate top quark tagging (t tagging) algorithms. For the analysis of the single-lepton final state we use the DNN-based DEEPRESOLVED t tagger [57, 58] while for the all-hadronic final state we use a custom boosted decision tree (BDT) t tagger [59, 60] based on the one described in Ref. [61], updated to use DEEPJET b tagging inputs.

In contrast, hadronically decaying top quarks with a large boost can result in a single merged jet. Such decays are identified in the all-hadronic channel by applying the CMS DEEPAK8 algorithm [62] to AK8 jets with $p_T > 400$ GeV. In order to avoid double counting of objects, we require merged top quark jets to be separated from resolved top quark candidates by $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.8$.

The OSDL events are collected using electron-muon, dimuon, and dielectron triggers. The $e\mu$ selection uses a combination of triggers that require either an electron with $p_T > 23$ GeV and a muon with $p_T > 12$ GeV, or vice-versa. For the dimuon channel, a trigger with p_T thresholds of 17 and 8 GeV for the two highest p_T muons is used. Similarly the dielectron channel uses a trigger with p_T thresholds of 23 and 12 GeV for the two highest p_T electrons. A prioritized trigger strategy of $e\mu$, $\mu\mu$, and ee is used to ensure that events satisfying multiple triggers exclusively enter the appropriate OSDL final state. For the single-lepton channel, two different triggers are used. The first requires events to contain an isolated electron (muon) with $p_T > 35$ (50) GeV. The second requires a very loosely isolated electron or muon with

$p_T > 15$ GeV in addition to the event having $H_T > 450$ GeV. All-hadronic events are selected with a variety of triggers that require at least six AK4 jets and H_T greater than thresholds in the range 380–450 GeV. A minimum of either one or two b-tagged jets is required, depending on the trigger. Scale factors are applied to simulated samples in all final states to correct for the differences in trigger efficiencies between data and simulation.

5 Opposite sign dilepton final state

The OSDL channel contains data corresponding to an integrated luminosity of 101 fb^{-1} collected in 2017–2018, with previously published results on 2016 data included in the final fit to all channels. Offline, events in the OSDL channel are required to have exactly two opposite-sign leptons, one with $p_T > 25$ GeV and the other with $p_T > 15$ GeV, at least 4 jets with $p_T > 30$ GeV, and $H_T > 500$ GeV. Events with ee and $\mu\mu$ invariant masses below 20 GeV or within 15 GeV of the Z boson mass are excluded. The distribution of H_T is chosen as the input to the final fit, as this variable is sensitive to the presence of the extra two hadronic top quark decays in the signal as compared to the $t\bar{t}$ background. To increase sensitivity, events are categorized by lepton decay channel (ee , $\mu\mu$, $e\mu$), the number of AK4 jets ($N_j = 4, 5, 6, 7, \geq 8$), and how many of them are b tagged ($N_b = 2, 3, \geq 4$). The signal regions (SRs) contain seven or more jets, three or more of which are b tagged by DEEJET, while categories containing fewer jets or exactly two b-tagged jets serve as CRs.

The number of simulated $t\bar{t}$ events with no jets from the hadronization of additional b quarks is corrected to ensure consistency with the observed data. The correction is determined from CRs which contain exactly one b-tagged jet but satisfy all other criteria of the OSDL SRs and CRs included in the fit (i.e., two opposite-sign leptons, $N_j \geq 4$, and $H_T > 500$ GeV). The selected sample is depleted of $t\bar{t}$ with extra b jets. The required correction is determined to be a scaling factor of 0.78 ± 0.05 (statistical uncertainty only), independent of lepton and jet kinematic properties.

The OSDL signal and background normalizations are obtained from a simultaneous binned maximum likelihood fit to all the categories, where a template is created for each jet and b tag category, leptonic decay channel, and year. Figure 2 shows the jet multiplicity distributions for the ≥ 4 b tag categories after the fit to data. The dominant background contribution changes with b tag multiplicity. With increasing N_b , backgrounds such as $t\bar{t} + \geq 1b$, $t\bar{t} + H$, and $t\bar{t} + V$ ($V = W, Z$) become more important. In the most sensitive categories, $t\bar{t} + \geq 1b$ becomes the dominant background.

6 Single-lepton final state

Single-lepton events are required to have exactly one lepton with $p_T > 20$ GeV, at least four AK4 jets, at least two of which must be b tagged using the DEEPCSV algorithm, and $H_T > 500$ GeV. A BDT is trained using the TMVA package [63] to discriminate between signal and background in regions with large N_j and N_b . A large number of possible BDT inputs are constructed, based on kinematic variables such as p_T , b tagging discriminants, resolved t tagging discriminants, mass, and angular separations of various objects and their combinations (e.g., jets, dijets, trijets, b-tagged jets, lepton–b pairs, and $b\bar{b}$ pairs). Information about the event topology is incorporated via event shape variables, such as centrality, planarity, sphericity, and the second Fox–Wolfram moment [64] calculated using all AK4 jets. These potential inputs are evaluated based on whether they are well modeled in the simulation (using χ^2 , Kolmogorov-

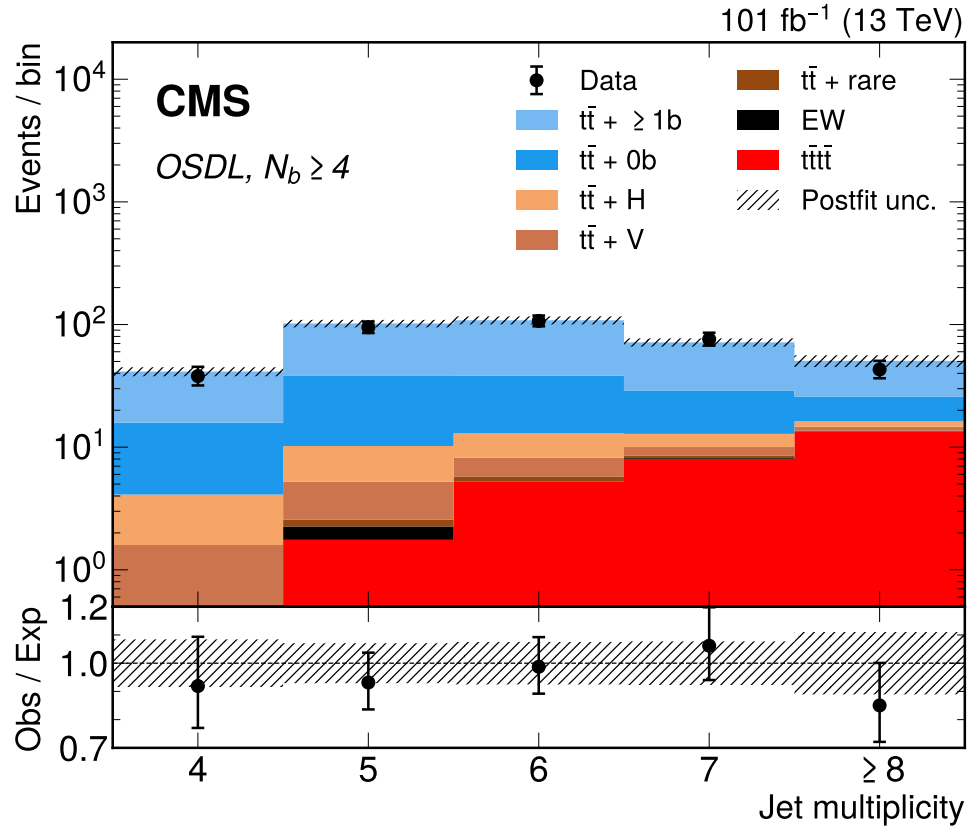


Figure 2: The jet multiplicity for $N_b \geq 4$ in the opposite-sign dilepton channel for the combined 2017–2018 dataset with dilepton decay categories combined. Here, $t\bar{t} + \geq 1b$ refers to $t\bar{t}$ events with at least one additional b jet, $t\bar{t} + 0b$ includes all other $t\bar{t}$ events not produced in association with a boson, and EW refers to events that contain W and Z bosons but no top quarks. The backgrounds and $t\bar{t}t\bar{t}$ signal (derived from the fit described below) are shown as a stacked histogram. The hatched bands correspond to the estimated total uncertainty after the fit.

Smirnov, or Anderson-Darling goodness of fit tests) and whether they increase the BDT discrimination power. The final BDT classifier uses 40 inputs. Signal and background samples are randomly divided into three equally populated parts: for training, for testing the performance, and for evaluating the classifier for the maximum likelihood fit. The contributions from the dominant $t\bar{t}$ background and all other SM processes are included in the training. The training is optimized by targeting a region enriched in signal events by requiring $N_j \geq 6$ and $N_b \geq 2$. The BDT is validated in the $N_b = 2$ region, which has a low signal-to-background ratio. Small corrections to the slope of the BDT distributions are derived in this region and applied to simulated events in the SR with $N_b \geq 3$. The correction is verified to be valid in higher b-tag multiplicities, within uncertainties.

To maximize sensitivity to $t\bar{t}t\bar{t}$ production, events are categorized based on lepton flavor (e, μ), N_j (6, 7, 8, 9, ≥ 10), N_b (3, ≥ 4), and the number of resolved top quark candidates ($N_{RT} = 0, \geq 1$). The distribution of the BDT discriminant is used as the input to the final fit. The statistical interpretation is based on a simultaneous binned maximum likelihood fit to all categories. The BDT distributions have variable bin sizes, chosen such that the statistical uncertainty in the total background in each bin is less than 30%. Representative distributions from three different signal region categories are shown in Fig. 3.

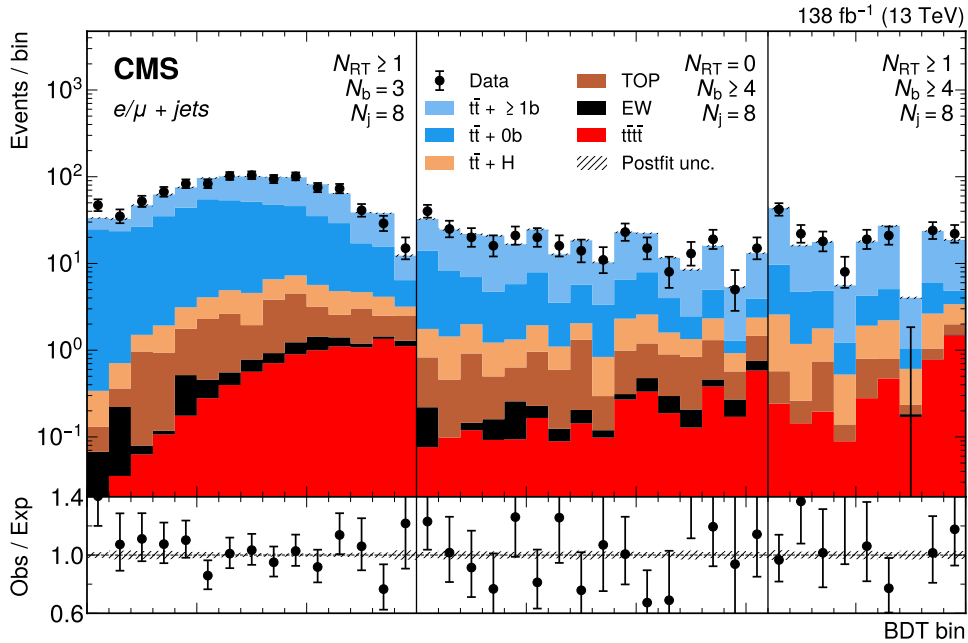


Figure 3: The distribution of the BDT discriminants for the 2016–2018 data set for three different categories in the combined single-electron and single-muon channels. The three categories are defined by the number of resolved t tags (N_{RT}), b tags (N_b), and jets (N_j), selected as representative based on their sensitivity to signal. Here, $t\bar{t} + \geq 1b$ refers to $t\bar{t}$ events with at least one additional b jet, while $t\bar{t} + 0b$ includes all other $t\bar{t}$ events not produced in association with a boson. The TOP grouping contains single top quark production along with the other $t\bar{t}$ processes not explicitly shown, and EW refers to events that contain W and Z bosons but no top quarks. The backgrounds and $t\bar{t}t\bar{t}$ signal (derived from the fit described below) are shown as a stacked histogram. The hatched bands correspond to the estimated total uncertainty after the fit. While the bins are shown to be equal width, they do not correspond to equal width in BDT value.

Table 1: Definition of the 12 signal region (SR) categories for the all-hadronic channel, as a function of the number of resolved top quark candidates (N_{RT}), the number of boosted top quark candidates (N_{BT}), and H_T .

N_{RT}	N_{BT}	H_T range (GeV)
1	0	700–800
1	0	800–900
1	0	900–1000
1	0	1000–1100
1	0	1100–1200
1	0	1200–1300
1	0	1300–1500
1	0	≥ 1500
1	≥ 1	700–1400
1	≥ 1	≥ 1400
≥ 2	≥ 0	700–1100
≥ 2	≥ 0	≥ 1100

7 All-hadronic final state

The all-hadronic SR is defined by requiring $H_T > 700$ GeV, no prompt isolated leptons, at least nine AK4 jets of which at least three are b tagged by DEEPJET, and at least one resolved top quark candidate. This selection results in a signal-to-background ratio of about 10^{-5} assuming the SM expectation for the signal.

Events in the SR are subdivided into 12 categories based on N_{RT} , the number of boosted top quarks (N_{BT}), and H_T as outlined in Table 1. The categorization by top quark tags defines three groups: $N_{\text{RT}} \geq 2$, $N_{\text{RT}} = 1$ and $N_{\text{BT}} \geq 1$, and $N_{\text{RT}} = 1$ and $N_{\text{BT}} = 0$. The first two groups are each further categorized into two ranges in H_T : 700–1100 and >1100 GeV. For the third group, there are six equally spaced bins in the range $700 < H_T < 1300$ GeV, and two additional bins with H_T in the ranges 1300–1500 and ≥ 1500 GeV. The SR categories were chosen to optimize sensitivity to $t\bar{t}t\bar{t}$ production.

