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Measurement of the $t\bar{t}$ production cross section using events with one lepton and at least one jet in pp collisions at $\sqrt{s} = 13$ TeV

The CMS collaboration

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

Abstract: A measurement of the $t\bar{t}$ production cross section at $\sqrt{s} = 13\,\mathrm{TeV}$ is presented using proton-proton collisions, corresponding to an integrated luminosity of $2.2\,\mathrm{fb}^{-1}$, collected with the CMS detector at the LHC. Final states with one isolated charged lepton (electron or muon) and at least one jet are selected and categorized according to the accompanying jet multiplicity. From a likelihood fit to the invariant mass distribution of the isolated lepton and a jet identified as coming from the hadronization of a bottom quark, the cross section is measured to be $\sigma_{t\bar{t}} = 888 \pm 2,(\mathrm{stat})^{+26}_{-28}\,(\mathrm{syst}) \pm 20\,(\mathrm{lumi})\,\mathrm{pb}$, in agreement with the standard model prediction. Using the expected dependence of the cross section on the pole mass of the top quark (m_t), the value of m_t is found to be $170.6 \pm 2.7\,\mathrm{GeV}$.

Keywords: Hadron-Hadron scattering (experiments), Top physics

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JHEP09(2017)051

Contents

JHEP09(2017)051

1 Introduction

The rate at which top quark-antiquark ($\mathrm{t\bar{t}}$) pairs are produced in proton-proton (pp) collisions at LHC has been measured at center-of-mass energies of 7 [1–14], 8 [15–23], and 13 TeV [24–26]. The latter has been determined experimentally with a 4.4% uncertainty. In addition, several analyses have explored the expected dependence of the $\mathrm{t\bar{t}}$ production cross section ($\sigma_{\mathrm{t\bar{t}}}$) on the mass of the top quark (m_{t}) to extract the latter. Recent examples of this can be found in ref. [23], where m_{t} is determined with a total uncertainty of $\approx$1%. Alternatively, the strong coupling strength (α_S) can be extracted from the $\mathrm{t\bar{t}}$ cross section, assuming m_{t} is known [27]. Knowledge of the parton distribution function (PDF) of the proton can be improved as well from a precise measurement of $\sigma_{\mathrm{t\bar{t}}}$ [28, 29]. In addition, the production of final states via processes beyond the standard model that mimic the ones produced by $\mathrm{t\bar{t}}$ decay can be revealed by a precise measurement of $\sigma_{\mathrm{t\bar{t}}}$ [30]. The above-mentioned interpretations of the measured $\sigma_{\mathrm{t\bar{t}}}$ provide a few examples, among others existing in the literature, that can benefit from such precision comparisons.

In this paper, a measurement of $\sigma_{\mathrm{t\bar{t}}}$ using final states with an isolated charged lepton ℓ (electron or muon) and at least one jet is presented. This selection is chosen in order to minimize the uncertainty in the extrapolation of the cross section to the fully inclusive phase space, and is expected to keep the impact of the dependence of the acceptance on the theoretical uncertainties in the PDFs and quantum chromodynamics (QCD) scale choice to a minimum. The selected events are split into categories according to the total number of jets in the event and the number of jets identified as coming from the hadronization of a b quark. Each category uses observables that can discriminate the main backgrounds (multijet and W+jets production) from the $\mathrm{t\bar{t}}$ signal. A combined fit to the distributions in data of these observables is used to minimize the main systematic uncertainties, while measuring $\sigma_{t\bar{t}}$ and m_t.

The paper is organized as follows: section 2 details the experimental setup, including the CMS detector, the data and simulation used in the analysis, the event selection, and the background estimations, section 3 describes the observables used in the analysis and the associated systematic uncertainties, while section 4 discusses the fit procedure and results. A summary is given in section 5.

2 Experimental setup

2.1 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in ref. [31].

2.2 Data and simulation

The analysis is based on pp collision data collected by the CMS experiment at the CERN LHC at $\sqrt{s} = 13\,\text{TeV}$ in 2015, corresponding to an integrated luminosity of $2.21 \pm 0.05\,\text{fb}^{-1}$ [32].

The analysis is complemented using simulated event samples that are used to estimate the main backgrounds and the signal distributions. The $t\bar{t}$ signal is modeled with the POWHEG v2 [33–36] generator, matched to PYTHIA v8.205 [37, 38] for shower evolution and hadronization. The NNPDF3.0 next-to-leading-order (NLO) PDFs [39] and the CUETP8M1 [40, 41] underlying-event tune are used in the simulation. To evaluate the systematic uncertainties associated with the QCD renormalization (μ_R) and factorization (μ_F) scales at the matrix-element level, we make use of a weighting scheme implemented in POWHEG v2 to vary the scales by a factor of 2 or 1/2 relative to its nominal value $\mu_R = \mu_F = m_T$, where $m_T = \sqrt{m_t^2 + p_{T,t}^2}$ is the transverse mass of the top quark, with $p_{T,t}$ being the top quark transverse momentum.

Furthermore, additional simulations in which the QCD renormalization and factorization scales at the parton shower level are changed by a factor of 2 or 1/2 relative to their nominal value are used. In the CUETP8M1 tune, the nominal QCD scale choice at the parton shower level is determined by $\alpha_S^{ISR} = 0.1365$, the value of the strong coupling strength at m_Z used for the initial-state shower. A different matrix-element generator is also used, for comparison: MG5_aMC@NLO v5_2.2.2 [42] with MADSPIN [43], and is matched to either PYTHIA 8 or HERWIG++ v2.7.1 [44].

In this analysis, we measure the $t\bar{t}$ cross section in a fiducial region of the phase space using as reference the theoretical cross section for $m_t = 172.5\,\text{GeV}$, computed at next-to-next-to-leading order (NNLO) with next-to-next-to-leading-log (NNLL) soft-gluon resummations, $\sigma_{t\bar{t}} = 832\,^{+20}_{-29}\,(\text{scale}) \pm 35\,(\text{PDF} + \alpha_S)\,\text{pb}$, from TOP++ v2.0 [45]. Single top quark processes are simulated with POWHEG v1 [46, 47] and normalized to the approximate NNLO prediction [48]. The W+jets process is simulated at NLO with MG5_aMC@NLO. To reach higher statistical accuracy, a larger Born-level MADGRAPH v5.1.3.30 [42] simulated sample, including up to four extra partons in the matrix-element calculations, is used for the derivation of the W+jets background shape. The Drell-Yan (DY) contribution is simulated with MADGRAPH. Both W+jets and DY cross sections are normalized to their NNLO predictions, computed using FEWZ (v3.1.b2) [49]. Diboson production (WW, ZZ, WZ) is simulated either with PYTHIA 8 (ZZ, WZ) or POWHEG v1 [50] (WW). Each diboson process is normalized to the NLO prediction for the cross section, computed with MCFM (v7.0) [51, 52]. The associated production of W or Z boson with $t\bar{t}$ ($t\bar{t}$ +V) is simulated at NLO with MG5_aMC@NLO.

All simulated events include an emulation of the response of the CMS detector using GEANT4 v9.4p03 [53, 54]. The effect due to multiple pp collisions in the same and neighboring beam crossings (pileup) is measured and added to the simulated $t\bar{t}$ interactions according to the pileup multiplicity observed in the data.

2.3 Event selection

The data are recorded using single-lepton triggers with a minimum transverse momentum (p_T) of 22 GeV and 20 GeV for electrons and muons, respectively. Identification and isolation criteria are applied at the trigger level, and the efficiency of these requirements is measured in a control data sample that is dominated by $Z \to \ell\ell$ decays. The results obtained from the control data sample are compared with the simulated predictions using a tag-and-probe method [55], and data-to-simulation scale correction factors are derived as function of the p_T and η of the lepton. The scale factors are observed to be $\leq$5%.

The events are reconstructed offline using a particle-flow (PF) algorithm that optimally combines the information from subdetectors to reconstruct and identify all individual particles in the event [56]. In addition, reconstruction, identification, and calibration algorithms are employed for electrons and muons, as described in refs. [57, 58]. The lepton candidates are required to have $p_T > 30\,\text{GeV}$ and $|\eta| < 2.1$. Identification and isolation requirements are imposed to reject misidentified muons from punchthrough hadrons, photon conversion, and other objects misreconstructed as lepton candidates. These criteria are tighter than the ones imposed at trigger level. The tag-and-probe method measures the efficiency of these requirements, yielding typical efficiencies of 70% and 92% for electrons and muons, respectively. Nonprompt leptons that come from the decays of long-lived hadrons are rejected by requiring that the significance of the three-dimensional (3D) impact parameter of the lepton track, relative to the primary event vertex, is less than four standard deviations. This requirement effectively reduces the contamination from multijet events, while keeping a high efficiency for the signal. The expected efficiency of this requirement is cross-checked using $Z \to \ell\ell$ candidate events. The primary event vertex used as reference is required to be reconstructed from at least four tracks, and have a longitudinal distance of less than 24 cm from the center of the detector. Among all the pp collision vertices in the event, the one with the largest scalar sum of associated particle transverse momenta is selected as the primary vertex. The event is rejected if an additional electron or muon is found within $|\eta| \leq 2.5$, passing looser identification and isolation criteria, and with $p_{\mathrm{T}} > 15$ or 10 GeV, respectively.