An event-level BDT is trained using CATBOOST [65] in each category of the SR to further distinguish between $t\bar{t}t\bar{t}$ signal events and the dominant backgrounds originating from $t\bar{t}$ and QCD multijet production, by exploiting differences in kinematic distributions of reconstructed objects. The 20 optimized BDT input variables include N_j and N_b ; the kinematic distributions of jets, b-tagged jets, and t-tagged candidates; and variables related to the angular distributions of jets.

Techniques using CRs in data are employed to estimate the dominant backgrounds from QCD multijet and $t\bar{t}$ + jet production, as described in the following text. The ratio of the QCD multijet to the $t\bar{t}$ + jet background is expected to be approximately 3:2 in the SR.

Estimates of the absolute normalization of the background and the shape of the BDT distributions in the 12 SR categories are obtained from an extrapolation based on five CRs. While the SR categories have $N_j \geq 9$ and $N_b \geq 3$, these five CRs are defined to have $(N_j, N_b) = (7, 2)$, $(8, 2)$, $(\geq 9, 2)$, $(7, \geq 3)$, and $(8, \geq 3)$. Figure 5 illustrates how these control regions are related as a function of N_j and N_b . The absolute normalization of the background is estimated using an “extended ABCD” method [66], where the number of events in the SR is derived from the number of events in several independent CRs. This method improves the accuracy of background yield estimates in cases where control variables are weakly correlated (such as N_j and

N_b), compared to the traditional ABCD method in which only three CRs are used. Specifically, this method is used to predict the number of $t\bar{t}$ and QCD multijet events in the SR from the number of events observed in the five (N_j, N_b) CRs, after subtracting the number of events from minor backgrounds.

The shape of the BDT distribution in each SR is predicted using a DNN trained on the same five CRs that are used to estimate the absolute normalization. A normalizing autoregressive flow [67] is trained on the CRs to learn a bijective transformation of the H_T and BDT output distributions between a source and a target. The procedure is sensitive to statistical fluctuations in the source sample, so the input source used is a $t\bar{t}$ sample with a large number of simulated events. The target is the total $t\bar{t}$ and multijet background (estimated by subtracting the other, simulated, background contributions from the data). The QCD simulation is not included as an input source due to the very small number of simulated events in the regions of interest. In each of the CRs, the normalizing flow algorithm learns a transformation from the source distribution to the target distribution, before applying that transformation to the source distribution in the SR. The validity of the method was demonstrated with various tests, including transformations between distributions from physics processes with large differences in shape. The algorithm is trained regressively, starting from the less SR-like CRs (in terms of N_j and N_b) and including weights from previous training cycles in subsequent more SR-like training cycles. For each data-taking period (2016, 2017, and 2018), the BDT output and H_T distributions are predicted simultaneously in the three SR N_{RT} and N_{BT} categories. The predicted BDT distributions are then split according to the predicted H_T , resulting in predicted BDT output distributions binned in H_T for each of the 12 SR categories per data-taking period. These distributions are normalized to the absolute normalizations estimated from the “extended ABCD” extrapolation.

The predictions are checked in validation regions (VRs) defined in parallel to those for the SR, but with $N_j = 8$, $N_b \geq 3$ and extrapolating from CRs in which $(N_j, N_b) = (6, 2), (7, 2), (8, 2), (6, \geq 3)$, and $(7, \geq 3)$. The VRs and their associated CRs are split into the same N_{RT} , N_{BT} , and H_T categories as the SRs and their associated CRs as detailed in Table 1. Figure 4 shows BDT discriminant distributions in two VRs, which demonstrate the robustness of this method.

For each category, the difference between the total number of predicted and observed events in the corresponding VR is taken as a normalization uncertainty. This is added in quadrature to a second normalization uncertainty estimated from the bin-to-bin variations within the VR. Shape uncertainties are also estimated for each category, characterized as a linear scaling of the BDT discriminant for each event. The maximum scaling required for the predicted and observed distribution shapes to agree within the uncertainty in all bins in any VR is $\pm 3\%$. These uncertainties are considered to be correlated for any H_T categories that use the same DNN training.

Other backgrounds, originating from the associated production of $t\bar{t}$ with W , Z , or H bosons, are estimated from simulation. Figure 6 shows the BDT output distributions for the two SR categories that are most sensitive to the $t\bar{t}t\bar{t}$ signal. The distribution of the BDT discriminant in each category is used as the input to the final fit.

8 Statistical procedure and systematic uncertainties

An estimate of the $t\bar{t}t\bar{t}$ production significance and the measurement of the cross section is obtained by a likelihood fit, based on the procedure described in Refs. [68, 69]. The fit incorporates the experimental and theoretical uncertainties as nuisance parameters, assuming that shared

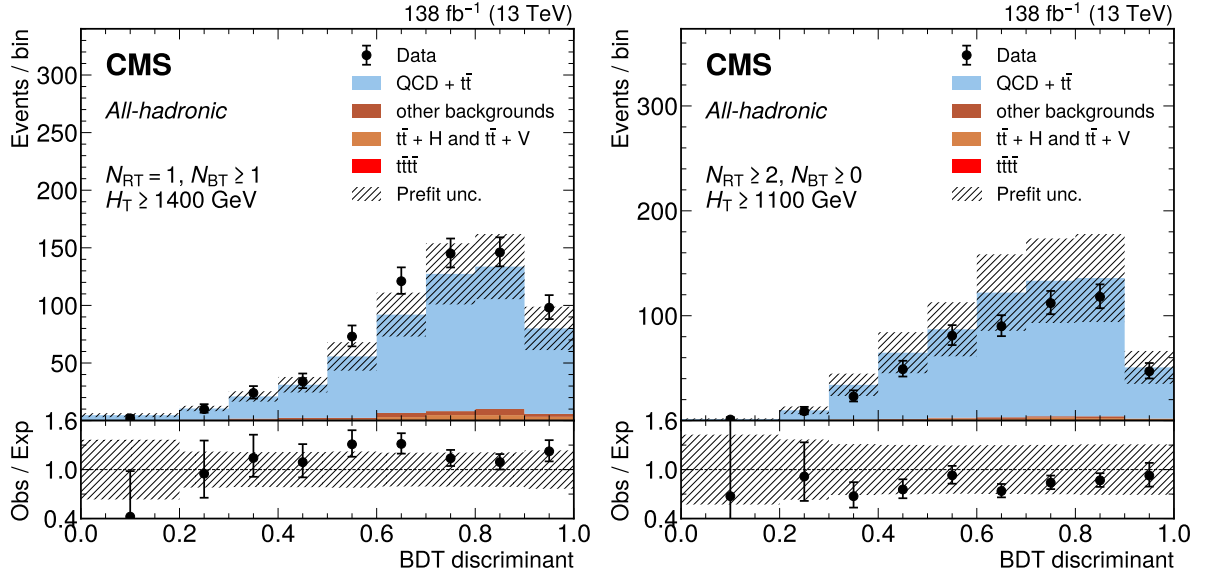


Figure 4: The distribution of the BDT discriminants for the full 2016–2018 data set in the all-hadronic channel for two VRs. The two sample VRs are defined by $N_{RT} = 1, N_{BT} \geq 1, H_T > 1400$ GeV (left), and $N_{BT} \geq 2, H_T > 1100$ GeV (right). The background from QCD multijet and $t\bar{t}$ production is derived from control regions in the data. Estimates for the $t\bar{t}t\bar{t}$ signal and other backgrounds are shown using simulated samples. The hatched bands correspond to the estimated total uncertainty.

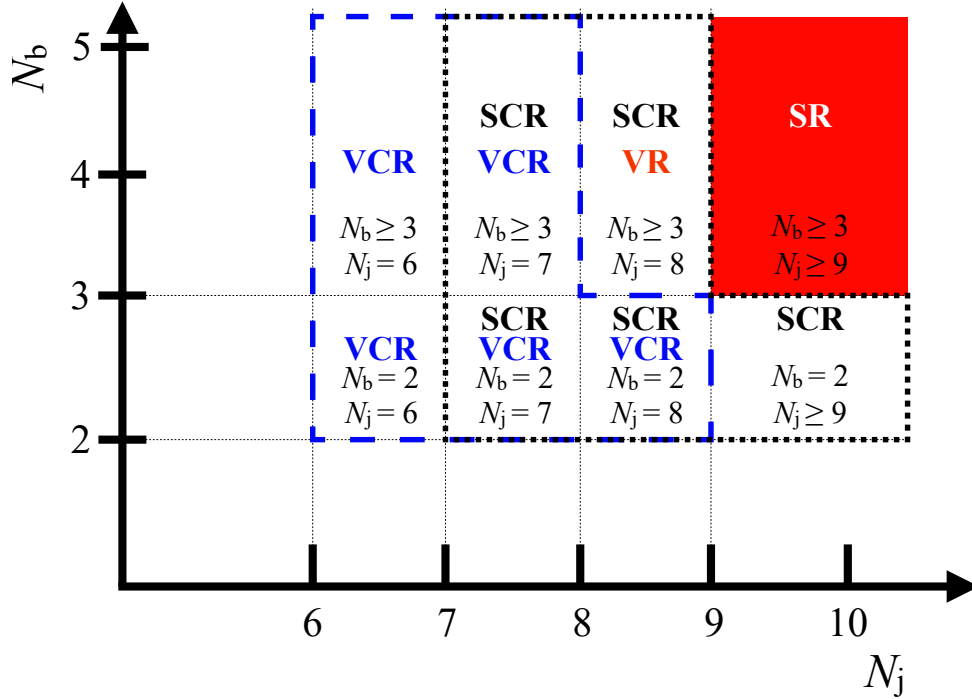


Figure 5: Schematic showing the definitions of the signal region (SR), validation region (VR), signal control region (SCR), and validation control region (VCR) used in the all-hadronic analysis as a function of N_j and N_b .

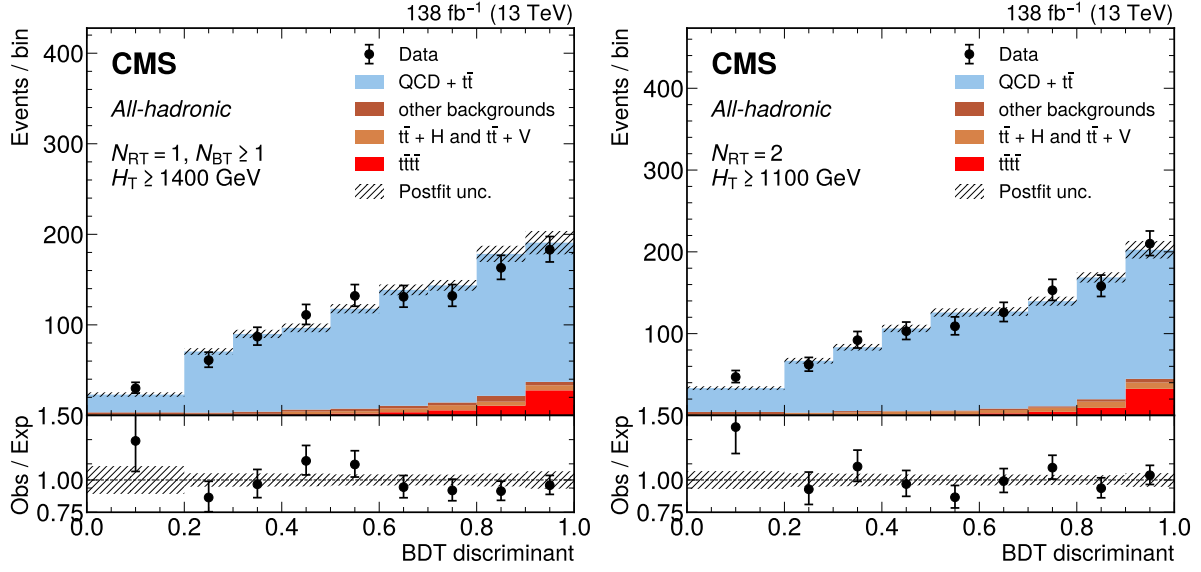


Figure 6: The distribution of the BDT discriminants for the full 2016–2018 data set in the all-hadronic channel. The two most sensitive SR categories are shown, defined by $N_{RT} = 1$, $N_{BT} \geq 1$, $H_T > 1400$ GeV (left), and $N_{BT} \geq 2$, $H_T > 1100$ GeV (right). The background from QCD multijet and $t\bar{t}$ production is derived from control regions in the data. Estimates for the $t\bar{t}t\bar{t}$ signal and other backgrounds are shown using simulated samples. The hatched bands correspond to the estimated total uncertainty after the fit.

systematic uncertainties between analyses are correlated. Different b tagging algorithms are treated as uncorrelated; studies confirm that this choice has no significant effect on the fit results. The significance of signal events is obtained from a comparison to the background-only hypothesis assuming the asymptotic regime as detailed in Ref. [70].

A likelihood fit is performed to the all-hadronic, single-lepton, and OSDL results first, and then a second likelihood fit is performed including previously published results. Uncertainties in both the normalizations and the shapes of the discriminant distributions are considered for all background processes. For the signal, the uncertainties are applied to the predicted shapes and normalizations of the discriminant distributions while the cross section is unconstrained. Systematic uncertainties that come from the same experimental or theoretical source are treated consistently between results.

The sensitivity of the analysis is limited primarily by the small size of the sample, which contributes an uncertainty of 22% in the measured signal strength. Approximately 400 nuisance parameters representing systematic uncertainties are considered; the two with the largest individual effects are the theoretical uncertainty in the $t\bar{t}H$ cross section (4.6% impact on signal strength) and the uncertainty in the modeling of $t\bar{t}$ with additional b jets (3.7%). The background estimation in the all-hadronic final state contributes up to 2.7% per SR category, dominated by statistical fluctuations in the CRs. The jet energy scale contributes up to 2.4% (depending on the year and channel), renormalization and factorization scales 2.1%, and leptonic fake rates 1.9%. The largest components of the b tagging and light quark mistagging efficiency uncertainties each contribute 1.8%.

Further nuisance parameters with smaller individual contributions include those relating to lepton reconstruction and trigger efficiencies, the input cross section for $t\bar{t}$ + additional b quark production, jet energy resolution, matrix element to parton shower matching, the modeling of the resolved t tagging in the single-lepton channel, PDFs, pileup, the theoretical uncertainty in

the $t\bar{t}$ cross section, the theoretical modeling of initial-state radiation in $t\bar{t}$ production, and the delivered luminosity. The total systematic uncertainty, considering the effects of all nuisance parameters, is 17%.

9 Results

Table 2 shows the fitted values of the signal strength (the ratio of the measured cross section to the prediction), the measured cross section, and the expected and observed significance of $t\bar{t}t\bar{t}$ production from 2017–2018 data in the OSDL channel, and 2016–2018 data in the single-lepton and all-hadronic channels. The signal strength is calculated with all systematic uncertainties, including all theoretical uncertainties. The cross section measurement is performed with all systematic uncertainties except theoretical uncertainties that affect the rate of the signal process. The table also includes the combination of these new results with the CMS OSDL analysis of 2016 data [22], and the same-sign dilepton and multilepton analysis of the 2016–2018 data [21], following the procedure described in Refs. [68, 69]. The expected and observed significances for each final state and the combination are also shown in Fig. 7. The combination of results described in this Letter gives a signal strength of 2.5 ± 0.5 (stat) ± 0.5 (syst) and a measured cross section of 36 ± 7 (stat) $^{+10}_{-8}$ (syst), providing evidence for $t\bar{t}t\bar{t}$ production with an observed significance of 3.9 standard deviations (1.5 expected). The full combination of all channels for the CMS 2016–2018 data set gives a signal strength of 1.4 ± 0.3 (stat) ± 0.2 (syst) and a measured cross section of 17 ± 4 (stat) ± 3 (syst), increasing the observed significance to 4.0 standard deviations (3.2 expected). This is the most sensitive $t\bar{t}t\bar{t}$ analysis to date.

Table 2: Measured signal strength ($\mu = \sigma_{t\bar{t}t\bar{t}}/\sigma_{t\bar{t}t\bar{t}}^{\text{SM}}$ where $\sigma_{t\bar{t}t\bar{t}}^{\text{SM}} = 12$ fb), corresponding cross section (in fb), and the expected and observed significance (in standard deviations) for $t\bar{t}t\bar{t}$ production from all analysis channels. This table shows production from each analysis channel in this Letter, the combination of those channels, the results from previously published results, and the full combination of all CMS 2016–2018 results.

Analysis	Signal strength (μ)			Cross section (fb)			Significance (s.d.)	
	(stat.)	(syst.)		(stat.)	(syst.)		Exp.	Obs.
OSDL (2017+2018)	2.8	± 1.0	$^{+1.9}_{-1.2}$	33	± 12	$^{+15}_{-14}$	0.6	1.8
Single-lepton	1.2	$^{+0.7}_{-0.6}$	± 0.6	15	± 8	$^{+10}_{-7}$	1.2	1.4
All-hadronic	5.8	± 1.4	± 2.0	70	± 17	$^{+25}_{-23}$	0.4	2.5
Combination of above	2.5	± 0.5	± 0.5	36	± 7	$^{+10}_{-8}$	1.5	3.9
SSDL&ML (2016–2018) [21]	1.0	± 0.4	$^{+0.3}_{-0.2}$	13	$^{+5}_{-4}$	± 3	2.7	2.6
OSDL (2016) [22]	−0.2	$^{+1.7}_{-1.5}$	± 1.5	−2	$^{+20}_{-18}$	± 18	0.4	0
Full combination	1.4	± 0.3	± 0.2	17	± 4	± 3	3.2	4.0

10 Summary

We have measured the cross section for the simultaneous production of four top quarks ($t\bar{t}t\bar{t}$) in proton-proton collisions. The data were collected by the CMS experiment at the LHC in 2016–2018, and correspond to an integrated luminosity of up to 138 fb^{-1} at a center-of-mass energy of 13 TeV. The all-hadronic final state has been studied for the first time in a $t\bar{t}t\bar{t}$ production analysis, using a background estimation strategy based on a deep neural network trained

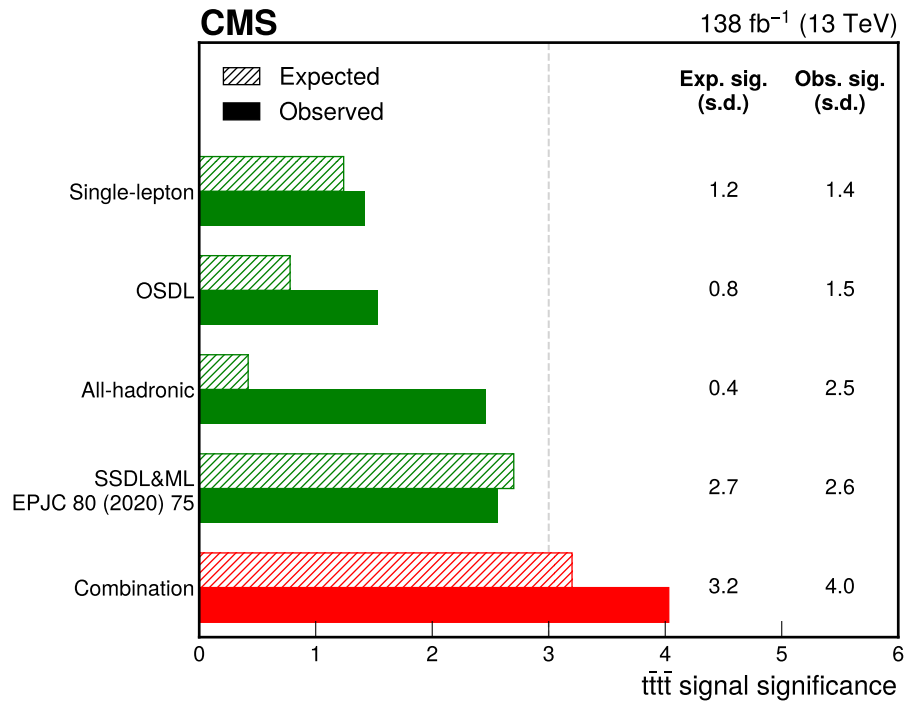


Figure 7: Expected and observed significance (in standard deviations) for $t\bar{t}t\bar{t}$ production from each final state and the combination with previous CMS results [21, 22]. The same-sign dilepton and multilepton (SSDL&ML) final state results are from Ref. [21].

using control regions in data. Final states with one lepton (electron or muon), or two opposite-sign leptons have also been analyzed. The observed and expected significances obtained from the combination of the new analyses described here are 3.9 and 1.5 standard deviations, respectively. When combined with published CMS results in other final states, the significances increase to 4.0 (observed) and 3.2 (expected) standard deviations. This is a significant improvement compared to previous CMS results and the first CMS evidence for $t\bar{t}t\bar{t}$ production with a significance above three standard deviations.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); Minciencias (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, 884104, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science – EOS" – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Deutsche Forschungsgemeinschaft (DFG), under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306, and under project number 400140256 - GRK2497; the Hungarian Academy of Sciences, the New National Excellence Program - ÚNKP, the NKFIH research grants K 124845, K 124850, K 128713, K 128786, K 129058, K 131991, K 133046, K 138136, K 143460, K 143477, 2020-2.2.1-ED-2021-00181, and TKP2021-NKTA-64 (Hungary); the Council of Science and Industrial Research, India; the Latvian Council of Science; the Ministry of Education and Science, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369 and 2021/43/B/ST2/01552 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); MCIN/AEI/10.13039/501100011033, ERDF "a way of making Europe", and the Programa Estatal de Fomento de la Investigación

Científica y Técnica de Excelencia María de Maeztu, grant MDM-2017-0765 and Programa Severo Ochoa del Principado de Asturias (Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, and the National Science, Research and Innovation Fund via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant B05F650021 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

- [1] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.
- [2] T. Ježo and M. Kraus, “Hadroproduction of four top quarks in the POWHEG BOX”, *Phys. Rev. D* **105** (2022) 114024, doi:10.1103/PhysRevD.105.114024, arXiv:2110.15159.
- [3] R. Frederix, D. Pagani, and M. Zaro, “Large NLO corrections in $t\bar{t}W^\pm$ and $t\bar{t}\bar{t}\bar{t}$ hadroproduction from supposedly subleading EW contributions”, *JHEP* **02** (2018) 031, doi:10.1007/JHEP02(2018)031, arXiv:1711.02116.
- [4] G. Bevilacqua and M. Worek, “Constraining BSM physics at the LHC: four top final states with NLO accuracy in perturbative QCD”, *JHEP* **07** (2012) 111, doi:10.1007/JHEP07(2012)111, arXiv:1206.3064.
- [5] R. Frederix et al., “The automation of next-to-leading order electroweak calculations”, *JHEP* **07** (2018) 185, doi:10.1007/JHEP07(2018)185, arXiv:1804.10017. [Erratum: doi:10.1007/JHEP11(2021)085].
- [6] H. P. Nilles, “Supersymmetry, supergravity and particle physics”, *Phys. Rept.* **110** (1984) 1, doi:10.1016/0370-1573(84)90008-5.
- [7] S. P. Martin, “A supersymmetry primer”, *Adv. Ser. Direct. High Energy Phys.* **18** (1998) 1, doi:10.1142/9789812839657_0001, arXiv:hep-ph/9709356.
- [8] G. Cacciapaglia et al., “Composite scalars at the LHC: the Higgs, the sextet and the octet”, *JHEP* **11** (2015) 201, doi:10.1007/JHEP11(2015)201, arXiv:1507.02283.
- [9] K. Kumar, T. M. P. Tait, and R. Vega-Morales, “Manifestations of top compositeness at colliders”, *JHEP* **05** (2009) 022, doi:10.1088/1126-6708/2009/05/022, arXiv:0901.3808.
- [10] D. Dicus, A. Stange, and S. Willenbrock, “Higgs decay to top quarks at hadron colliders”, *Phys. Lett. B* **333** (1994) 126, doi:10.1016/0370-2693(94)91017-0, arXiv:hep-ph/9404359.
- [11] N. Craig et al., “The hunt for the rest of the Higgs bosons”, *JHEP* **06** (2015) 137, doi:10.1007/JHEP06(2015)137, arXiv:1504.04630.
- [12] N. Craig et al., “Heavy Higgs bosons at low $\tan\beta$: from the LHC to 100 TeV”, *JHEP* **01** (2017) 018, doi:10.1007/JHEP01(2017)018, arXiv:1605.08744.

- [13] G. Cacciapaglia, A. Deandrea, and J. Llodra-Perez, “A dark matter candidate from Lorentz invariance in 6D”, *JHEP* **03** (2010) 083, doi:10.1007/JHEP03(2010)083, arXiv:0907.4993.
- [14] O. Ducu, L. Heurtier, and J. Maurer, “LHC signatures of a Z' mediator between dark matter and the SU(3) sector”, *JHEP* **03** (2016) 006, doi:10.1007/JHEP03(2016)006, arXiv:1509.05615.
- [15] C. Degrande et al., “Non-resonant new physics in top pair production at hadron colliders”, *JHEP* **03** (2011) 125, doi:10.1007/JHEP03(2011)125, arXiv:1010.6304.
- [16] ATLAS Collaboration, “Search for four-top-quark production in the single-lepton and opposite-sign dilepton final states in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *Phys. Rev. D* **99** (2019) 052009, doi:10.1103/PhysRevD.99.052009, arXiv:1811.02305.
- [17] ATLAS Collaboration, “Search for new phenomena in events with same-charge leptons and b -jets in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *JHEP* **12** (2018) 039, doi:10.1007/JHEP12(2018)039, arXiv:1807.11883.
- [18] ATLAS Collaboration, “Evidence for $t\bar{t}\bar{t}$ production in the multilepton final state in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *Eur. Phys. J. C* **80** (2020) 1085, doi:10.1140/epjc/s10052-020-08509-3, arXiv:2007.14858.
- [19] CMS Collaboration, “Search for physics beyond the standard model in events with two leptons of same sign, missing transverse momentum, and jets in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Eur. Phys. J. C* **77** (2017) 578, doi:10.1140/epjc/s10052-017-5079-z, arXiv:1704.07323.
- [20] CMS Collaboration, “Search for standard model production of four top quarks with same-sign and multilepton final states in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Eur. Phys. J. C* **78** (2018) 140, doi:10.1140/epjc/s10052-018-5607-5, arXiv:1710.10614.
- [21] CMS Collaboration, “Search for production of four top quarks in final states with same-sign or multiple leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Eur. Phys. J. C* **80** (2020) 75, doi:10.1140/epjc/s10052-019-7593-7, arXiv:1908.06463.
- [22] CMS Collaboration, “Search for the production of four top quarks in the single-lepton and opposite-sign dilepton final states in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **11** (2019) 082, doi:10.1007/JHEP11(2019)082, arXiv:1906.02805.
- [23] CMS Collaboration, “Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016 at CMS”, *Eur. Phys. J. C* **81** (2021) 800, doi:10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.
- [24] CMS Collaboration, “CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV”, CMS Physics Analysis Summary CMS-PAS-LUM-17-004, 2018.
- [25] CMS Collaboration, “CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV”, CMS Physics Analysis Summary CMS-PAS-LUM-18-002, 2019.
- [26] HEPData record for this analysis, 2023. doi:10.17182/hepdata.135833.