Jets are reconstructed using all PF candidates as inputs to the anti-k_{T} algorithm with a distance parameter of 0.4, utilizing the FastJet 3.1 software package [59, 60]. The jet momentum is defined as the vectorial sum of all particle momenta inside the jet cone, and is found from the simulation to be within 5–10% of the generated jet momentum at particle level over the whole p_{T} range and detector acceptance. Since pileup collisions result in unwanted calorimetric energy depositions and extra tracks, part of this contribution is reduced by performing a charged-hadron subtraction that removes tracks identified as originating from pileup vertices [61]. In addition, an offset correction is applied to remove the additional energy included in the jets that come from pileup [62, 63]. The energy scale corrections, derived from simulation, are cross-checked with in situ measurements of the energy balance in dijet and photon+jet events [61].

We require at least one jet with $p_{\mathrm{T}} > 30$ GeV and $|\eta| \leq 2.5$ in the accepted events. The jets are required to not overlap with the isolated lepton within a cone of angular radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$, where $\Delta\eta$ and $\Delta\phi$, represent the difference in pseudorapidity and azimuthal angle (in radians), between the directions of each jet and the lepton. Jets coming from the fragmentation and hadronization of b quarks (b jets) are identified by a combined secondary vertex (CSV) algorithm [64]. A b jet is identified with a CSV threshold efficiency >65% and a misidentification rate ≈1%. This b tagging efficiency is measured using a $\mathrm{b\bar{b}}$ enriched data sample from a method similar to that described in ref. [64].

In the analysis, events with one, two, three, or four or more jets are considered as separate event categories. We expect the low-multiplicity categories to be dominated by W+jets processes, and the high jet multiplicities by $\mathrm{t\bar{t}}$ events. An additional separation of the signal is achieved by counting the number of b-tagged jets in each category, since two b jets in the event are expected, given that each top quark decays to a Wb pair. Therefore, we further subdivide the four jet-multiplicity categories according to the number of reconstructed b-tagged jets, considering events with none, one, or at least two b-tagged jets, for a total of 11 orthogonal categories. Since the collision particles are protons, an asymmetric production of W bosons, with more W^+ produced than W^-, is expected [65]. Given the charge-symmetric decays of the W bosons in $\mathrm{t\bar{t}}$ decays, $\mathrm{t\bar{t}}$ final states are expected to have the same number of W^+ and W^- bosons. We use this property to further categorize the events according to the lepton charge (+−) and flavor (electron or muon). Hence, our analysis makes use of a total of $2\times2\times11 = 44$ categories.

All backgrounds are estimated using simulation except for that from multijet events, which is difficult to model correctly from simulation in the $\mathrm{t\bar{t}}$ phase-space region. The contribution from the multijet background is estimated using an independent data control sample where the prompt-lepton candidate passes the loose trigger-isolation requirements, but fails the tighter isolation required offline. The expected residual contamination from

JHEP09(2017)051

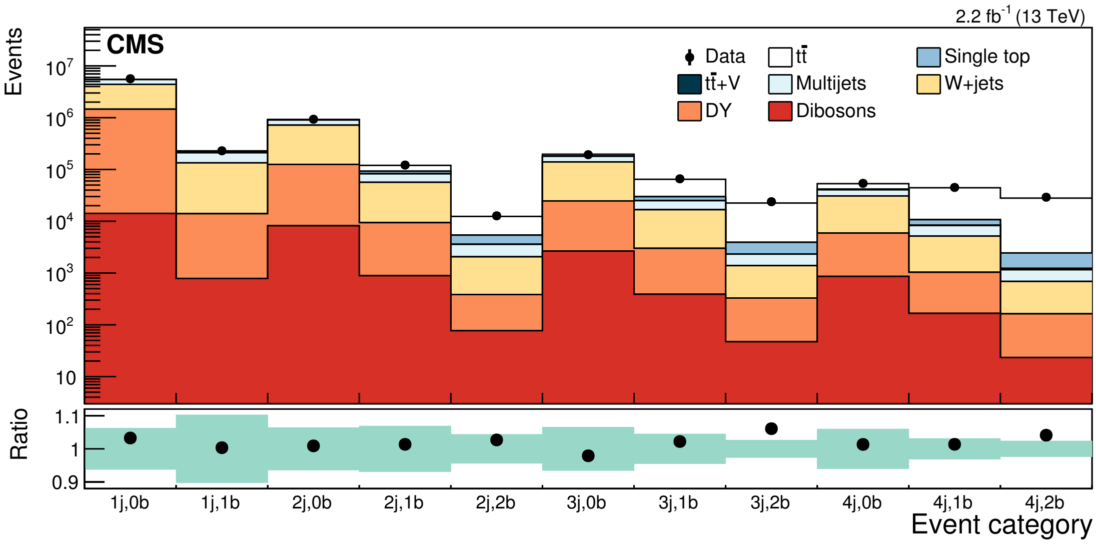

Figure 1. Event yields from data and the expected $t\bar{t}$ signal and backgrounds for each of the 11 independent categories. Distributions are combined for the two lepton charges and flavors. The bins represent the measured number of jets (j) and b-tagged jets (b), with the 4j and 2b categories being inclusive. The bottom panel shows the ratio between the data and the expectations. The relative uncertainty owing to the statistical uncertainty in the simulation, the uncertainty in the normalization of the multijet contribution, and the systematic uncertainty in the total integrated luminosity is represented as a shaded band.

background processes other than multijets is estimated from simulation and subtracted from the control sample. The resulting distributions are used to model the multijet background contribution. The initial multijet normalization is obtained from events containing one isolated lepton and having the measured absolute value of the imbalance in the p_T of all PF candidates in the event less than 20 GeV. The contributions from backgrounds other than multijets are subtracted in the referred to isolated-lepton region, and the ratio of events observed in data in this region with respect to the number of events found in the nonisolated-lepton control region is assigned as the renormalization scale factor. Given the tight requirements on leptons, we expect $b\bar{b}$ +jets events to dominate the multijet contamination. An isolated, prompt lepton coming from such a process is likely to arise from the decay of a bottom hadron. We can therefore expect a jet in the event to be b-tagged. This motivates the initial normalization for the multijet process through the one-b-tagged-jet category. However, for events with at least three jets, the $t\bar{t}$ contribution is expected to be nonnegligible, so the multijet process is estimated from events without any b-tagged jets.

Figure 1 compares the numbers of selected events in data with the signal and expected backgrounds from simulation in each category. For simplicity, the contributions from the electron and muon final states, as well as from the two lepton charges, are summed. Within the uncertainties, we observe agreement between the data and the expectations. Although not shown explicitly, agreement is also found separately for each lepton flavor and charge.

JHEP09(2017)051

3 Observables and related uncertainties

For each event category, we select a variable that discriminates the signal from the backgrounds. Categories without b-tagged jets are likely to be dominated by backgrounds and thus are counted without analyzing any distribution. For events with b-tagged jets, we exploit the distinct kinematic character of $\mathrm{t} \to \mathrm{Wb}$ decays, and use the following mass variables: (i) for events with only one b-tagged jet, we use the invariant mass of the system formed by the lepton and the b-tagged jet ($M(\ell, \mathrm{b})$); and (ii) for events with at least two b-tagged jets, the invariant masses of all the lepton and b-tagged jet combinations in the event are calculated, and the minimum mass ($\min M(\ell, \mathrm{b})$) is chosen as a discriminant. The $M(\ell, \mathrm{b})$-related variables are expected to be sensitive to $\mathrm{t\bar{t}}$ production, as well as to m_{t}, defined by the endpoint in the invariant mass spectrum expected at leading order (LO). The endpoint is determined by the values of the top quark and W boson masses [66].

Figures 2 shows the $M(\ell, \mathrm{b})$ and $\min M(\ell, \mathrm{b})$ distributions for data, and the expected contributions from signal and backgrounds in the various event categories. When normalized by the reference cross sections described in section 2.2 there is an overall good agreement between data and expectations. The most noticeable differences are related to the initial multijet background normalization and the uncertainty in the W+jets normalization which is improved by the fitting procedure (see section 4).

In the signal region, the agreement is good for the simulation using the reference value $m_{\mathrm{t}} = 172.5\,\mathrm{GeV}$.

The expectations for the rates and distributions considered in the analysis are affected by different sources of systematic uncertainties. For each source, an induced variation can be parametrized, and treated as a nuisance parameter in the fit that is described in the next section.