-
- [27] CMS Collaboration, “Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **15** (2020) P10017, doi:10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.
- [28] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
- [29] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [30] P. Nason, “A new method for combining NLO QCD with shower Monte Carlo algorithms”, *JHEP* **11** (2004) 040, doi:10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.
- [31] S. Frixione, P. Nason, and C. Oleari, “Matching NLO QCD computations with parton shower simulations: the POWHEG method”, *JHEP* **11** (2007) 070, doi:10.1088/1126-6708/2007/11/070, arXiv:0709.2092.
- [32] S. Alioli, P. Nason, C. Oleari, and E. Re, “A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX”, *JHEP* **06** (2010) 043, doi:10.1007/JHEP06(2010)043, arXiv:1002.2581.
- [33] T. Sjöstrand et al., “An introduction to PYTHIA 8.2”, *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.
- [34] J. Alwall et al., “Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions”, *Eur. Phys. J. C* **53** (2008) 473, doi:10.1140/epjc/s10052-007-0490-5, arXiv:0706.2569.
- [35] R. Frederix and S. Frixione, “Merging meets matching in MC@NLO”, *JHEP* **12** (2012) 061, doi:10.1007/JHEP12(2012)061, arXiv:1209.6215.
- [36] CMS Collaboration, “Event generator tunes obtained from underlying event and multiparton scattering measurements”, *Eur. Phys. J. C* **76** (2016) 155, doi:10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.
- [37] CMS Collaboration, “Investigations of the impact of the parton shower tuning in Pythia 8 in the modelling of $t\bar{t}$ at $\sqrt{s} = 8$ and 13 TeV”, CMS Physics Analysis Summary CMS-PAS-TOP-16-021, 2016.
- [38] CMS Collaboration, “Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements”, *Eur. Phys. J. C* **80** (2020) 4, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.
- [39] NNPDF Collaboration, “Parton distributions for the LHC Run II”, *JHEP* **04** (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849.
- [40] NNPDF Collaboration, “Parton distributions from high-precision collider data”, *Eur. Phys. J. C* **77** (2017) 663, doi:10.1140/epjc/s10052-017-5199-5, arXiv:1706.00428.
- [41] CMS Collaboration, “Measurement of the cross section for $t\bar{t}$ production with additional jets and b jets in pp collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **07** (2020) 125, doi:10.1007/JHEP07(2020)125, arXiv:2003.06467.

- [42] CMS Collaboration, “First measurement of the cross section for top quark pair production with additional charm jets using dileptonic final states in pp collisions at $\sqrt{s} = 13$ TeV”, *Phys. Lett. B* **820** (2021) 136565, doi:10.1016/j.physletb.2021.136565, arXiv:2012.09225.
- [43] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [44] CMS Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.
- [45] CMS Collaboration, “Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC”, *JINST* **16** (2021) P05014, doi:10.1088/1748-0221/16/05/P05014, arXiv:2012.06888.
- [46] CMS Collaboration, “ECAL 2016 refined calibration and Run2 summary plots”, CMS Detector Performance Note CMS-DP-2020-021, 2020.
- [47] CMS Collaboration, “Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **13** (2018) P06015, doi:10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.
- [48] K. Rehermann and B. Tweedie, “Efficient identification of boosted semileptonic top quarks at the LHC”, *JHEP* **03** (2011) 059, doi:10.1007/JHEP03(2011)059, arXiv:1007.2221.
- [49] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- k_T jet clustering algorithm”, *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
- [50] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet user manual”, *Eur. Phys. J. C* **72** (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.
- [51] CMS Collaboration, “Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV”, *JINST* **12** (2017) P02014, doi:10.1088/1748-0221/12/02/P02014, arXiv:1607.03663.
- [52] D. Bertolini, P. Harris, M. Low, and N. Tran, “Pileup per particle identification”, *JHEP* **10** (2014) 059, doi:10.1007/JHEP10(2014)059, arXiv:1407.6013.
- [53] CMS Collaboration, “Pileup mitigation at CMS in 13 TeV data”, *JINST* **15** (2020) P09018, doi:10.1088/1748-0221/15/09/P09018, arXiv:2003.00503.
- [54] CMS Collaboration, “Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV”, *JINST* **13** (2018) P05011, doi:10.1088/1748-0221/13/05/P05011, arXiv:1712.07158.
- [55] E. Bols et al., “Jet flavour classification using DeepJet”, *JINST* **15** (2020) P12012, doi:10.1088/1748-0221/15/12/P12012, arXiv:2008.10519.
- [56] CMS Collaboration, “Performance of the DeepJet b tagging algorithm using 41.9/fb of data from proton-proton collisions at 13 TeV with Phase 1 CMS detector”, CMS Detector Performance Note CMS-DP-2018-058, 2018.

-
- [57] CMS Collaboration, “Search for direct top squark pair production in events with one lepton, jets, and missing transverse momentum at 13 TeV with the CMS experiment”, *JHEP* **05** (2020) 032, doi:10.1007/JHEP05(2020)032, arXiv:1912.08887.
- [58] CMS Collaboration, “Search for top squark production in fully-hadronic final states in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Rev. D* **104** (2021) 052001, doi:10.1103/PhysRevD.104.052001, arXiv:2103.01290.
- [59] T. Hastie, R. Tibshirani, and J. Friedman, “The elements of statistical learning”. Springer-Verlag, second edition, 2013. doi:10.1007/978-0-387-84858-7, ISBN 978-0-387-84858-7.
- [60] L. Breiman, J. Friedman, R. Olshen, and C. Stone, “Classification and regression trees”. Wadsworth, 1984. ISBN 978-0412048418.
- [61] CMS Collaboration, “Search for direct production of supersymmetric partners of the top quark in the all-jets final state in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **10** (2017) 005, doi:10.1007/JHEP10(2017)005, arXiv:1707.03316.
- [62] CMS Collaboration, “Machine learning-based identification of highly Lorentz-boosted hadronically decaying particles at the CMS experiment”, CMS Physics Analysis Summary CMS-PAS-JME-18-002, 2019.
- [63] H. Voss, A. Höcker, J. Stelzer, and F. Tegenfeldt, “TMVA, the toolkit for multivariate data analysis with ROOT”, in *XIth International Workshop on Advanced Computing and Analysis Techniques in Physics Research (ACAT)*, p. 40. 2007. arXiv:physics/0703039. [PoS(ACAT)040]. doi:10.22323/1.050.0040.
- [64] G. C. Fox and S. Wolfram, “Observables for the analysis of event shapes in e^+e^- annihilation and other processes”, *Phys. Rev. Lett.* **41** (1978) 1581, doi:10.1103/PhysRevLett.41.1581.
- [65] L. Prokhorenkova et al., “Catboost: unbiased boosting with categorical features”, 2019. arXiv:1706.09516.
- [66] S. Choi and H. Oh, “Improved extrapolation methods of data-driven background estimations in high energy physics”, *Eur. Phys. J. C* **81** (2021) 643, doi:10.1140/epjc/s10052-021-09404-1, arXiv:1906.10831.
- [67] S. Choi, J. Lim, and H. Oh, “Data-driven estimation of background distribution through neural autoregressive flows”, 2020. arXiv:2008.03636.
- [68] A. L. Read, “Presentation of search results: the CL_s technique”, *J. Phys. G* **28** (2002) 2693, doi:10.1088/0954-3899/28/10/313.
- [69] T. Junk, “Confidence level computation for combining searches with small statistics”, *Nucl. Instrum. Meth. A* **434** (1999) 435, doi:10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.
- [70] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, “Asymptotic formulae for likelihood-based tests of new physics”, *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727. [Erratum: doi:10.1140/epjc/s10052-013-2501-z].

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

A. Tumasyan¹ 

Institut für Hochenergiephysik, Vienna, Austria

W. Adam , J.W. Andrejkovic , T. Bergauer , S. Chatterjee , K. Damanakis , M. Dragicevic , A. Escalante Del Valle , P.S. Hussain , M. Jeitler² , N. Krammer , L. Lechner , D. Liko , I. Mikulec , P. Paulitsch , J. Schieck² , R. Schöfbeck , D. Schwarz , M. Sonawane , S. Templ , W. Waltenberger , C.-E. Wulz² 

Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish³ , T. Janssen , T. Kello⁴ , H. Rejeb Sfar , P. Van Mechelen 

Vrije Universiteit Brussel, Brussel, Belgium

E.S. Bols , J. D'Hondt , A. De Moor , M. Delcourt , H. El Faham , S. Lowette , A. Morton , D. Müller , A.R. Sahasransu , S. Tavernier , W. Van Doninck , S. Van Putte , D. Vannerom 

Université Libre de Bruxelles, Bruxelles, Belgium

B. Clerbaux , S. Dansana , G. De Lentdecker , L. Favart , D. Hohov , J. Jaramillo , K. Lee , M. Mahdavihorrami , I. Makarenko , A. Malara , S. Paredes , L. Pétré , N. Postiau , L. Thomas , M. Vanden Bemden , C. Vander Velde , P. Vanlaer 

Ghent University, Ghent, Belgium

D. Dobur , J. Knolle , L. Lambrecht , G. Mestdach , C. Rendón , A. Samalan , K. Skovpen , M. Tytgat , N. Van Den Bossche , B. Vermassen , L. Wezenbeek 

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

A. Benecke , G. Bruno , F. Bury , C. Caputo , P. David , C. Delaere , I.S. Donertas , A. Giammanco , K. Jaffel , Sa. Jain , V. Lemaitre , K. Mondal , A. Taliencio , T.T. Tran , P. Vischia , S. Wertz 

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G.A. Alves , E. Coelho , C. Hensel , A. Moraes , P. Rebello Teles 

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

W.L. Aldá Júnior , M. Alves Gallo Pereira , M. Barroso Ferreira Filho , H. Brandao Malbouisson , W. Carvalho , J. Chinellato⁵ , E.M. Da Costa , G.G. Da Silveira⁶ , D. De Jesus Damiao , V. Dos Santos Sousa , S. Fonseca De Souza , J. Martins⁷ , C. Mora Herrera , K. Mota Amarilo , L. Mundim , H. Nogima , A. Santoro , S.M. Silva Do Amaral , A. Sznajder , M. Thiel , A. Vilela Pereira 

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil

C.A. Bernardes⁶ , L. Calligaris , T.R. Fernandez Perez Tomei , E.M. Gregores , P.G. Mercadante , S.F. Novaes , Sandra S. Padula 

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

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

University of Sofia, Sofia, Bulgaria

A. Dimitrov , T. Ivanov , L. Litov , B. Pavlov , P. Petkov , A. Petrov , E. Shumka 

Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile

S. Thakur 

Beihang University, Beijing, China

T. Cheng , Q. Guo, T. Javaid⁸ , M. Mittal , L. Yuan 

Department of Physics, Tsinghua University, Beijing, China

M. Ahmad , G. Bauer⁹, Z. Hu , S. Lezki , K. Yi^{9,10} 

Institute of High Energy Physics, Beijing, China

G.M. Chen⁸ , H.S. Chen⁸ , M. Chen⁸ , F. Iemmi , C.H. Jiang, A. Kapoor , H. Liao , Z.-A. Liu¹¹ , V. Milosevic , F. Monti , R. Sharma , J. Tao , J. Thomas-Wilsker , J. Wang , H. Zhang , J. Zhao 

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

A. Agapitos , Y. An , Y. Ban , A. Levin , C. Li , Q. Li , X. Lyu, Y. Mao, S.J. Qian , X. Sun , D. Wang , J. Xiao , H. Yang

Sun Yat-Sen University, Guangzhou, China

M. Lu , Z. You 

University of Science and Technology of China, Hefei, China

N. Lu 

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China

X. Gao⁴ , D. Leggat, H. Okawa , Y. Zhang 

Zhejiang University, Hangzhou, Zhejiang, China

Z. Lin , C. Lu , M. Xiao 

Universidad de Los Andes, Bogota, Colombia

C. Avila , D.A. Barbosa Trujillo, A. Cabrera , C. Florez , J. Fraga 

Universidad de Antioquia, Medellin, Colombia

J. Mejia Guisao , F. Ramirez , M. Rodriguez , J.D. Ruiz Alvarez 

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

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

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac , T. Sculac 

Institute Rudjer Boskovic, Zagreb, Croatia

P. Bargassa , V. Brigljevic , B.K. Chitroda , D. Ferencek , S. Mishra , M. Roguljic , A. Starodumov¹² , T. Susa 

University of Cyprus, Nicosia, Cyprus

A. Attikis , K. Christoforou , S. Konstantinou , J. Mousa , C. Nicolaou, F. Ptochos , P.A. Razis , H. Rykaczewski, H. Saka , A. Stepennov 

Charles University, Prague, Czech Republic

M. Finger¹² , M. Finger Jr.¹² , A. Kveton 

Escuela Politecnica Nacional, Quito, Ecuador

E. Ayala 

Universidad San Francisco de Quito, Quito, Ecuador

E. Carrera Jarrin 

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

A.A. Abdelalim^{13,14} , E. Salama^{15,16} 

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt

M. Abdullah Al-Mashad , M.A. Mahmoud 

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

S. Bhowmik , R.K. Dewanjee , K. Ehataht , M. Kadastik, T. Lange , S. Nandan , C. Nielsen , J. Pata , M. Raidal , L. Tani , C. Veelken 

Department of Physics, University of Helsinki, Helsinki, Finland

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

Helsinki Institute of Physics, Helsinki, Finland

S. Bharthuar , E. Brücken , F. Garcia , J. Havukainen , M.S. Kim , R. Kinnunen, T. Lampén , K. Lassila-Perini , S. Lehti , T. Lindén , M. Lotti, L. Martikainen , M. Myllymäki , M.m. Rantanen , H. Siikonen , E. Tuominen , J. Tuominiemi 

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland

P. Luukka , H. Petrow , T. Tuuva[†]

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

C. Amendola , M. Besancon , F. Couderc , M. Dejardin , D. Denegri, J.L. Faure, F. Ferri , S. Ganjour , P. Gras , G. Hamel de Monchenault , V. Lohezic , J. Malcles , J. Rander, A. Rosowsky , M.Ö. Sahin , A. Savoy-Navarro¹⁷ , P. Simkina , M. Titov 

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

C. Baldenegro Barrera , F. Beaudette , A. Buchot Perraguin , P. Busson , A. Cappati , C. Charlot , F. Damas , O. Davignon , B. Diab , G. Falmagne , B.A. Fontana Santos Alves , S. Ghosh , R. Granier de Cassagnac , A. Hakimi , B. Harikrishnan , G. Liu , J. Motta , M. Nguyen , C. Ochando , L. Portales , R. Salerno , U. Sarkar , J.B. Sauvan , Y. Sirois , A. Tarabini , E. Vernazza , A. Zabi , A. Zghiche 

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

J.-L. Agram¹⁸ , J. Andrea , D. Apparu , D. Bloch , G. Bourgatte , J.-M. Brom , E.C. Chabert , C. Collard , D. Darej, U. Goerlach , C. Grimault, A.-C. Le Bihan , P. Van Hove 

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France

S. Beauceron , B. Blancon , G. Boudoul , A. Carle, N. Chanon , J. Choi , D. Contardo , P. Depasse , C. Dozen¹⁹ , H. El Mamouni, J. Fay , S. Gascon , M. Gouzevitch , G. Grenier , B. Ille , I.B. Laktineh, M. Lethuillier , L. Mirabito, S. Perries, L. Torterotot , M. Vander Donckt , P. Verdier , S. Viret

Georgian Technical University, Tbilisi, Georgia

I. Lomidze , T. Toriashvili²⁰ , Z. Tsamalaidze¹² 

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

V. Botta , L. Feld , K. Klein , M. Lipinski , D. Meuser , A. Pauls , N. Röwert , M. Teroerde 

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

S. Diekmann , A. Dodonova , N. Eich , D. Eliseev , M. Erdmann , P. Fackeldey , D. Fasanella , B. Fischer , T. Hebbeker , K. Hoepfner , F. Ivone , M.y. Lee , L. Mastrolorenzo , M. Merschmeyer , A. Meyer , S. Mondal , S. Mukherjee , D. Noll , A. Novak , F. Nowotny , A. Pozdnyakov , Y. Rath , W. Redjeb , F. Rehm , H. Reithler , A. Schmidt , S.C. Schuler , A. Sharma , A. Stein , F. Torres Da Silva De Araujo²¹ , L. Vigilante , S. Wiedenbeck , S. Zaleski 

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

C. Dziwok , G. Flügge , W. Haj Ahmad²² , O. Hlushchenko , T. Kress , A. Nowack , O. Pooth , A. Stahl , T. Ziemons , A. Zotz 

Deutsches Elektronen-Synchrotron, Hamburg, Germany

H. Aarup Petersen , M. Aldaya Martin , J. Alimena , P. Asmuss , S. Baxter , M. Bayatmakou , H. Becerril Gonzalez , O. Behnke , S. Bhattacharya , F. Blekman²³ , K. Borrás²⁴ , D. Brunner , A. Campbell , A. Cardini , C. Cheng , F. Colombina , S. Consuegra Rodríguez , G. Correia Silva , M. De Silva , G. Eckerlin , D. Eckstein , L.I. Estevez Banos , O. Filatov , E. Gallo²³ , A. Geiser , A. Giraldi , G. Greau , A. Grohsjean , V. Guglielmi , M. Guthoff , A. Jafari²⁵ , N.Z. Jomhari , B. Kaech , M. Kasemann , H. Kaveh , C. Kleinwort , R. Kogler , M. Komm , D. Krücker , W. Lange , D. Leyva Pernia , K. Lipka²⁶ , W. Lohmann²⁷ , R. Mankel , I.-A. Melzer-Pellmann , M. Mendizabal Morentin , J. Metwally , A.B. Meyer , G. Milella , M. Mormile , A. Mussgiller , A. Nürnberg , Y. Otariid , D. Pérez Adán , E. Ranken , A. Raspereza , B. Ribeiro Lopes , J. Rübenach , A. Saggio , M. Savitskyi , M. Scham^{28,24} , V. Scheurer , S. Schnake²⁴ , P. Schütze , C. Schwanenberger²³ , M. Shchedrolosiev , R.E. Sosa Ricardo , D. Stafford , N. Tonon[†] , M. Van De Klundert , F. Vazzoler , A. Ventura Barroso , R. Walsh , Q. Wang , Y. Wen , K. Wichmann , L. Wiens²⁴ , C. Wissing , S. Wuchterl , Y. Yang , A. Zimmermann Castro Santos 

University of Hamburg, Hamburg, Germany

A. Albrecht , S. Albrecht , M. Antonello , S. Bein , L. Benato , M. Bonanomi , P. Connor , K. De Leo , M. Eich , K. El Morabit , F. Feindt , A. Fröhlich , C. Garbers , E. Garutti , M. Hajheidari , J. Haller , A. Hinzmann , H.R. Jabusch , G. Kasieczka , P. Keicher , R. Klanner , W. Korcar , T. Kramer , V. Kutzner , F. Labe , J. Lange , A. Lobanov , C. Matthies , A. Mehta , L. Moureaux , M. Mrowietz , A. Nigamova , Y. Nissan , A. Paasch , K.J. Pena Rodriguez , T. Quadfasel , M. Rieger , D. Savoia , J. Schindler , P. Schleper , M. Schröder , J. Schwandt , M. Sommerhalder , H. Stadie , G. Steinbrück , A. Tews , M. Wolf 

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

S. Brommer , M. Burkart , E. Butz , T. Chwalek , A. Dierlamm , A. Droll , N. Faltermann , M. Giffels , J.O. Gosewisch , A. Gottmann , F. Hartmann²⁹ , M. Horzela , U. Husemann , M. Klute , R. Koppenhöfer , M. Link , A. Lintuluoto , S. Maier , S. Mitra , Th. Müller , M. Neukum , M. Oh , G. Quast , K. Rabbertz , I. Shvetsov , H.J. Simonis , N. Trevisani , R. Ulrich , J. van der Linden , R.F. Von Cube , M. Wassmer , S. Wieland , R. Wolf , S. Wozniowski , S. Wunsch , X. Zuo 

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

G. Anagnostou , P. Assiouras , G. Daskalakis , A. Kyriakis , A. Stakia 

National and Kapodistrian University of Athens, Athens, Greece

M. Diamantopoulou , D. Karasavvas , P. Kontaxakis , A. Manousakis-Katsikakis , A. Pana-

giotou, I. Papavergou , N. Saoulidou , K. Theofilatos , E. Tziaferi , K. Vellidis , I. Zisopoulos 

National Technical University of Athens, Athens, Greece

G. Bakas , T. Chatzistavrou, G. Karapostoli , K. Kousouris , I. Papakrivopoulos , G. Tsipolitis, A. Zacharopoulou

University of Ioánnina, Ioánnina, Greece

K. Adamidis, I. Bestintzanos, I. Evangelou , C. Foudas, P. Gianneios , C. Kamtsikis, P. Katsoulis, P. Kokkas , P.G. Kosmoglou Kioseoglou , N. Manthos , I. Papadopoulos , J. Strologas 

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

M. Csanád , K. Farkas , M.M.A. Gadallah³⁰ , P. Major , K. Mandal , G. Pásztor , A.J. Rádl³¹ , O. Surányi , G.I. Veres 

Wigner Research Centre for Physics, Budapest, Hungary

M. Bartók³² , G. Bencze, C. Hajdu , D. Horvath^{33,34} , F. Sikler , V. Veszpremi 

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni , S. Czellar, J. Karancsi³² , J. Molnar, Z. Szillasi, D. Teyssier 

Institute of Physics, University of Debrecen, Debrecen, Hungary

P. Raics, B. Ujvari³⁵ , G. Zilizi 

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary

T. Csorgo³¹ , F. Nemes³¹ , T. Novak 

Panjab University, Chandigarh, India

J. Babbar , S. Bansal , S.B. Beri, V. Bhatnagar , G. Chaudhary , S. Chauhan , N. Dhingra³⁶ , R. Gupta, A. Kaur , A. Kaur , H. Kaur , M. Kaur , S. Kumar , P. Kumari , M. Meena , K. Sandeep , T. Sheokand, J.B. Singh³⁷ , A. Singla 

University of Delhi, Delhi, India

A. Ahmed , A. Bhardwaj , A. Chhetri , B.C. Choudhary , A. Kumar , M. Naimuddin , K. Ranjan , S. Saumya 

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

S. Baradia , S. Barman³⁸ , S. Bhattacharya , D. Bhowmik, S. Dutta , S. Dutta, B. Gomber³⁹ , M. Maity³⁸ , P. Palit , G. Saha , B. Sahu , S. Sarkar

Indian Institute of Technology Madras, Madras, India

P.K. Behera , S.C. Behera , S. Chatterjee , P. Kalbhor , J.R. Komaragiri⁴⁰ , D. Kumar⁴⁰ , A. Muhammad , L. Panwar⁴⁰ , R. Pradhan , P.R. Pujahari , N.R. Saha , A. Sharma , A.K. Sikdar , S. Verma 

Bhabha Atomic Research Centre, Mumbai, India

K. Naskar⁴¹ 

Tata Institute of Fundamental Research-A, Mumbai, India

T. Aziz, I. Das , S. Dugad, M. Kumar , G.B. Mohanty , P. Suryadevara

Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee , M. Guchait , S. Karmakar , S. Kumar , G. Majumder , K. Mazumdar , S. Mukherjee , A. Thachayath 

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India

S. Bahinipati⁴² , A.K. Das , C. Kar , P. Mal , T. Mishra , V.K. Muraleedharan Nair Bindhu⁴³ , A. Nayak⁴³ , P. Saha , S.K. Swain , D. Vats⁴³

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

A. Alpana , S. Dube , B. Kansal , A. Laha , S. Pandey , A. Rastogi , S. Sharma 

Isfahan University of Technology, Isfahan, Iran

H. Bakhshiansohi^{44,45} , E. Khazaie⁴⁵ , M. Zeinali⁴⁶ 

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

S. Chenarani⁴⁷ , S.M. Etesami , M. Khakzad , M. Mohammadi Najafabadi 

University College Dublin, Dublin, Ireland

M. Grunewald 

INFN Sezione di Bari^a, Università di Bari^b, Politecnico di Bari^c, Bari, Italy

M. Abbrescia^{a,b} , R. Aly^{a,b,13} , C. Aruta^{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} , W. Elmetenawee^{a,b} , F. Errico^{a,b} , L. Fiore^a , G. Iaselli^{a,c} , G. Maggi^{a,c} , M. Maggi^a , I. Margjeka^{a,b} , V. Mastrapasqua^{a,b} , S. My^{a,b} , S. Nuzzo^{a,b} , A. Pellecchia^{a,b} , A. Pompili^{a,b} , G. Pugliese^{a,c} , R. Radogna^a , D. Ramos^a , A. Ranieri^a , G. Selvaggi^{a,b} , L. Silvestris^a , F.M. Simone^{a,b} , Ü. Sözbilir^a , A. Stamerra^a , R. Venditti^a , P. Verwilligen^a

INFN Sezione di Bologna^a, Università di Bologna^b, Bologna, Italy

G. Abbiendi^a , C. Battilana^{a,b} , D. Bonacorsi^{a,b} , L. Borghonovi^a , L. Brigliadori^a , R. Campanini^{a,b} , P. Capiluppi^{a,b} , A. Castro^{a,b} , F.R. Cavallo^a , M. Cuffiani^{a,b} , G.M. Dallavalle^a , T. Diotallevi^{a,b} , F. Fabbri^a , A. Fanfani^{a,b} , P. Giacomelli^a , L. Giommi^{a,b} , C. Grandi^a , L. Guiducci^{a,b} , S. Lo Meo^{a,48} , L. Lunerti^{a,b} , 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}

INFN Sezione di Catania^a, Università di Catania^b, Catania, Italy

S. Costa^{a,b,49} , A. Di Mattia^a , R. Potenza^{a,b} , A. Tricomi^{a,b,49} , C. Tuve^{a,b} 

INFN Sezione di Firenze^a, Università di Firenze^b, Firenze, Italy

G. Barbagli^a , G. Bardelli^{a,b} , B. Camaiani^{a,b} , A. Cassese^a , R. Ceccarelli^{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. Lizzo^{a,b} , M. Meschini^a , S. Paoletti^a , G. Sguazzoni^a , L. Viliani^a

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi , S. Bianco , S. Meola⁵⁰ , D. Piccolo 

INFN Sezione di Genova^a, Università di Genova^b, Genova, Italy

M. Bozzo^{a,b} , P. Chatagnon^a , F. Ferro^a , E. Robutti^a , S. Tosi^{a,b} 

INFN Sezione di Milano-Bicocca^a, Università di Milano-Bicocca^b, Milano, Italy

A. Benaglia^a , G. Boldrini^a , F. Brivio^{a,b} , F. Cetorelli^{a,b} , F. De Guio^{a,b} , M.E. Dinardo^{a,b} , P. Dini^a , S. Gennai^a , A. Ghezzi^{a,b} , P. Govoni^{a,b} , L. Guzzi^{a,b} , M.T. Lucchini^{a,b} , M. Malberti^a , S. Malvezzi^a , A. Massironi^a , D. Menasce^a , L. Moroni^a , M. Paganoni^{a,b} , D. Pedrini^a , B.S. Pinolini^a , S. Ragazzi^{a,b} , N. Redaelli^a , T. Tabarelli de Fatis^{a,b} , D. Zuolo^{a,b}