Experimental uncertainties pertain mostly to the calibration of the detector and to our assessment of its performance in the simulation. The uncertainty in the efficiency of the trigger and the offline selection is estimated by applying different scale factors as a function of the p_{T} and η of the isolated lepton. The scale factors and their uncertainties are obtained using $\mathrm{Z} \to \ell\ell$ data, based on a tag-and-probe method [55]. The one standard deviation changes applied to the parameters of the simulated events are typically on the order of 1–3%.

The energy scales of the objects used in the analysis (leptons and jets) are varied according to their estimated uncertainties. This can lead to a migration of events to different categories because of the thresholds applied in the preselection and the categorization of the events, as well as to changes in the expected distributions of the observables. When the energy scale of the leptons or jets changes, it affects other variables (e.g., the missing momentum), which are recomputed to reflect the new scales. The uncertainty in the jet energy scale is subdivided into independent sources. A total of 29 nuisance parameters related to the jet energy scale are included in the fit described in the next section. The parameters refer to the effect of uncertainties related to pileup, relative (η-dependent) calibration, high- and low-p_{T} extrapolation, absolute-scale determination, and flavor-specific differences, amongst others. The categories used for the jet energy scale are similar to those used in the $\sqrt{s} = 8\,\mathrm{TeV}$ analyses [61, 67].

JHEP09(2017)051

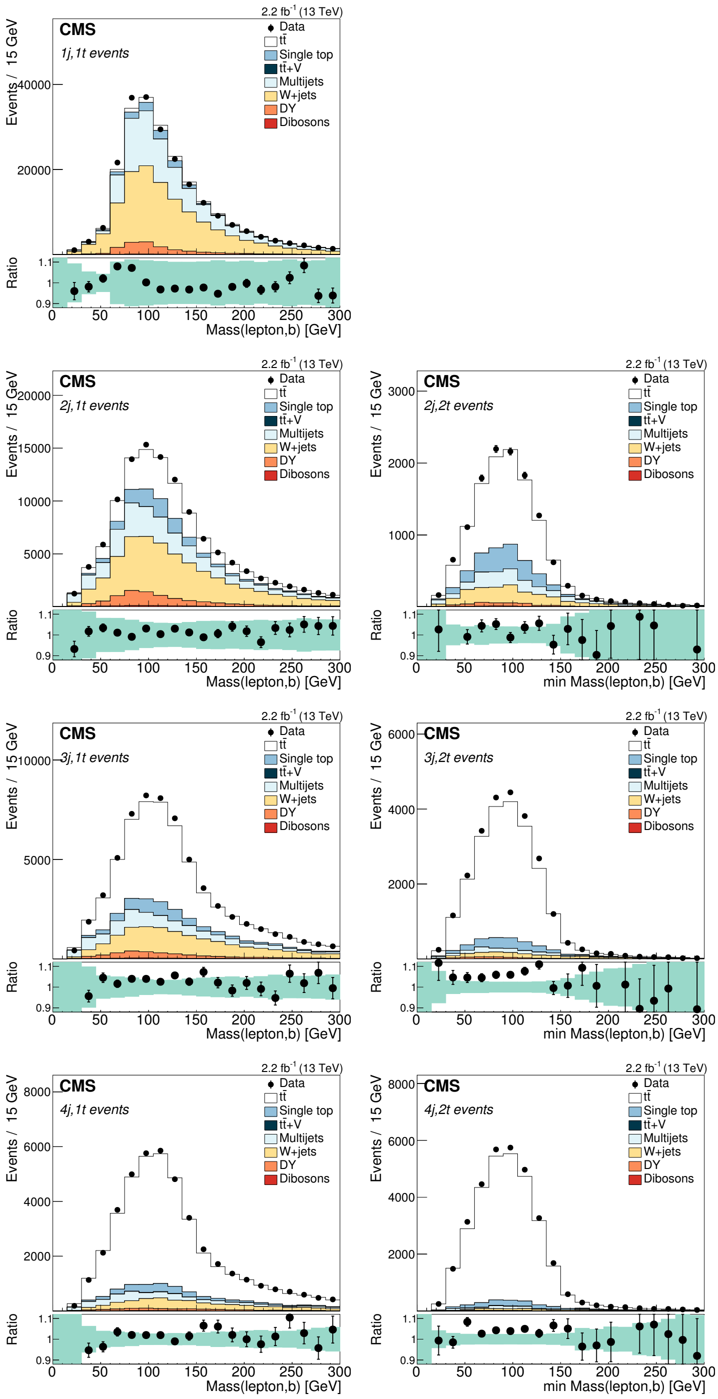

Figure 2. Distributions in the observables used to fit the data with the contributions from all leptons and charges combined. Panels on the left show the distributions in $M(\ell, \mathrm{b})$, and on the right in min $M(\ell, \mathrm{b})$, for events with one and two b-tagged jets, respectively. From top to bottom, the events correspond to those with 1, 2, 3, or at least 4 jets. The lower plot in each panel shows the ratio between the data and expectations. The relative uncertainty owing to the statistical uncertainty in the simulations, to the uncertainty in the normalization of the contribution from multijet events and to the systematic uncertainty in the total integrated luminosity is represented as a shaded band.

JHEP09(2017)051

The jet energy resolution is also affected by an uncertainty that is estimated in our analysis by changing the simulated resolution by one standard deviation as a function of the η of the jet. The corrections applied to the simulated b jet, c jet, and light-flavor jet tagging efficiencies of the CSV algorithm are changed according to their uncertainties [64]. This also causes a migration of events across the different b tagging categories within the same jet multiplicity. The uncertainty from the model used for the average pileup in the simulation is estimated by implementing a 5% change to the assumed inelastic pp cross section [68]. Finally, a 2.3% uncertainty is assigned to the estimated integrated luminosity [32].

For the estimate of the contribution from QCD multijet events we determine an uncertainty owing to the normalization method of the nonisolated-lepton sideband in data through an alternative scale factor obtained from events with $M_T < 50\,\mathrm{GeV}$, where M_T is the transverse mass computed from the lepton candidate and the missing momentum of the event. This yields an intrinsic uncertainty of ≈30–60%, depending on the category. Furthermore, uncertainties in the distributions of events caused by the normalizations of other than multijet contributions are obtained by changing the individual sources in the control regions by ±30%. These uncertainties are considered uncorrelated across all categories of the analysis.

Theoretical uncertainties affect the predictions for the acceptance and the distributions in the signal and nonmultijet background processes. We consider independent changes in μ_R or μ_F in the $t\bar{t}$, W+jets, and tW processes by factors of 2 and 1/2. For the signal, we estimate the parton shower uncertainty by using alternative POWHEG +PYTHIA 8 samples, with the parton shower scale value changed by factors of 2 and 1/2. This affects the fragmentation and hadronization of the jets initiated by the matrix-element calculation, as well as the emission of extra jets. The variation in the acceptance and distributions obtained by using HERWIG++ instead of PYTHIA 8 to interface the POWHEG generator is included as a systematic uncertainty in the modeling of $t\bar{t}$ in the fit. An additional uncertainty is assigned based on the difference found between the POWHEG and MG5_aMC@NLO simulations.

For the signal, we also consider an uncertainty in the p_T distribution of the top quark, based on the CMS measurements at $\sqrt{s} = 8$ [69] and 13 TeV [66]. The simulation is reweighted using a data-to-simulation scale factor that is verified to be consistent with the measurements performed in both data sets, and the difference is used to assign the uncertainty in the modeling of the top quark p_T.

Uncertainties in the modeling of the single top quark background include changes of μ_R/μ_F for the t and t W channels. At NLO QCD, t W production is expected to interfere with $t\bar{t}$ production, owing to the similar initial and final states of some diagrams [70–72]. Two schemes for defining the t W signal that distinguish it from $t\bar{t}$ production have therefore been compared in this analysis: the "diagram removal" method [70], in which all doubly-resonant NLO t W diagrams are removed, and the "diagram subtraction" scheme [70, 73], where a gauge-invariant subtraction term modifies the NLO t W cross section to locally cancel the contribution from $t\bar{t}$. In addition to the theoretical uncertainties described above, all background processes are assigned their corresponding theoretical uncertainties in their normalization.