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

S. Buontempo^a , A. Cagnotta^{a,b} , F. Carnevali^{a,b} , N. Cavallo^{a,c} , A. De Iorio^{a,b} , F. Fabozzi^{a,c} , A.O.M. Iorio^{a,b} , L. Lista^{a,b,51} , P. Paolucci^{a,29} , B. Rossi^a , C. Sciacca^{a,b} 

INFN Sezione di Padova^a, Università di Padova^b, Padova, Italy; Università di Trento^c, Trento, Italy

P. Azzi^a , N. Bacchetta^{a,52} , D. Bisello^{a,b} , P. Bortignon^a , A. Bragagnolo^{a,b} , R. Carlin^{a,b} , T. Dorigo^a , F. Gasparini^{a,b} , U. Gasparini^{a,b} , G. Grosso^a, L. Layer^{a,53}, E. Lusiani^a , A.T. Meneguzzo^{a,b} , F. Montecassiano^a , M. Passaseo^a , J. Pazzini^{a,b} , P. Ronchese^{a,b} , R. Rossin^{a,b} , F. Simonetto^{a,b} , G. Strong^a , M. Tosi^{a,b} , H. Yarar^{a,b}, M. Zanetti^{a,b} , P. Zotto^{a,b} , A. Zucchetta^{a,b} , G. Zumerle^{a,b} 

INFN Sezione di Pavia^a, Università di Pavia^b, Pavia, Italy

S. Abu Zeid^{a,16} , C. Aimè^{a,b} , A. Braghieri^a , S. Calzaferri^{a,b} , D. Fiorina^{a,b} , P. Montagna^{a,b} , V. Re^a , C. Riccardi^{a,b} , P. Salvini^a , I. Vai^{a,b} , P. Vitulo^{a,b} 

INFN Sezione di Perugia^a, Università di Perugia^b, Perugia, Italy

P. Asenov^{a,54} , G.M. Bilei^a , D. Ciangottini^{a,b} , L. Fanò^{a,b} , M. Magherini^{a,b} , G. Mantovani^{a,b}, V. Mariani^{a,b} , M. Menichelli^a , F. Moscatelli^{a,54} , A. Piccinelli^{a,b} , M. Presilla^{a,b} , A. Rossi^{a,b} , A. Santocchia^{a,b} , D. Spiga^a , T. Tedeschi^{a,b} 

INFN Sezione di Pisa^a, Università di Pisa^b, Scuola Normale Superiore di Pisa^c, Pisa, Italy; Università di Siena^d, Siena, Italy

P. Azzurri^a , G. Bagliesi^a , V. Bertacchi^{a,c} , R. Bhattacharya^a , L. Bianchini^{a,b} , T. Boccali^a , E. Bossini^{a,b} , D. Bruschini^{a,c} , R. Castaldi^a , M.A. Ciocci^{a,b} , V. D'Amante^{a,d} , R. Dell'Orso^a , S. Donato^a , A. Giassi^a , F. Ligabue^{a,c} , D. Matos Figueiredo^a , A. Messineo^{a,b} , M. Musich^{a,b} , F. Palla^a , S. Parolia^a , G. Ramirez-Sanchez^{a,c} , A. Rizzi^{a,b} , G. Rolandi^{a,c} , S. Roy Chowdhury^a , T. Sarkar^a , A. Scribano^a , P. Spagnolo^a , R. Tenchini^a , G. Tonelli^{a,b} , N. Turini^{a,d} , A. Venturi^a , P.G. Verdini^a 

INFN Sezione di Roma^a, Sapienza Università di Roma^b, Roma, Italy

P. Barria^a , M. Campana^{a,b} , F. Cavallari^a , D. Del Re^{a,b} , E. Di Marco^a , M. Diemoz^a , E. Longo^{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 , R. Tramontano^{a,b} 

INFN Sezione di Torino^a, Università di Torino^b, Torino, Italy; Università del Piemonte Orientale^c, Novara, 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^{a,b} , C. Biino^a , N. Cartiglia^a , M. Costa^{a,b} , R. Covarelli^{a,b} , N. Demaria^a , M. Grippa^{a,b} , B. Kiani^{a,b} , F. Legger^a , F. Luongo^{a,b} , C. Mariotti^a , S. Maselli^a , A. Mecca^{a,b} , E. Migliore^{a,b} , M. Monteno^a , R. Mulargia^a , M.M. Obertino^{a,b} , G. Ortona^a , L. Pacher^{a,b} , N. Pastrone^a , M. Pelliccioni^a , M. Ruspa^{a,c} , K. Shchelina^a , F. Siviero^{a,b} , V. Sola^{a,b} , A. Solano^{a,b} , D. Soldi^{a,b} , A. Staiano^a , C. Tarricone^{a,b} , M. Tornago^{a,b} , D. Trocino^a , G. Umoret^{a,b} , A. Vagnerini^{a,b} , E. Vlasov^{a,b} 

INFN Sezione di Trieste^a, Università di Trieste^b, Trieste, Italy

S. Belforte^a , V. Candelise^{a,b} , M. Casarsa^a , F. Cossutti^a , G. Della Ricca^{a,b} , G. Sorrentino^{a,b} 

Kyungpook National University, Daegu, Korea

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

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

H. Kim , D.H. Moon 

Hanyang University, Seoul, Korea

E. Asilar , T.J. Kim , J. Park 

Korea University, Seoul, Korea

S. Choi , S. Han , B. Hong , K. Lee , K.S. Lee , J. Lim , J. Park , S.K. Park , J. Yoo 

Kyung Hee University, Department of Physics, Seoul, Korea

J. Goh 

Sejong University, Seoul, Korea

H. S. Kim , Y. Kim , S. Lee 

Seoul National University, Seoul, Korea

J. Almond , J.H. Bhyun , J. Choi , S. Jeon , J. Kim , J.S. Kim , S. Ko , H. Kwon , H. Lee , S. Lee , B.H. Oh , S.B. Oh , H. Seo , U.K. Yang , I. Yoon 

University of Seoul, Seoul, Korea

W. Jang , D.Y. Kang , Y. Kang , D. Kim , S. Kim , B. Ko , J.S.H. Lee , Y. Lee , J.A. Merlin , I.C. Park , Y. Roh , D. Song , I.J. Watson , S. Yang 

Yonsei University, Department of Physics, Seoul, Korea

S. Ha , H.D. Yoo 

Sungkyunkwan University, Suwon, Korea

M. Choi , M.R. Kim , H. Lee , Y. Lee , I. Yu 

College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait

T. Beyrouthy , Y. Maghrbi 

Riga Technical University, Riga, Latvia

K. Dreimanis , G. Pikurs , A. Potrebko , M. Seidel , V. Veckalns 

Vilnius University, Vilnius, Lithuania

M. Ambrozaitis , A. Carvalho Antunes De Oliveira , A. Juodagalvis , A. Rinkevicius , G. Tamulaitis 

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

N. Bin Norjoharuddeen , S.Y. Hoh⁵⁵ , I. Yusuff⁵⁵ , Z. Zolkapli 

Universidad de Sonora (UNISON), Hermosillo, Mexico

J.F. Benitez , A. Castaneda Hernandez , H.A. Encinas Acosta , L.G. Gallegos Maríñez , M. León Coello , J.A. Murillo Quijada , A. Sehwat , L. Valencia Palomo 

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

G. Ayala , H. Castilla-Valdez , I. Heredia-De La Cruz⁵⁶ , R. Lopez-Fernandez , C.A. Mondragon Herrera , D.A. Perez Navarro , A. Sánchez Hernández 

Universidad Iberoamericana, Mexico City, Mexico

C. Oropeza Barrera , F. Vazquez Valencia 

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

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

University of Montenegro, Podgorica, Montenegro

I. Bubanja, J. Mijuskovic⁵⁷ , N. Raicevic 

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

A. Ahmad , M.I. Asghar, A. Awais , M.I.M. Awan, M. Gul , H.R. Hoorani , W.A. Khan 

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

V. Avati, L. Grzanka , M. Malawski 

National Centre for Nuclear Research, Swierk, Poland

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

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

K. Bunkowski , K. Doroba , A. Kalinowski , M. Konecki , J. Krolikowski 

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

M. Araujo , D. Bastos , A. Boletti , P. Faccioli , M. Gallinaro , J. Hollar , N. Leonardo , T. Niknejad , M. Pisano , J. Seixas , J. Varela 

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

M. Dordevic , J. Milosevic 

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

M. Aguilar-Benitez, J. Alcaraz Maestre , M. Barrio Luna, Cristina F. Bedoya , M. Cepeda , M. Cerrada , N. Colino , B. De La Cruz , A. Delgado Peris , D. Fernández Del Val , J.P. Fernández Ramos , J. Flix , M.C. Fouz , O. Gonzalez Lopez , S. Goy Lopez , J.M. Hernandez , M.I. Josa , J. León Holgado , D. Moran , C. Perez Dengra , A. Pérez-Calero Yzquierdo , J. Puerta Pelayo , I. Redondo , D.D. Redondo Ferrero , L. Romero, S. Sánchez Navas , J. Sastre , L. Urda Gómez , J. Vazquez Escobar , C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain

J.F. de Trocóniz 

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

B. Alvarez Gonzalez , J. Cuevas , J. Fernandez Menendez , S. Folgueras , I. Gonzalez Caballero , J.R. González Fernández , E. Palencia Cortezon , C. Ramón Álvarez , V. Rodríguez Bouza , A. Soto Rodríguez , A. Trapote , C. Vico Villalba 

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

J.A. Brochero Cifuentes , I.J. Cabrillo , A. Calderon , J. Duarte Campderros , M. Fernandez , C. Fernandez Madrazo , A. García Alonso, G. Gomez , C. Lasasa García , C. Martinez Rivero , P. Martinez Ruiz del Arbol , F. Matorras , P. Matorras Cuevas , J. Piedra Gomez , C. Prieels, L. Scodellaro , I. Vila , J.M. Vizan Garcia 

University of Colombo, Colombo, Sri Lanka

M.K. Jayananda , B. Kailasapathy⁵⁸ , D.U.J. Sonnadara , D.D.C. Wickramarathna 

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

W.G.D. Dharmaratna , K. Liyanage , N. Perera , N. Wickramage 

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo , E. Auffray , G. Auzinger , J. Baechler , P. Baillon[†], D. Barney , J. Bendauid , A. Bermúdez Martínez , M. Bianco , B. Bilin , A.A. Bin Anuar , A. Bocci , E. Brondolin , C. Caillol , T. Camporesi , G. Cerminara , N. Chernyavskaya , S.S. Chhibra , S. Choudhury , M. Cipriani , D. d'Enterria , A. Dabrowski , A. David , A. De Roeck , M.M. Defranchis , M. Deile , M. Dobson , M. Dünser , N. Dupont , F. Fallavollita⁵⁹, A. Florent , L. Forthomme , G. Franzoni , W. Funk , S. Ghosh , S. Giani , D. Gigi , K. Gill , F. Glege , L. Gouskos , E. Govorkova , M. Haranko , J. Hegeman , V. Innocente , T. James , P. Janot , J. Kaspar , J. Kieseler , N. Kratochwil , S. Laurila , P. Lecoq , E. Leutgeb , C. Lourenço , B. Maier , L. Malgeri , M. Mannelli , A.C. Marini , F. Meijers , S. Mersi , E. Meschi , F. Moortgat , M. Mulders , S. Orfanelli , L. Orsini , F. Pantaleo , E. Perez , M. Peruzzi , A. Petrilli , G. Petrucciani , A. Pfeiffer , M. Pierini , D. Piparo , M. Pitt , H. Qu , T. Quast , D. Rabady , A. Racz , G. Reales Gutiérrez , M. Rovere , H. Sakulin , J. Salfeld-Nebgen , S. Scarfi , M. Selvaggi , A. Sharma , P. Silva , P. Sphicas⁶⁰ , A.G. Stahl Leitner , S. Summers , K. Tatar , D. Treille , P. Tropea , A. Tsiros , D. Walter , J. Wanczyk⁶¹ , K.A. Wozniak , W.D. Zeuner 

Paul Scherrer Institut, Villigen, Switzerland

T. Bevilacqua , L. Caminada⁶² , A. Ebrahimi , W. Erdmann , R. Horisberger , Q. Ingram , H.C. Kaestli , D. Kotlinski , C. Lange , M. Missiroli⁶² , L. Noehte⁶² , T. Rohe 

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

T.K. Aarrestad , K. Androsov⁶¹ , M. Backhaus , A. Calandri , K. Datta , A. De Cosa , G. Dissertori , M. Dittmar , M. Donegà , F. Eble , M. Galli , K. Gedia , F. Glessgen , T.A. Gómez Espinosa , C. Grab , D. Hits , W. Lustermann , A.-M. Lyon , R.A. Manzoni , L. Marchese , C. Martin Perez , A. Mascellani⁶¹ , F. Nessi-Tedaldi , J. Niedziela , F. Pauss , V. Perovic , S. Pigazzini , M.G. Ratti , M. Reichmann , C. Reissel , T. Reitenspiess , B. Ristic , F. Riti , D. Ruini , D.A. Sanz Becerra , R. Seidita , J. Steggemann⁶¹ , D. Valsecchi , R. Wallny 

Universität Zürich, Zurich, Switzerland

C. Amsler⁶³ , P. Bärtschi , C. Botta , D. Brzhechko , M.F. Canelli , K. Cormier , A. De Wit , R. Del Burgo , J.K. Heikkilä , M. Huwiler , W. Jin , A. Jofrehei , B. Kilminster , S. Leontsinis , S.P. Liechti , A. Macchiolo , P. Meiring , V.M. Mikuni , U. Molinatti , I. Neutelings , A. Reimers , P. Robmann , S. Sanchez Cruz , K. Schweiger , M. Senger , Y. Takahashi 