JHEP09(2017)051

4 Fitting procedure and results

The $t\bar{t}$ production cross section is measured by performing a maximum-likelihood fit to the number of events counted in the different categories. The likelihood function takes into account the expectations for contributions from different background processes as well as signal. The expectations for signal and backgrounds depend on: (i) the simulation- or data-based expectations ($\hat{S}$ or $\hat{B}$ for signal and background, respectively), and (ii) nuisance parameters (θ_i) that reflect the uninteresting variables used to control the effect of the systematic variations described in the previous section. The effect of each source of uncertainty is separated in a rate-changing and shape-changing nuisance parameter. In the fit, the nuisance parameters are assumed to be distributed according to log-normal probability distribution functions (pdfs) if affecting the rate, or Gaussian pdfs if affecting the shapes. We denote generally the pdfs associated with a nuisance parameter as $\rho(\theta_i)$. The signal expectation is also modulated by a multiplicative factor, which is defined by the ratio of the measured cross section to the reference theoretical value, i.e., the signal strength $\mu = \sigma/\sigma_{\text{th}}$ for $m_t = 172.5\,\text{GeV}$. For each category (k), we write the total number of expected events as:

$$\hat{N}_k(\mu, \Theta) = \mu\,\hat{S}_k \prod_i (1 + \delta_i^S \theta_i) + \hat{B}_k \prod_i (1 + \delta_i^B \theta_i)\,, \tag{4.1}$$

where Θ is the set of all nuisance parameters, the index k runs over the bins of the distributions (or the counts in different event categories for the cross-check analysis), and δ_i^S and δ_i^B are changes in yields induced through one-standard-deviation changes in the i^{th} sources of uncertainty in the signal and backgrounds, respectively. The likelihood function is defined as:

$$\mathcal{L}(\mu, \Theta) = \prod_k \mathcal{P}\left[N_k | \hat{N}_k(\mu, \theta_i)\right] \prod_i \rho(\theta_i), \tag{4.2}$$

where $\mathcal{P}$ is a Poisson distribution and N_k is the number of events observed in the kth category. The cross section is measured by maximizing the profile likelihood ratio (PLR) test statistic:

$$\lambda(\mu) = \frac{\mathcal{L}(\mu, \hat{\hat{\Theta}})}{\mathcal{L}(\hat{\mu}, \hat{\Theta})}, \tag{4.3}$$

where the quantities $\hat{\hat{\Theta}}$ correspond to the set of nuisance parameter values θ_i that maximize the likelihood for the specified signal strength (also known as the conditional likelihood), and $\hat{\mu}$, $\hat{\Theta}$ are respectively the values of μ and the set of θ_i that maximize the likelihood. In the presence of nuisance parameters, the resulting PLR as a function of μ tends to be broader relative to the one obtained when the values are well known and fixed. This reflects the loss of information in μ because of the presence of systematic uncertainties [74].

Although m_t does not contribute an intrinsic uncertainty in the measurement of the cross section, since the $M(\ell, \text{b})$ distribution is used in the fit, its shape has a direct dependence on m_t that needs to be taken into account. We thus include in the fit a parameterization of the effect of varying m_t by $\pm 3\,\text{GeV}$ while measuring the cross section as the parameter of interest. This parameterization is performed for both the signal and the single top quark simulations. With this procedure, the fit accomodates for a possibly different value of m_{t} than that assumed by default in the simulation but witout correlating this with the pole mass to be extracted from the inclusive $\mathrm{t\bar{t}}$ production rate, as originally proposed in ref. [75].

Figure 3 (left) shows the variation of the likelihood as a function of the signal strength from the data and the expected variation from the simulation. From the fit, we measure $\mu = 1.067 \pm 0.002\,(\mathrm{stat})\ ^{+0.037}_{-0.035}\,(\mathrm{syst})$. The $\mathrm{t\bar{t}}$ cross section in the visible phase space is thus measured with a total uncertainty of 3.4%. As a check, the Monte Carlo simulated signal and background events corresponding to the same integrated luminosity as the data are used as pseudo-data with $m_{\mathrm{t}} = 172.5\,\mathrm{GeV}$ in the fit. The resulting value of the signal strength is $\mu = 1.000 \pm 0.002\,(\mathrm{stat})\ ^{+0.035}_{-0.034}\,(\mathrm{syst})$. This is the expected value of μ, and the agreement of the statistical and systematic uncertainties with those from the fit to the data is a good check on the fitting procedure.

The default analysis using the shapes of the distributions (labeled "Distr.") is also compared with a simpler cross-check analysis (labeled "Count"). The cross-check analysis does not use kinematic information, but uses the number of events in the different jet and b-tagged jet categories, and the expected yields. The two results are in agreement with each other, with the cross-check analysis having a larger uncertainty: $\mu = 1.054 \pm 0.002\,(\mathrm{stat})\ ^{+0.043}_{-0.041}\,(\mathrm{syst})$.

The post-fit normalizations for the main backgrounds (W+jets and multijets) tend to be higher by 1–6% in the main analysis with respect to those from the cross-check analysis. This results in a different signal strength between the two analyses.

Figure 3 (right) compares the inclusive μ result for both the default and cross-check analyses (top set of points) with the corresponding values for the different lepton charges and flavors. The results are found to be consistent with each other in the different combinations.

The impact of the sources of uncertainty in the fit is evaluated by making use of the set of post-fit values of the nuisance parameters, and computing the shift induced in the signal strength as each nuisance parameter is fixed at its ± 1 standard deviation post-fit value, with all other parameters profiled as normal. By repeating the fits, the effect of some nuisance parameters being fixed may be reabsorbed by a variation of the ones being profiled, owing to correlations. Figure 4 summarizes the values obtained for the leading sources of uncertainty in the fit. The dominant sources of uncertainty in both analyses are related to the integrated luminosity, trigger and selection efficiencies, and the model of the W+jets background. These are expected to impact the signal strength at the level of 1–2.5% The analysis of the distributions is effectively able to mitigate most uncertainties related to the modeling of $\mathrm{t\bar{t}}$. The modeling of the top quark p_{T} and the choice of the hadronizer are the dominant signal modeling uncertainties but their impact in the fit is observed to be <1%. Uncertainties related to the modeling of the multijets background are observed to impact the fit at the level of <0.5% None of the nuisance parameters used in the fit is observed to be significantly pulled from its initial value and its behavior is similar to that expected by performing the fit using simulated events with $m_{\mathrm{t}} = 172.5\,\mathrm{GeV}$. Nuisance parameters related to the integrated luminosity and the trigger and selection efficiencies are observed not to be constrained in the fit procedure.

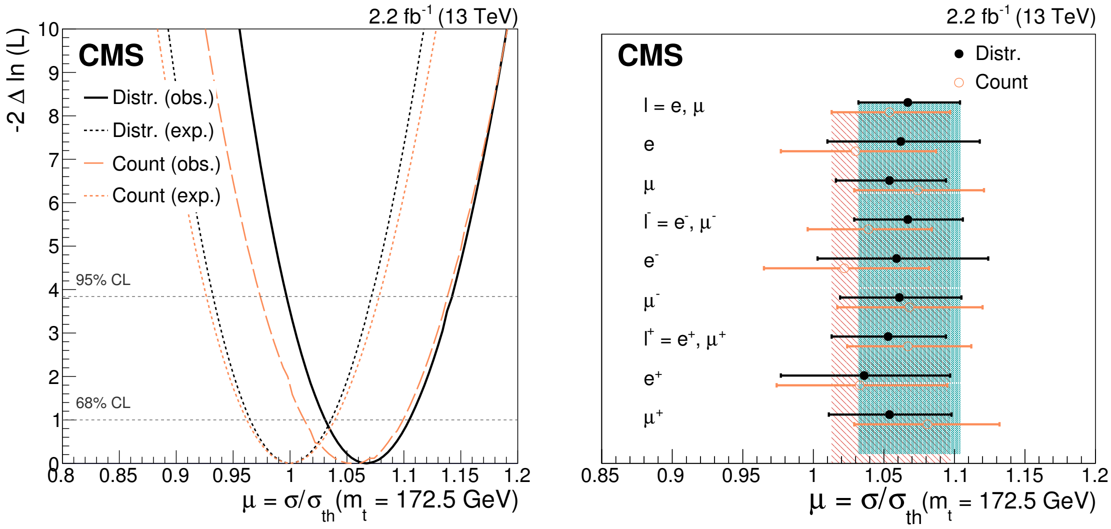

Figure 3. (Left) The observed (solid curve) and expected (dashed curve) variation of the likelihood as a function of the signal strength μ for the distribution-based analysis. The expected curve is obtained by performing the fit using simulated events with $m_{\mathrm{t}} = 172.5\,\mathrm{GeV}$. For comparison, the corresponding curves for the counting cross-check analysis are also shown. The two horizontal lines represent the values in the PLR that are used to determine the 68% and 95% confidence level (CL) intervals for the signal strength. (right) Comparison of the values of the signal strength extracted for different combinations of events for the distribution-based default analysis (solid circles) and the cross-check counting analysis (open circles). The horizontal bars represent the total uncertainties, except the beam energy uncertainty. The shaded bands represent the uncertainty in the final combined signal strength obtained from the distribution-based and cross-check analyses.

The signal strength is measured in a region of phase space where the lepton has $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 2.1$, and at least one jet has $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 2.5$. The resulting visible $\mathrm{t\bar{t}}$ cross section in this phase-space region is determined to be

$$\sigma_{\mathrm{t\bar{t}}}^{\mathrm{vis}} = 208.2 \pm 0.4\,(\mathrm{stat})\ {}^{+5.5}_{-4.9}\,(\mathrm{syst}) \pm 4.8\,(\mathrm{lumi})\,\mathrm{pb},$$

where the last uncertainty is from the integrated luminosity.

The extrapolation to the full phase space is performed by using the acceptance estimated from the $\mathrm{t\bar{t}}$ simulation. Using POWHEG, we determine the acceptance to be $0.2345 \pm 0.0001\,(\mathrm{stat})\ {}^{+0.0044}_{-0.0043}\,(\mathrm{syst})$, where the systematic uncertainty comes from changing $\mu_{\mathrm{R}}/\mu_{\mathrm{F}}$ (± 0.0017), considering the CT14 PDF and α_{S} uncertainties (${}^{+0.0009}_{-0.0007}$) [76], and changing the parton shower algorithm used to interface with the matrix-element generator, i.e., PYTHIA 8 vs. HERWIG++, (± 0.0039). The total uncertainty associated with the extrapolation is estimated to be 1.6%. This uncertainty is added in quadrature to the systematic uncertainty obtained in the fitted fiducial region when extrapolating the measurement to the full phase space.

Summing the statistical (0.2%), systematic (3.0%), and integrated luminosity (2.3%) uncertainties in quadrature, we obtain a total relative uncertainty in the $\mathrm{t\bar{t}}$ cross section of 3.9%. The final result is:

$$\sigma_{\mathrm{t\bar{t}}} = 888 \pm 2\,(\mathrm{stat})\ {}^{+28}_{-26}\,(\mathrm{syst}) \pm 20\,(\mathrm{lumi})\,\mathrm{pb},$$

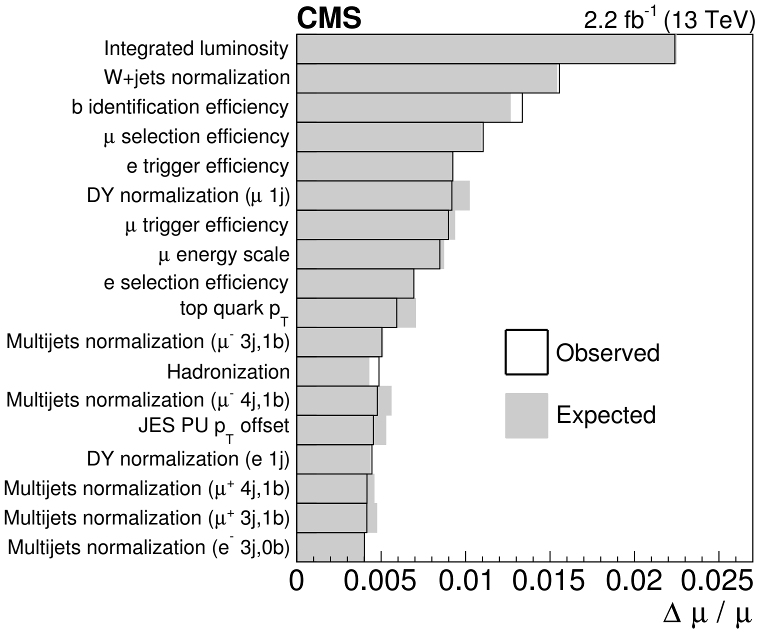

Figure 4. Estimated change $\Delta\mu$ in the measured signal strength μ, coming from the listed experimental and theoretical sources of uncertainties in the main analysis. The open bars represent the values of the observed impact relative to the fitted signal strength. The values are compared to the expectations (shaded bars) by performing the fit using simulated events with $m_{\mathrm{t}} = 172.5\,\mathrm{GeV}$. The various contributions are shown from the largest to the smallest observed impact.

in agreement with the NNLO+NNLL prediction [45] and the measurement derived from analyzing events in the electron + muon final state from the same data set [26].

The result can be reinterpreted to extract the pole mass m_{t} of the top quark by using the dependence of the cross section on this parameter. We make use of the TOP++ program [45] and the CT14 NNLO PDF [76] to parametrize the dependence of the cross section on the top quark mass. The parametrization used is:

$$\sigma(m_{\mathrm{t}}) = \sigma(m_{\mathrm{ref}}) \left(\frac{m_{\mathrm{ref}}}{m_{\mathrm{t}}}\right)^4 \left[1 + a_1\left(\frac{m_{\mathrm{t}}}{m_{\mathrm{ref}}} - 1\right) + a_2\left(\frac{m_{\mathrm{t}}}{m_{\mathrm{ref}}} - 1\right)^2\right], \tag{4.4}$$

where $m_{\mathrm{ref}} = 172.5\,\mathrm{GeV}$ is the reference mass value, and a_1 and a_2 are coefficients determined after performing the calculations with various m_{t} hypotheses. The effects induced by the choice of $\mu_{\mathrm{R}}/\mu_{\mathrm{F}}$, the uncertainty in the PDF+α_{S}, and uncertainties in the beam energy, are evaluated by recomputing the cross section after changing these parameters within their uncertainties. The resulting typical uncertainties in $\sigma(m_{\mathrm{t}})$ amount to $^{+2.5\%}_{-3.7\%}$, $^{+2.7\%}_{-2.6\%}$, and $\pm0.23\%$, respectively. The latter reflects a $\pm0.1\%$ uncertainty in the beam energy at which the data have been collected [77].

To measure the pole mass, the likelihood function (eq. (4.2)) is reparametrized, transforming μ into a functional form that depends on the top quark mass

$$\mu(m_{\mathrm{t}}) = \frac{\sigma(m_{\mathrm{t}})}{\sigma_{\mathrm{th}}} \frac{A}{A(m_{\mathrm{t}})}, \tag{4.5}$$

Source	Δm_{t} [GeV]
Uncertainties from the fit in the fiducial region	-2.2 / $+2.5$
Extrapolation to the full phase space	-0.7 / $+1.1$
Beam energy	-0.08 / $+0.12$
$\mu_{\mathrm{R}}/\mu_{\mathrm{F}}$ and PDF+α_{S}	-0.9 / $+1.1$
Total	± 2.7

Table 1. The source and value of the systematic uncertainties in the measurement of m_{t}.

where the last factor $(A/A(m_{\mathrm{t}}))$, is a mass-dependent correction to the acceptance. Using simulated $\mathrm{t\bar{t}}$ samples with different m_{t}, we find that the acceptance changes by 0.08% per $\Delta m_{\mathrm{t}} = 1\,\mathrm{GeV}$.

The uncertainty in the extrapolation, as well as the theoretical uncertainties that affect the parameterization as a function of m_{t} coming from the choices of $\mu_{\mathrm{R}}/\mu_{\mathrm{F}}$, PDF, α_{S}, and beam energy, are added as extra nuisance parameters in the fit for the pole mass. With the exception of $\mu_{\mathrm{R}}/\mu_{\mathrm{F}}$, which is defined through a log-uniform probability distribution consistent with the procedure adopted in ref. [27], the remaining uncertainties are assigned a log-normal function. After repeating the maximum-likelihood fit, we obtain

$$m_{\mathrm{t}} = 170.6 \pm 2.7\,\mathrm{GeV},$$

where the quoted uncertainty contains both statistical and systematic contributions. The result agrees with that obtained using the NNPDF3.0 NNLO PDF [28]: $m_{\mathrm{t}} = 170.3\ ^{+2.6}_{-2.7}\,\mathrm{GeV}$. The latter is only used as a cross-check as the NNPDF3.0 PDF includes top-quark-related data in the determination of the proton PDFs. In both cases, the best-fit value is determined by fixing the nuisance parameter associated with the choice of the μ_{R} and μ_{F} ratio to its post-fit value, and repeating the scan of the likelihood. This procedure is adopted to resolve the almost degenerate behavior of the likelihood, induced through the use of a log-uniform pdf assigned to the choice of the μ_{R} and μ_{F} ratio.

Figure 5 shows the variation of the likelihood as a function of the top quark pole mass. For comparison, the expected likelihood from the Asimov set of nuisance parameters at $m_{\mathrm{t}} = 172.5\,\mathrm{GeV}$ is shown.

The impact of each source of systematic uncertainty in the values corresponding to the fit is estimated using a similar procedure to the one described above for the cross section measurement. Table 1 summarizes the estimated uncertainties in the determination of m_{t} from the measured cross section.

5 Summary

A measurement of the $\mathrm{t\bar{t}}$ production cross section at $\sqrt{s} = 13\,\mathrm{TeV}$ has been presented by CMS in final states containing one isolated lepton and at least one jet. The acceptance in the fiducial part of the phase space is estimated with an uncertainty of 1.6% and has a negligible dependence on m_{t}. By performing a simultaneous fit to event distributions in 44 independent categories, we measure the strength of the $\mathrm{t\bar{t}}$ signal relative to the

JHEP09(2017)051

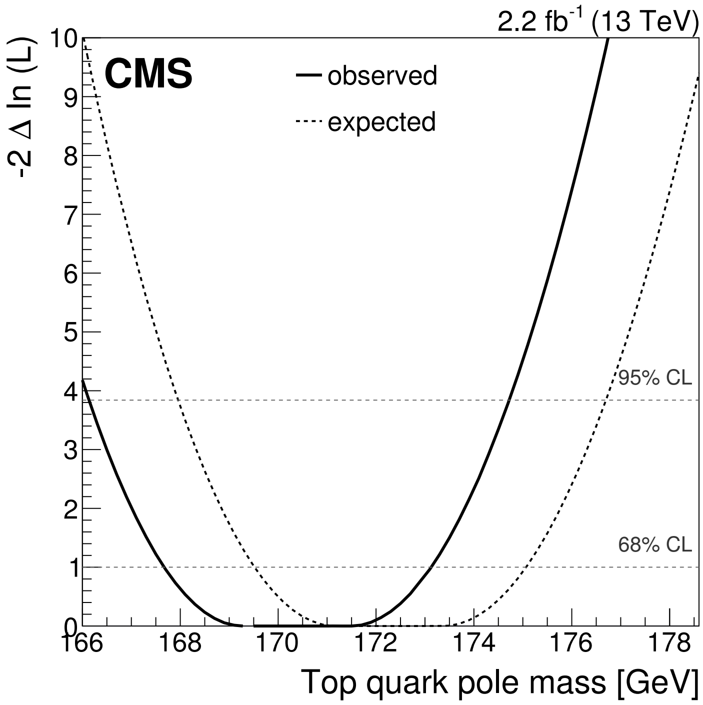

Figure 5. Dependence of the likelihood on the top quark pole mass (solid curve). The expected dependence from the simulation, using the a priori set of nuisance parameters with their expected values at $m_{\mathrm{t}} = 172.5\,\mathrm{GeV}$, is shown for comparison as the dotted curve. The changes in the likelihood corresponding to the 68% and 95% confidence levels (CL) are shown by the dashed lines.

NNLO+NNLL [45] computation with an uncertainty of 3.9%. We obtain an inclusive $\mathrm{t\bar{t}}$ production cross section $\sigma_{\mathrm{t\bar{t}}} = 888 \pm 2\,(\mathrm{stat})\,^{+28}_{-26}\,(\mathrm{syst}) \pm 20\,(\mathrm{lumi})\,\mathrm{pb}$, which is compatible with the standard model prediction, competing in precision with it [45] and with similar measurements of this quantity at the same $\sqrt{s}$ [24–26]. In addition, the top quark pole mass, m_{t}, is extracted at NNLO using the same data and the CT14 PDF set and found to be $m_{\mathrm{t}} = 170.6 \pm 2.7\,\mathrm{GeV}$. This value is in good agreement with measurements using other techniques.

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JHEP09(2017)051

The CMS collaboration

Yerevan Physics Institute, Yerevan, Armenia

A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria

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

Institute for Nuclear Problems, Minsk, Belarus

V. Chekhovsky, O. Dvornikov, Y. Dydyshka, I. Emeliantchik, A. Litomin, V. Makarenko, V. Mossolov, R. Stefanovitch, J. Suarez Gonzalez, V. Zykunov

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

N. Shumeiko

Universiteit Antwerpen, Antwerpen, Belgium

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

Vrije Universiteit Brussel, Brussel, Belgium

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

Université Libre de Bruxelles, Bruxelles, Belgium

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

Ghent University, Ghent, Belgium

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

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

H. Bakhshiansohi, C. Beluffi[3], O. Bondu, S. Brochet, G. Bruno, A. Caudron, S. De Visscher, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, A. Jafari, M. Komm, G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, C. Nuttens, K. Piotrzkowski, L. Quertenmont, M. Selvaggi, M. Vidal Marono, S. Wertz

Université de Mons, Mons, Belgium

N. Beliy

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

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

JHEP09(2017)051

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato[4], A. Custódio, E.M. Da Costa, G.G. Da Silveira[5], D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, D. Matos Figueiredo, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, A. Sznajder, E.J. Tonelli Manganote[4], A. Vilela Pereira

Universidade Estadual Paulista [a], Universidade Federal do ABC [b], São Paulo, Brazil
S. Ahuja[a], C.A. Bernardes[a], S. Dogra[a], T.R. Fernandez Perez Tomei[a], E.M. Gregores[b], P.G. Mercadante[b], C.S. Moon[a], S.F. Novaes[a], Sandra S. Padula[a], D. Romero Abad[b], J.C. Ruiz Vargas[a]

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

University of Sofia, Sofia, Bulgaria
A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China
W. Fang[6]

Institute of High Energy Physics, Beijing, China
M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen[7], T. Cheng, C.H. Jiang, D. Leggat, Z. Liu, F. Romeo, M. Ruan, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, H. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
Y. Ban, G. Chen, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, C.F. González Hernández, J.D. Ruiz Alvarez, J.C. Sanabria

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano, T. Sculac

University of Split, Faculty of Science, Split, Croatia
Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, S. Micanovic, L. Sudic, T. Susa

University of Cyprus, Nicosia, Cyprus
A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, D. Tsiakkouri

Charles University, Prague, Czech Republic
M. Finger[8], M. Finger Jr.[8]

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[9,10], Y. Mohammed[11], E. Salama[12,13]

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
M. Kadastik, L. Perrini, M. Raidal, A. Tiko, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
J. Härkönen, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, J. Tuominiemi, E. Tuovinen, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland
J. Talvitie, T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, C. Favaro, F. Ferri, S. Ganjour, S. Ghosh, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, I. Kucher, E. Locci, M. Machet, J. Malcles, J. Rander, A. Rosowsky, M. Titov, A. Zghiche

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
A. Abdulsalam, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, O. Davignon, R. Granier de Cassagnac, M. Jo, S. Lisniak, P. Miné, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, Y. Sirois, T. Strebler, Y. Yilmaz, A. Zabi

Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS-IN2P3
J.-L. Agram[14], J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte[14], X. Coubez, J.-C. Fontaine[14], D. Gelé, U. Goerlach, A.-C. Le Bihan, P. Van Hove

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

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
S. Beauceron, C. Bernet, G. Boudoul, C.A. Carrillo Montoya, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch,

JHEP09(2017)051

G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov[15], D. Sabes, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret

Georgian Technical University, Tbilisi, Georgia
A. Khvedelidze[8]

Tbilisi State University, Tbilisi, Georgia
D. Lomidze

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, S. Beranek, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, C. Schomakers, J. Schulz, T. Verlage

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

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
V. Cherepanov, G. Flügge, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, A. Stahl[16]

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A.A. Bin Anuar, K. Borras[17], A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Dolinska, G. Eckerlin, D. Eckstein, T. Eichhorn, E. Eren, E. Gallo[18], J. Garay Garcia, A. Geiser, A. Gizhko, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, A. Harb, J. Hauk, M. Hempel[19], H. Jung, A. Kalogeropoulos, O. Karacheban[19], M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann[19], R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M.Ö. Sahin, P. Saxena, T. Schoerner-Sadenius, C. Seitz, S. Spannagel, N. Stefaniuk, G.P. Van Onsem, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany
V. Blobel, M. Centis Vignali, A.R. Draeger, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, M. Hoffmann, A. Junkes, R. Klanner, R. Kogler, N. Kovalchuk, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo[16], T. Peiffer, A. Perieanu, J. Poehlsen, C. Sander, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

Institut für Experimentelle Kernphysik, Karlsruhe, Germany
M. Akbiyik, C. Barth, S. Baur, C. Baus, J. Berger, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, S. Fink, B. Freund, R. Friese, M. Giffels, A. Gilbert,

JHEP09(2017)051

P. Goldenzweig, D. Haitz, F. Hartmann[16], S.M. Heindl, U. Husemann, I. Katkov[15], S. Kudella, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

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

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

National and Kapodistrian University of Athens, Athens, Greece

S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi

University of Ioánnina, Ioánnina, Greece

I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Loukas, N. Manthos, I. Papadopoulos, E. Paradas

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

N. Filipovic

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath[20], F. Sikler, V. Veszpremi, G. Vesztergombi[21], A.J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi[22], A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen

M. Bartók[21], P. Raics, Z.L. Trocsanyi, B. Ujvari

National Institute of Science Education and Research, Bhubaneswar, India

S. Bahinipati, S. Choudhury[23], P. Mal, K. Mandal, A. Nayak[24], D.K. Sahoo, N. Sahoo, S.K. Swain

Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India

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

Saha Institute of Nuclear Physics, Kolkata, India

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

Indian Institute of Technology Madras, Madras, India

P.K. Behera

JHEP09(2017)051

Bhabha Atomic Research Centre, Mumbai, India
R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty[16], P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, S. Dugad, G. Kole, B. Mahakud, S. Mitra, G.B. Mohanty, B. Parida, N. Sur, B. Sutar

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, S. Bhowmik[25], R.K. Dewanjee, S. Ganguly, M. Guchait, Sa. Jain, S. Kumar, M. Maity[25], G. Majumder, K. Mazumdar, T. Sarkar[25], N. Wickramage[26]

Indian Institute of Science Education and Research (IISER), Pune, India
S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani[27], E. Eskandari Tadavani, S.M. Etesami[27], M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi[28], F. Rezaei Hosseinabadi, B. Safarzadeh[29], M. Zeinali

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy
M. Abbrescia[a,b], C. Calabria[a,b], C. Caputo[a,b], A. Colaleo[a], D. Creanza[a,c], L. Cristella[a,b], N. De Filippis[a,c], M. De Palma[a,b], L. Fiore[a], G. Iaselli[a,c], G. Maggi[a,c], M. Maggi[a], G. Miniello[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a,b], A. Ranieri[a], G. Selvaggi[a,b], A. Sharma[a], L. Silvestris[a,16], R. Venditti[a,b], P. Verwilligen[a]

INFN Sezione di Bologna [a], Università di Bologna [b], Bologna, Italy
G. Abbiendi[a], C. Battilana, D. Bonacorsi[a,b], S. Braibant-Giacomelli[a,b], L. Brigliadori[a,b], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], S.S. Chhibra[a,b], G. Codispoti[a,b], M. Cuffiani[a,b], G.M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a,b], P. Giacomelli[a], C. Grandi[a], L. Guiducci[a,b], S. Marcellini[a], G. Masetti[a], A. Montanari[a], F.L. Navarria[a,b], A. Perrotta[a], A.M. Rossi[a,b], T. Rovelli[a,b], G.P. Siroli[a,b], N. Tosi[a,b,16]

INFN Sezione di Catania [a], Università di Catania [b], Catania, Italy
S. Albergo[a,b], S. Costa[a,b], A. Di Mattia[a], F. Giordano[a,b], R. Potenza[a,b], A. Tricomi[a,b], C. Tuve[a,b]

INFN Sezione di Firenze [a], Università di Firenze [b], Firenze, Italy
G. Barbagli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], P. Lenzi[a,b], M. Meschini[a], S. Paoletti[a], G. Sguazzoni[a], L. Viliani[a,b,16]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera[16]

INFN Sezione di Genova [a], Università di Genova [b], Genova, Italy
V. Calvelli[a,b], F. Ferro[a], M.R. Monge[a,b], E. Robutti[a], S. Tosi[a,b]

JHEP09(2017)051

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

L. Brianza[a,b,16], F. Brivio[a,b], V. Ciriolo, M.E. Dinardo[a,b], S. Fiorendi[a,b,16], S. Gennai[a], A. Ghezzi[a,b], P. Govoni[a,b], M. Malberti[a,b], S. Malvezzi[a], R.A. Manzoni[a,b], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], S. Pigazzini[a,b], S. Ragazzi[a,b], T. Tabarelli de Fatis[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], N. Cavallo[a,c], G. De Nardo, S. Di Guida[a,d,16], M. Esposito[a,b], F. Fabozzi[a,c], F. Fienga[a,b], A.O.M. Iorio[a,b], G. Lanza[a], L. Lista[a], S. Meola[a,d,16], P. Paolucci[a,16], C. Sciacca[a,b], F. Thyssen[a]

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

P. Azzi[a,16], N. Bacchetta[a], L. Benato[a,b], D. Bisello[a,b], A. Boletti[a,b], R. Carlin[a,b], P. Checchia[a], M. Dall'Osso[a,b], P. De Castro Manzano[a], T. Dorigo[a], U. Dosselli[a], F. Gasparini[a,b], U. Gasparini[a,b], A. Gozzelino[a], S. Lacaprara[a], M. Margoni[a,b], A.T. Meneguzzo[a,b], J. Pazzini[a,b], N. Pozzobon[a,b], P. Ronchese[a,b], F. Simonetto[a,b], E. Torassa[a], S. Ventura[a], M. Zanetti[a,b], P. Zotto[a,b], G. Zumerle[a,b]

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

A. Braghieri[a], A. Magnani[a,b], P. Montagna[a,b], S.P. Ratti[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

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

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

K. Androsov[a,30], P. Azzurri[a,16], G. Bagliesi[a], J. Bernardini[a], T. Boccali[a], R. Castaldi[a], M.A. Ciocci[a,30], R. Dell'Orso[a], S. Donato[a,c], G. Fedi, A. Giassi[a], M.T. Grippo[a,30], F. Ligabue[a,c], T. Lomtadze[a], L. Martini[a,b], A. Messineo[a,b], F. Palla[a], A. Rizzi[a,b], A. Savoy-Navarro[a,31], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma [a], Università di Roma [b], Roma, Italy

L. Barone[a,b], F. Cavallari[a], M. Cipriani[a,b], D. Del Re[a,b,16], M. Diemoz[a], S. Gelli[a,b], E. Longo[a,b], F. Margaroli[a,b], B. Marzocchi[a,b], P. Meridiani[a], G. Organtini[a,b], R. Paramatti[a], F. Preiato[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[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,16], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a], R. Bellan[a,b], C. Biino[a], N. Cartiglia[a], F. Cenna[a,b], M. Costa[a,b], R. Covarelli[a,b], A. Degano[a,b], N. Demaria[a], L. Finco[a,b], B. Kiani[a,b], C. Mariotti[a], S. Maselli[a],

JHEP09(2017)051

E. Migliore[a,b], V. Monaco[a,b], E. Monteil[a,b], M. Monteno[a], M.M. Obertino[a,b], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], G.L. Pinna Angioni[a,b], F. Ravera[a,b], A. Romero[a,b], M. Ruspa[a,c], R. Sacchi[a,b], K. Shchelina[a,b], V. Sola[a], A. Solano[a,b], A. Staiano[a], P. Traczyk[a,b]

INFN Sezione di Trieste [a], Università di Trieste [b], Trieste, Italy
S. Belforte[a], M. Casarsa[a], F. Cossutti[a], G. Della Ricca[a,b], A. Zanetti[a]

Kyungpook National University, Daegu, Korea
D.H. Kim, G.N. Kim, M.S. Kim, S. Lee, S.W. Lee, Y.D. Oh, S. Sekmen, D.C. Son, Y.C. Yang

Chonbuk National University, Jeonju, Korea
A. Lee

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

Hanyang University, Seoul, Korea
J.A. Brochero Cifuentes, T.J. Kim

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

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

University of Seoul, Seoul, Korea
M. Choi, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park, G. Ryu, M.S. Ryu

Sungkyunkwan University, Suwon, Korea
Y. Choi, J. Goh, C. Hwang, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania
V. Dudenas, A. Juodagalvis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Ahmed, Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali[32], F. Mohamad Idris[33], W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz[34], A. Hernandez-Almada, R. Lopez-Fernandez, R. Magaña Villalba, J. Mejia Guisao, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

JHEP09(2017)051

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
S. Carpinteyro, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
A. Morelos Pineda

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, A. Byszuk[35], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
P. Bargassa, C. Beirão Da Cruz E Silva, B. Calpas, A. Di Francesco, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadruccio, J. Varela, P. Vischia

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev[36,37], V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
L. Chtchipounov, V. Golovtsov, Y. Ivanov, V. Kim[38], E. Kuznetsova[39], V. Murzin, V. Oreshkin, V. Sulimov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia
A. Bylinkin[37]

JHEP09(2017)051

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

E. Popova, E. Tarkovskii, E. Zhemchugov

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin[37], I. Dremin[37], M. Kirakosyan, A. Leonidov[37], A. Terkulov

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

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

Novosibirsk State University (NSU), Novosibirsk, Russia

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

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

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

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

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

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

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

Universidad Autónoma de Madrid, Madrid, Spain

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

Universidad de Oviedo, Oviedo, Spain

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

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

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

JHEP09(2017)051

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, P. Bloch, A. Bocci, A. Bonato, C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, Y. Chen, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, A. De Roeck, E. Di Marco[43], M. Dobson, B. Dorney, T. du Pree, D. Duggan, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, S. Fartoukh, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, M. Girone, F. Glege, D. Gulhan, S. Gundacker, M. Guthoff, J. Hammer, P. Harris, J. Hegeman, V. Innocente, P. Janot, J. Kieseler, H. Kirschenmann, V. Knünz, A. Kornmayer[16], M.J. Kortelainen, K. Kousouris, M. Krammer[1], C. Lange, P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic[44], F. Moortgat, S. Morovic, M. Mulders, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, A. Racz, T. Reis, G. Rolandi[45], M. Rovere, H. Sakulin, J.B. Sauvan, C. Schäfer, C. Schwick, M. Seidel, A. Sharma, P. Silva, P. Sphicas[46], J. Steggemann, M. Stoye, Y. Takahashi, M. Tosi, D. Treille, A. Triossi, A. Tsirou, V. Veckalns[47], G.I. Veres[21], M. Verweij, N. Wardle, H.K. Wöhri, A. Zagozdzinska[35], W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

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

Universität Zürich, Zurich, Switzerland

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

National Central University, Chung-Li, Taiwan

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

National Taiwan University (NTU), Taipei, Taiwan

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

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

B. Asavapibhop, G. Singh, N. Srimanobhas, N. Suwonjandee

JHEP09(2017)051

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

Middle East Technical University, Physics Department, Ankara, Turkey
B. Bilin, S. Bilmis, B. Isildak[56], G. Karapinar[57], M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey
E. Gülmez, M. Kaya[58], O. Kaya[59], E.A. Yetkin[60], T. Yetkin[61]

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak, S. Sen[62]

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk, P. Sorokin

University of Bristol, Bristol, United Kingdom
R. Aggleton, F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, D.M. Newbold[63], S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, A. Belyaev[64], C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom
M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, R. Di Maria, P. Dunne, A. Elwood, D. Futyan, Y. Haddad, G. Hall, G. Iles, T. James, R. Lane, C. Laner, R. Lucas[63], L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, J. Nash, A. Nikitenko[48], J. Pela, B. Penning, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, C. Seez, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta[65], T. Virdee[16], J. Wright, S.C. Zenz

Brunel University, Uxbridge, United Kingdom
J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leslie, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, U.S.A.
A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika

JHEP09(2017)051

The University of Alabama, Tuscaloosa, U.S.A.

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

Boston University, Boston, U.S.A.

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

Brown University, Providence, U.S.A.

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

University of California, Davis, Davis, U.S.A.

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

University of California, Los Angeles, U.S.A.

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

University of California, Riverside, Riverside, U.S.A.

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

University of California, San Diego, La Jolla, U.S.A.

J.G. Branson, G.B. Cerati, S. Cittolin, M. Derdzinski, R. Gerosa, A. Holzner, D. Klein, V. Krutelyov, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech[66], C. Welke, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara - Department of Physics, Santa Barbara, U.S.A.

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

California Institute of Technology, Pasadena, U.S.A.

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

Carnegie Mellon University, Pittsburgh, U.S.A.

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

JHEP09(2017)051

University of Colorado Boulder, Boulder, U.S.A.

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

Cornell University, Ithaca, U.S.A.

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

Fairfield University, Fairfield, U.S.A.

D. Winn

Fermi National Accelerator Laboratory, Batavia, U.S.A.

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

University of Florida, Gainesville, U.S.A.

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

Florida International University, Miami, U.S.A.

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

Florida State University, Tallahassee, U.S.A.

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

Florida Institute of Technology, Melbourne, U.S.A.

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

University of Illinois at Chicago (UIC), Chicago, U.S.A.

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, K. Jung, I.D. Sandoval Gonzalez, N. Varelas, H. Wang, Z. Wu, M. Zakaria, J. Zhang

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

Johns Hopkins University, Baltimore, U.S.A.
I. Anderson, B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, C. Martin, M. Osherson, J. Roskes, U. Sarica, M. Swartz, M. Xiao, Y. Xin, C. You

The University of Kansas, Lawrence, U.S.A.
A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, J. Castle, L. Forthomme, R.P. Kenny III, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, S. Sanders, R. Stringer, J.D. Tapia Takaki, Q. Wang

Kansas State University, Manhattan, U.S.A.
A. Ivanov, K. Kaadze, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

Lawrence Livermore National Laboratory, Livermore, U.S.A.
F. Rebassoo, D. Wright

University of Maryland, College Park, U.S.A.
C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, J.A. Gomez, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Kolberg, J. Kunkle, Y. Lu, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, M.B. Tonjes, S.C. Tonwar

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

University of Minnesota, Minneapolis, U.S.A.
A.C. Benvenuti, R.M. Chatterjee, A. Evans, A. Finkel, A. Gude, P. Hansen, S. Kalafut, S.C. Kao, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, N. Tambe, J. Turkewitz

University of Mississippi, Oxford, U.S.A.
J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, U.S.A.
E. Avdeeva, R. Bartek[70], K. Bloom, D.R. Claes, A. Dominguez[70], C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, A. Malta Rodrigues, F. Meier, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

JHEP09(2017)051

State University of New York at Buffalo, Buffalo, U.S.A.
M. Alyari, J. Dolen, A. Godshalk, C. Harrington, I. Iashvili, J. Kaisen, A. Kharchilava, A. Parker, S. Rappoccio, B. Roozbahani

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

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

University of Notre Dame, Notre Dame, U.S.A.
N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, N. Marinelli, F. Meng, C. Mueller, Y. Musienko[36], M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, M. Wayne, M. Wolf, A. Woodard

The Ohio State University, Columbus, U.S.A.
J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, R. Hughes, W. Ji, B. Liu, W. Luo, D. Puigh, B.L. Winer, H.W. Wulsin

Princeton University, Princeton, U.S.A.
S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, D. Lange, J. Luo, D. Marlow, T. Medvedeva, K. Mei, J. Olsen, C. Palmer, P. Piroué, D. Stickland, A. Svyatkovskiy, C. Tully

University of Puerto Rico, Mayaguez, U.S.A.
S. Malik

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

Purdue University Calumet, Hammond, U.S.A.
N. Parashar, J. Stupak

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

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

Rutgers, The State University of New Jersey, Piscataway, U.S.A.
A. Agapitos, J.P. Chou, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, K. Nash, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, U.S.A.

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

Texas A&M University, College Station, U.S.A.

O. Bouhali[71], A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, E. Juska, T. Kamon[72], R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov, K.A. Ulmer

Texas Tech University, Lubbock, U.S.A.

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

Vanderbilt University, Nashville, U.S.A.

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

University of Virginia, Charlottesville, U.S.A.

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

Wayne State University, Detroit, U.S.A.

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

University of Wisconsin - Madison, Madison, WI, U.S.A.

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

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
3: Also at Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS/IN2P3, Strasbourg, France
4: Also at Universidade Estadual de Campinas, Campinas, Brazil
5: Also at Universidade Federal de Pelotas, Pelotas, Brazil
6: Also at Université Libre de Bruxelles, Bruxelles, Belgium
7: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
8: Also at Joint Institute for Nuclear Research, Dubna, Russia
9: Also at Helwan University, Cairo, Egypt
10: Now at Zewail City of Science and Technology, Zewail, Egypt
11: Now at Fayoum University, El-Fayoum, Egypt
12: Also at British University in Egypt, Cairo, Egypt
13: Now at Ain Shams University, Cairo, Egypt
14: Also at Université de Haute Alsace, Mulhouse, France

JHEP09(2017)051

15: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
16: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
17: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
18: Also at University of Hamburg, Hamburg, Germany
19: Also at Brandenburg University of Technology, Cottbus, Germany
20: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
21: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
22: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
23: Also at Indian Institute of Science Education and Research, Bhopal, India
24: Also at Institute of Physics, Bhubaneswar, India
25: Also at University of Visva-Bharati, Santiniketan, India
26: Also at University of Ruhuna, Matara, Sri Lanka
27: Also at Isfahan University of Technology, Isfahan, Iran
28: Also at Yazd University, Yazd, Iran
29: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
30: Also at Università degli Studi di Siena, Siena, Italy
31: Also at Purdue University, West Lafayette, U.S.A.
32: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
33: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
34: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
35: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
36: Also at Institute for Nuclear Research, Moscow, Russia
37: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
38: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
39: Also at University of Florida, Gainesville, U.S.A.
40: Also at California Institute of Technology, Pasadena, U.S.A.
41: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
42: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
43: Also at INFN Sezione di Roma; Università di Roma, Roma, Italy
44: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
45: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
46: Also at National and Kapodistrian University of Athens, Athens, Greece
47: Also at Riga Technical University, Riga, Latvia
48: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
49: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
50: Also at Gaziosmanpasa University, Tokat, Turkey
51: Also at Istanbul Aydin University, Istanbul, Turkey
52: Also at Mersin University, Mersin, Turkey
53: Also at Cag University, Mersin, Turkey
54: Also at Piri Reis University, Istanbul, Turkey
55: Also at Adiyaman University, Adiyaman, Turkey
56: Also at Ozyegin University, Istanbul, Turkey
57: Also at Izmir Institute of Technology, Izmir, Turkey

58: Also at Marmara University, Istanbul, Turkey
59: Also at Kafkas University, Kars, Turkey
60: Also at Istanbul Bilgi University, Istanbul, Turkey
61: Also at Yildiz Technical University, Istanbul, Turkey
62: Also at Hacettepe University, Ankara, Turkey
63: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
64: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
65: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
66: Also at Utah Valley University, Orem, U.S.A.
67: Also at Argonne National Laboratory, Argonne, U.S.A.
68: Also at Erzincan University, Erzincan, Turkey
69: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
70: Now at The Catholic University of America, Washington, U.S.A.
71: Also at Texas A&M University at Qatar, Doha, Qatar
72: Also at Kyungpook National University, Daegu, Korea

JHEP09(2017)051