National Central University, Chung-Li, Taiwan

C. Adloff⁶⁴, C.M. Kuo , W. Lin , P.K. Rout , P.C. Tiwari⁴⁰ , S.S. Yu 

National Taiwan University (NTU), Taipei, Taiwan

L. Ceard , Y. Chao , K.F. Chen , P.s. Chen , H. Cheng , W.-S. Hou , R. Khurana , G. Kole , Y.y. Li , R.-S. Lu , E. Paganis , A. Psallidas , A. Steen , H.y. Wu , E. Yazgan 

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

C. Asawatangkuldee , N. Srimanobhas , V. Wachirapusanand 

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

D. Agyel , F. Boran , Z.S. Demiroglu , F. Dolek , I. Dumanoglu⁶⁵ , E. Eskut , Y. Guler⁶⁶ , E. Gurpinar Guler⁶⁶ , C. Isik , O. Kara, A. Kayis Topaksu , U. Kiminsu , G. Onengut , K. Ozdemir⁶⁷ , A. Polatoz , B. Tali⁶⁸ , U.G. Tok , S. Turkcapar , E. Uslan , I.S. Zorbakir 

Middle East Technical University, Physics Department, Ankara, Turkey

G. Karapinar⁶⁹, K. Ocalan⁷⁰ , M. Yalvac⁷¹ 

Bogazici University, Istanbul, Turkey

B. Akgun , I.O. Atakisi , E. Gülmez , M. Kaya⁷² , O. Kaya⁷³ , S. Tekten⁷⁴ 

Istanbul Technical University, Istanbul, Turkey

A. Cakir , K. Cankocak⁶⁵ , Y. Komurcu , S. Sen⁷⁵ 

Istanbul University, Istanbul, Turkey

O. Aydilek , S. Cerci⁶⁸ , B. Hacisahinoglu , I. Hos⁷⁶ , B. Isildak⁷⁷ , B. Kaynak , S. Ozkorucuklu , C. Simsek , D. Sunar Cerci⁶⁸ 

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

B. Grynyov 

National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine

L. Levchuk 

University of Bristol, Bristol, United Kingdom

D. Anthony , J.J. Brooke , A. Bundock , E. Clement , D. Cussans , H. Flacher , M. Glowacki, J. Goldstein , H.F. Heath , L. Kreczko , B. Krikler , S. Paramesvaran , S. Seif El Nasr-Storey, V.J. Smith , N. Stylianou⁷⁸ , K. Walkingshaw Pass, R. White 

Rutherford Appleton Laboratory, Didcot, United Kingdom

A.H. Ball, K.W. Bell , A. Belyaev⁷⁹ , C. Brew , R.M. Brown , D.J.A. Cockerill , C. Cooke , K.V. Ellis, K. Harder , S. Harper , M.-L. Holmberg⁸⁰ , Sh. Jain , J. Linacre , K. Manolopoulos, D.M. Newbold , E. Olaiya, D. Petyt , T. Reis , G. Salvi , T. Schuh, C.H. Shepherd-Themistocleous , I.R. Tomalin , T. Williams 

Imperial College, London, United Kingdom

R. Bainbridge , P. Bloch , S. Bonomally, J. Borg , C.E. Brown , O. Buchmuller, V. Cacchio, C.A. Carrillo Montoya , V. Cepaitis , G.S. Chahal⁸¹ , D. Colling , J.S. Dancu, P. Dauncey , G. Davies , J. Davies, M. Della Negra , S. Fayer, G. Fedi , G. Hall , M.H. Hassanshahi , A. Howard, G. Iles , J. Langford , L. Lyons , A.-M. Magnan , S. Malik, A. Martelli , M. Mieskolainen , D.G. Monk , J. Nash⁸² , M. Pesaresi, B.C. Radburn-Smith , A. Richards, A. Rose , E. Scott , C. Seez , R. Shukla , A. Tapper , K. Uchida , G.P. Uttley , L.H. Vage, T. Virdee²⁹ , M. Vojinovic , N. Wardle , S.N. Webb , D. Winterbottom 

Brunel University, Uxbridge, United Kingdom

K. Coldham, J.E. Cole , A. Khan, P. Kyberd , I.D. Reid 

Baylor University, Waco, Texas, USA

S. Abdullin , A. Brinkerhoff , B. Caraway , J. Dittmann , K. Hatakeyama , A.R. Kanuganti , B. McMaster , M. Saunders , S. Sawant , C. Sutantawibul , M. Toms , J. Wilson 

Catholic University of America, Washington, DC, USA

R. Bartek , A. Dominguez , C. Huerta Escamilla, A.E. Simsek , R. Uniyal , A.M. Vargas Hernandez 

The University of Alabama, Tuscaloosa, Alabama, USA

R. Chudasama , S.I. Cooper , D. Di Croce , S.V. Gleyzer , C.U. Perez , P. Rumerio⁸³ , E. Usai , C. West 

Boston University, Boston, Massachusetts, USA

A. Akpinar , A. Albert , D. Arcaro , C. Cosby , Z. Demiragli , C. Erice , E. Fontanesi , D. Gastler , S. May , J. Rohlf , K. Salyer , D. Sperka , D. Spitzbart , I. Suarez , A. Tsatsos , S. Yuan 

Brown University, Providence, Rhode Island, USA

G. Benelli , X. Coubez²⁴, D. Cutts , M. Hadley , U. Heintz , J.M. Hogan⁸⁴ , T. Kwon , G. Landsberg , K.T. Lau , D. Li , J. Luo , M. Narain , N. Pervan , S. Sagir⁸⁵ , F. Simpson , W.Y. Wong, X. Yan , D. Yu , W. Zhang

University of California, Davis, Davis, California, USA

S. Abbott , J. Bonilla , C. Brainerd , R. Breedon , M. Calderon De La Barca Sanchez , M. Chertok , J. Conway , P.T. Cox , R. Erbacher , G. Haza , F. Jensen , O. Kukral , G. Mocellin , M. Mulhearn , D. Pellett , B. Regnery , Y. Yao , F. Zhang 

University of California, Los Angeles, Los Angeles, California, USA

M. Bachtis , R. Cousins , A. Datta , J. Hauser , M. Ignatenko , M.A. Iqbal , T. Lam , E. Manca , W.A. Nash , D. Saltzberg , B. Stone , V. Valuev 

University of California, Riverside, Riverside, California, USA

R. Clare , J.W. Gary , M. Gordon, G. Hanson , O.R. Long , N. Manganelli , W. Si , S. Wimpenny 

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

J.G. Branson , S. Cittolin , S. Cooperstein , D. Diaz , J. Duarte , R. Gerosa , L. Gianini , J. Guiang , R. Kansal , V. Krutelyov , R. Lee , J. Letts , M. Masciovecchio , F. Mokhtar , M. Pieri , M. Quinnan , B.V. Sathia Narayanan , V. Sharma , M. Tadel , E. Vourliotis , F. Würthwein , Y. Xiang , A. Yagil 

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

L. Brennan, C. Campagnari , M. Citron , G. Collura , A. Dorsett , J. Incandela , M. Kilpatrick , J. Kim , A.J. Li , P. Masterson , H. Mei , M. Oshiro , J. Richman , U. Sarica , R. Schmitz , F. Setti , J. Sheplock , P. Siddireddy, D. Stuart , S. Wang 

California Institute of Technology, Pasadena, California, USA

A. Bornheim , O. Cerri, I. Dutta , A. Latorre, J.M. Lawhorn , J. Mao , H.B. Newman , T. Q. Nguyen , M. Spiropulu , J.R. Vlimant , C. Wang , S. Xie , R.Y. Zhu 

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA

J. Alison , S. An , M.B. Andrews , P. Bryant , V. Dutta , T. Ferguson , A. Harilal , C. Liu , T. Mudholkar , S. Murthy , M. Paulini , A. Roberts , A. Sanchez , W. Terrill 

University of Colorado Boulder, Boulder, Colorado, USA

J.P. Cumalat , W.T. Ford , A. Hassani , G. Karathanasis , E. MacDonald, F. Marini , A. Perloff , C. Savard , N. Schonbeck , K. Stenson , K.A. Ulmer , S.R. Wagner , N. Zipper 

Cornell University, Ithaca, New York, USA

J. Alexander , S. Bright-Thonney , X. Chen , D.J. Cranshaw , J. Fan , X. Fan , D. Gadkari , S. Hogan , J. Monroy , J.R. Patterson , J. Reichert , M. Reid , A. Ryd , J. Thom , P. Wittich , R. Zou 

Fermi National Accelerator Laboratory, Batavia, Illinois, USA

M. Albrow , M. Alyari , G. Apollinari , A. Apresyan , L.A.T. Bauerdick , D. Berry , J. Berryhill , P.C. Bhat , K. Burkett , J.N. Butler , A. Canepa , G.B. Cerati , H.W.K. Cheung , F. Chlebana , K.F. Di Petrillo , J. Dickinson , V.D. Elvira , Y. Feng , J. Freeman , A. Gandrakota , Z. Gece , L. Gray , D. Green , S. Grünendahl , D. Guerrero , O. Gutsche , R.M. Harris , R. Heller , T.C. Herwig , J. Hirschauer , L. Horyn , B. Jayatilaka , S. Jindariani , M. Johnson , U. Joshi , T. Klijnsma , B. Klima , K.H.M. Kwok , S. Lammel , D. Lincoln , R. Lipton , T. Liu , C. Madrid , K. Maeshima , C. Mantilla , D. Mason , P. McBride , P. Merkel , S. Mrenna , S. Nahn , J. Ngadiuba , D. Noonan , S. Norberg , V. Papadimitriou , N. Pastika , K. Pedro , C. Pena⁸⁶ , F. Ravera , A. Reinsvold Hall⁸⁷ , L. Ristori , E. Sexton-Kennedy , N. Smith , A. Soha , L. Spiegel , J. Strait , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger , E.W. Vaandering , I. Zoi 

University of Florida, Gainesville, Florida, USA

P. Avery , D. Bourilkov , L. Cadamuro , P. Chang , V. Cherepanov , R.D. Field , E. Koenig , M. Kolosova , J. Konigsberg , A. Korytov , E. Kuznetsova , K.H. Lo , K. Matchev , N. Menendez , G. Mitselmakher , A. Muthirakalayil Madhu , N. Rawal , D. Rosenzweig , S. Rosenzweig , K. Shi , J. Wang , Z. Wu 

Florida State University, Tallahassee, Florida, USA

T. Adams , A. Askew , N. Bower , R. Habibullah , V. Hagopian , T. Kolberg , G. Martinez , H. Prosper , O. Viazlo , M. Wulansatiti , R. Yohay , J. Zhang 

Florida Institute of Technology, Melbourne, Florida, USA

M.M. Baarmand , S. Butalla , T. Elkafrawy¹⁶ , M. Hohlmann , R. Kumar Verma , M. Rahmani , F. Yumiceva 

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

M.R. Adams , R. Cavanaugh , S. Dittmer , O. Evdokimov , C.E. Gerber , D.J. Hofman , D. S. Lemos , A.H. Merrit , C. Mills , G. Oh , T. Roy , S. Rudrabhatla , M.B. Tonjes , N. Varelas , X. Wang , Z. Ye , J. Yoo 

The University of Iowa, Iowa City, Iowa, USA

M. Alhousseini , K. Dilsiz⁸⁸ , L. Emediato , G. Karaman , O.K. Köseyan , J.-P. Merlo , A. Mestvirishvili⁸⁹ , J. Nachtman , O. Neogi , H. Ogul⁹⁰ , Y. Onel , A. Penzo , C. Snyder , E. Tiras⁹¹ 

Johns Hopkins University, Baltimore, Maryland, USA

O. Amram , B. Blumenfeld , L. Corcodilos , J. Davis , A.V. Gritsan , S. Kyriacou , P. Maksimovic , J. Roskes , S. Sekhar , M. Swartz , T.Á. Vámi 

The University of Kansas, Lawrence, Kansas, USA

A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , P. Baringer , A. Bean , Z. Flowers , J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu , C. Lindsey , J. Marquez , N. Minafra , M. Murray , M. Nickel , C. Rogan , C. Royon , R. Salvatico , S. Sanders , C. Smith , Q. Wang , G. Wilson 

Kansas State University, Manhattan, Kansas, USA

B. Allmond , S. Duric, A. Ivanov , K. Kaadze , A. Kalogeropoulos , D. Kim, Y. Maravin , T. Mitchell, A. Modak, K. Nam, D. Roy 

Lawrence Livermore National Laboratory, Livermore, California, USA

F. Rebassoo , D. Wright 

University of Maryland, College Park, Maryland, USA

E. Adams , A. Baden , O. Baron, A. Belloni , A. Bethani , S.C. Eno , N.J. Hadley , S. Jabeen , R.G. Kellogg , T. Koeth , Y. Lai , S. Lascio , A.C. Mignerey , S. Nabili , C. Palmer , C. Papageorgakis , L. Wang , K. Wong 

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

W. Busza , I.A. Cali , Y. Chen , M. D'Alfonso , J. Eysermans , C. Freer , G. Gomez-Ceballos , M. Goncharov, P. Harris, D. Kovalskyi , J. Krupa , Y.-J. Lee , K. Long , C. Mironov , C. Paus , D. Rankin , C. Roland , G. Roland , Z. Shi , G.S.F. Stephans , J. Wang, Z. Wang , B. Wyslouch , T. J. Yang 

University of Minnesota, Minneapolis, Minnesota, USA

R.M. Chatterjee, B. Crossman , J. Hiltbrand , B.M. Joshi , C. Kapsiak , M. Krohn , Y. Kubota , D. Mahon , J. Mans , M. Revering , R. Rusack , R. Saradhy , N. Schroeder , N. Strobbe , M.A. Wadud 

University of Mississippi, Oxford, Mississippi, USA

L.M. Cremaldi 

University of Nebraska-Lincoln, Lincoln, Nebraska, USA

K. Bloom , M. Bryson, D.R. Claes , C. Fangmeier , L. Finco , F. Golf , C. Joo , R. Kamalieddin, I. Kravchenko , I. Reed , J.E. Siado , G.R. Snow[†], W. Tabb , A. Wightman , F. Yan , A.G. Zecchinelli 

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

G. Agarwal , H. Bandyopadhyay , L. Hay , I. Iashvili , A. Kharchilava , C. McLean , M. Morris , D. Nguyen , J. Pekkanen , S. Rappoccio , A. Williams 

Northeastern University, Boston, Massachusetts, USA

G. Alverson , E. Barberis , Y. Haddad , Y. Han , A. Krishna , J. Li , J. Lidrych , G. Madigan , B. Marzocchi , D.M. Morse , V. Nguyen , T. Orimoto , A. Parker , L. Skinnari , A. Tishelman-Charny , T. Wamorkar , B. Wang , A. Wisecarver , D. Wood 

Northwestern University, Evanston, Illinois, USA

S. Bhattacharya , J. Bueghly, Z. Chen , A. Gilbert , K.A. Hahn , Y. Liu , N. Odell , M.H. Schmitt , M. Velasco

University of Notre Dame, Notre Dame, Indiana, USA

R. Band , R. Bucci, M. Cremonesi, A. Das , R. Goldouzian , M. Hildreth , K. Hurtado Anampa , C. Jessop , K. Lannon , J. Lawrence , N. Loukas , L. Lutton , J. Mariano, N. Marinelli, I. Mcalister, T. McCauley , C. Mcgrady , K. Mohrman , C. Moore , Y. Musienko¹² , R. Ruchti , A. Townsend , M. Wayne , H. Yockey, M. Zarucki , L. Zygala 

The Ohio State University, Columbus, Ohio, USA

B. Bylsma, M. Carrigan , L.S. Durkin , C. Hill , M. Joyce , A. Lesauvage , M. Nunez Ornelas , K. Wei, B.L. Winer , B. R. Yates 

Princeton University, Princeton, New Jersey, USA

F.M. Addesa , H. Bouchamaoui , P. Das , G. Dezoort , P. Elmer , A. Frankenthal ,
B. Greenberg , N. Haubrich , S. Higginbotham , G. Kopp , S. Kwan , D. Lange ,
A. Loeliger , D. Marlow , I. Ojalvo , J. Olsen , D. Stickland , C. Tully 

University of Puerto Rico, Mayaguez, Puerto Rico, USA

S. Malik 

Purdue University, West Lafayette, Indiana, USA

A.S. Bakshi , V.E. Barnes , R. Chawla , S. Das , L. Gutay, M. Jones , A.W. Jung ,
D. Kondratyev , A.M. Koshy, M. Liu , G. Negro , N. Neumeister , G. Paspalaki ,
S. Piperov , A. Purohit , J.F. Schulte , M. Stojanovic , J. Thieman , A. K. Viridi ,
F. Wang , R. Xiao , W. Xie 

Purdue University Northwest, Hammond, Indiana, USA

J. Dolen , N. Parashar 

Rice University, Houston, Texas, USA

D. Acosta , A. Baty , T. Carnahan , S. Dildick , K.M. Ecklund , P.J. Fernández Manteca ,
S. Freed, P. Gardner, F.J.M. Geurts , A. Kumar , W. Li , B.P. Padley , R. Redjimi,
J. Rotter , S. Yang , E. Yigitbasi , Y. Zhang 

University of Rochester, Rochester, New York, USA

A. Bodek , P. de Barbaro , R. Demina , J.L. Dulemba , C. Fallon, A. Garcia-Bellido ,
O. Hindrichs , A. Khukhunaishvili , P. Parygin , E. Popova , R. Taus ,
G.P. Van Onsem 

The Rockefeller University, New York, New York, USA

K. Goulianos 

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

B. Chiarito, J.P. Chou , Y. Gershtein , E. Halkiadakis , A. Hart , M. Heindl ,
D. Jaroslawski , O. Karacheban²⁷ , I. Laflotte , A. Lath , R. Montalvo, K. Nash,
M. Osherson , H. Routray , S. Salur , S. Schnetzer, S. Somalwar , R. Stone ,
S.A. Thayil , S. Thomas, H. Wang 

University of Tennessee, Knoxville, Tennessee, USA

H. Acharya, A.G. Delannoy , S. Fiorendi , T. Holmes , E. Nibigira , S. Spanier 

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

O. Bouhali⁹² , M. Dalchenko , A. Delgado , R. Eusebi , J. Gilmore , T. Huang ,
T. Kamon⁹³ , H. Kim , S. Luo , S. Malhotra, R. Mueller , D. Overton , D. Rathjens ,
A. Safonov 

Texas Tech University, Lubbock, Texas, USA

N. Akchurin , J. Damgov , V. Hegde , K. Lamichhane , S.W. Lee , T. Mengke,
S. Muthumuni , T. Peltola , I. Volobouev , A. Whitbeck 

Vanderbilt University, Nashville, Tennessee, USA

E. Appelt , S. Greene, A. Gurrola , W. Johns , A. Melo , F. Romeo , P. Sheldon ,
S. Tuo , J. Velkovska , J. Viinikainen 

University of Virginia, Charlottesville, Virginia, USA

B. Cardwell , B. Cox , G. Cummings , J. Hakala , R. Hirosky , A. Ledovskoy ,
A. Li , C. Neu , C.E. Perez Lara 

Wayne State University, Detroit, Michigan, USAP.E. Karchin **University of Wisconsin - Madison, Madison, Wisconsin, USA**

A. Aravind, S. Banerjee , K. Black , T. Bose , S. Dasu , I. De Bruyn , P. Everaerts ,
 C. Galloni, H. He , M. Herndon , A. Herve , C.K. Koraka , A. Lanaro, R. Loveless ,
 J. Madhusudanan Sreekala , A. Mallampalli , A. Mohammadi , S. Mondal, G. Parida ,
 D. Pinna, A. Savin, V. Shang , V. Sharma , W.H. Smith , D. Teague, H.F. Tsoi ,
 W. Vetens , A. Warden 

Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN

S. Afanasiev , V. Andreev , Yu. Andreev , T. Aushev , M. Azarkin , A. Babaev ,
 A. Belyaev , V. Blinov⁹⁴, E. Boos , V. Borshch , D. Budkouski , V. Bunichev ,
 V. Chekhovsky, R. Chistov⁹⁴ , M. Danilov⁹⁴ , A. Dermenev , T. Dimova⁹⁴ , I. Dremin ,
 M. Dubinin⁸⁶ , L. Dudko , V. Epshteyn , A. Ershov , G. Gavrillov , V. Gavrillov ,
 S. Gninenko , V. Golovtcov , N. Golubev , I. Golutvin , I. Gorbunov , A. Gribushin ,
 Y. Ivanov , V. Kachanov , L. Kardapoltsev⁹⁴ , V. Karjavine , A. Karneyeu , V. Kim⁹⁴ ,
 M. Kirakosyan, D. Kirpichnikov , M. Kirsanov , V. Klyukhin , D. Konstantinov ,
 V. Korenkov , A. Kozyrev⁹⁴ , N. Krasnikov , A. Lanev , P. Levchenko⁹⁵ , A. Litomin,
 N. Lychkovskaya , V. Makarenko , A. Malakhov , V. Matveev⁹⁴ , V. Murzin ,
 A. Nikitenko^{96,97} , S. Obraztsov , A. Oskin, I. Ovtin⁹⁴ , V. Palichik , V. Perelygin ,
 M. Perfilov, S. Polikarpov⁹⁴ , V. Popov, O. Radchenko⁹⁴ , M. Savina , V. Savrin ,
 V. Shalaev , S. Shmatov , S. Shulha , Y. Skovpen⁹⁴ , S. Slabospitskii , V. Smirnov ,
 D. Sosnov , V. Sulimov , E. Tcherniaev , A. Terkulov , O. Teryaev , I. Tlisova ,
 A. Toropin , L. Uvarov , A. Uzunian , P. Volkov, A. Vorobyev[†], N. Voytishin ,
 B.S. Yuldashev⁹⁸, A. Zarubin , I. Zhizhin , A. Zhokin 

†: Deceased

¹Also at Yerevan State University, Yerevan, Armenia²Also at TU Wien, Vienna, Austria³Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt⁴Also at Université Libre de Bruxelles, Bruxelles, Belgium⁵Also at Universidade Estadual de Campinas, Campinas, Brazil⁶Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil⁷Also at UFMS, Nova Andradina, Brazil⁸Also at University of Chinese Academy of Sciences, Beijing, China⁹Also at Nanjing Normal University, Nanjing, China¹⁰Now at The University of Iowa, Iowa City, Iowa, USA¹¹Also at University of Chinese Academy of Sciences, Beijing, China¹²Also at an institute or an international laboratory covered by a cooperation agreement with CERN¹³Also at Helwan University, Cairo, Egypt¹⁴Now at Zewail City of Science and Technology, Zewail, Egypt¹⁵Also at British University in Egypt, Cairo, Egypt¹⁶Now at Ain Shams University, Cairo, Egypt¹⁷Also at Purdue University, West Lafayette, Indiana, USA¹⁸Also at Université de Haute Alsace, Mulhouse, France¹⁹Also at Department of Physics, Tsinghua University, Beijing, China²⁰Also at Tbilisi State University, Tbilisi, Georgia

-
- ²¹Also at The University of the State of Amazonas, Manaus, Brazil
- ²²Also at Erzincan Binali Yildirim University, Erzincan, Turkey
- ²³Also at University of Hamburg, Hamburg, Germany
- ²⁴Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- ²⁵Also at Isfahan University of Technology, Isfahan, Iran
- ²⁶Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
- ²⁷Also at Brandenburg University of Technology, Cottbus, Germany
- ²⁸Also at Forschungszentrum Jülich, Juelich, Germany
- ²⁹Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- ³⁰Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
- ³¹Also at Wigner Research Centre for Physics, Budapest, Hungary
- ³²Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
- ³³Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- ³⁴Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
- ³⁵Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary
- ³⁶Also at Punjab Agricultural University, Ludhiana, India
- ³⁷Also at UPES - University of Petroleum and Energy Studies, Dehradun, India
- ³⁸Also at University of Visva-Bharati, Santiniketan, India
- ³⁹Also at University of Hyderabad, Hyderabad, India
- ⁴⁰Also at Indian Institute of Science (IISc), Bangalore, India
- ⁴¹Also at Indian Institute of Technology (IIT), Mumbai, India
- ⁴²Also at IIT Bhubaneswar, Bhubaneswar, India
- ⁴³Also at Institute of Physics, Bhubaneswar, India
- ⁴⁴Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- ⁴⁵Now at Department of Physics, Isfahan University of Technology, Isfahan, Iran
- ⁴⁶Also at Sharif University of Technology, Tehran, Iran
- ⁴⁷Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- ⁴⁸Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- ⁴⁹Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- ⁵⁰Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- ⁵¹Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
- ⁵²Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
- ⁵³Also at Università di Napoli 'Federico II', Napoli, Italy
- ⁵⁴Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- ⁵⁵Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
- ⁵⁶Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- ⁵⁷Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- ⁵⁸Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- ⁵⁹Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
- ⁶⁰Also at National and Kapodistrian University of Athens, Athens, Greece
- ⁶¹Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- ⁶²Also at Universität Zürich, Zurich, Switzerland
- ⁶³Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- ⁶⁴Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
- ⁶⁵Also at Near East University, Research Center of Experimental Health Science, Mersin,

Turkey

⁶⁶Also at Konya Technical University, Konya, Turkey

⁶⁷Also at Izmir Bakircay University, Izmir, Turkey

⁶⁸Also at Adiyaman University, Adiyaman, Turkey

⁶⁹Also at Istanbul Gedik University, Istanbul, Turkey

⁷⁰Also at Necmettin Erbakan University, Konya, Turkey

⁷¹Also at Bozok Universitеси Rektörlüğü, Yozgat, Turkey

⁷²Also at Marmara University, Istanbul, Turkey

⁷³Also at Milli Savunma University, Istanbul, Turkey

⁷⁴Also at Kafkas University, Kars, Turkey

⁷⁵Also at Hacettepe University, Ankara, Turkey

⁷⁶Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey

⁷⁷Also at Ozyegin University, Istanbul, Turkey

⁷⁸Also at Vrije Universiteit Brussel, Brussel, Belgium

⁷⁹Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom

⁸⁰Also at University of Bristol, Bristol, United Kingdom

⁸¹Also at IPPP Durham University, Durham, United Kingdom

⁸²Also at Monash University, Faculty of Science, Clayton, Australia

⁸³Also at Università di Torino, Torino, Italy

⁸⁴Also at Bethel University, St. Paul, Minnesota, USA

⁸⁵Also at Karamanoğlu Mehmetbey University, Karaman, Turkey

⁸⁶Also at California Institute of Technology, Pasadena, California, USA

⁸⁷Also at United States Naval Academy, Annapolis, Maryland, USA

⁸⁸Also at Bingol University, Bingol, Turkey

⁸⁹Also at Georgian Technical University, Tbilisi, Georgia

⁹⁰Also at Sinop University, Sinop, Turkey

⁹¹Also at Erciyes University, Kayseri, Turkey

⁹²Also at Texas A&M University at Qatar, Doha, Qatar

⁹³Also at Kyungpook National University, Daegu, Korea

⁹⁴Also at another institute or international laboratory covered by a cooperation agreement with CERN

⁹⁵Also at Northeastern University, Boston, Massachusetts, USA

⁹⁶Also at Imperial College, London, United Kingdom

⁹⁷Now at Yerevan Physics Institute, Yerevan, Armenia

⁹⁸Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan