

CERN-EP-2017-155
2018/06/18

CMS-B2G-17-007

Search for single production of a vector-like T quark decaying to a Z boson and a top quark in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

A search is presented for single production of a vector-like quark (T) decaying to a Z boson and a top quark, with the Z boson decaying leptonically and the top quark decaying hadronically. The search uses data collected by the CMS experiment in proton-proton collisions at a center-of-mass energy of 13 TeV in 2016, corresponding to an integrated luminosity of 35.9 fb^{-1} . The presence of forward jets is a particular characteristic of single production of vector-like quarks that is used in the analysis. For the first time, different T quark width hypotheses are studied, from negligibly small to 30% of the new particle mass. At the 95% confidence level, the product of cross section and branching fraction is excluded above values in the range 0.26–0.04 pb for T quark masses in the range 0.7–1.7 TeV, assuming a negligible width. A similar sensitivity is observed for widths of up to 30% of the T quark mass. The production of a heavy Z' boson decaying to Tt , with $T \rightarrow tZ$, is also searched for, and limits on the product of cross section and branching fractions for this process are set between 0.13 and 0.06 pb for Z' boson masses in the range from 1.5 to 2.5 TeV.

Published in Physics Letters B as doi:10.1016/j.physletb.2018.04.036.

1 Introduction

A possible extension of the standard model (SM), able to address some of the problems related to the nature of electroweak symmetry breaking, involves heavy particles called vector-like quarks (VLQs) [1–5]. Unlike the chiral fermions of the SM, these new particles do not obtain mass through a Yukawa coupling but through a direct mass term of the form $m\bar{\psi}\psi$. This means that they are not excluded by precision SM measurements as are fourth-generation chiral quarks [6].

Previous searches for VLQs have been performed by both the ATLAS [7–14] and CMS [15–22] Collaborations, as well as by the D0 [23, 24] and CDF [25–30] Collaborations.

We study the single production of vector-like T quarks with charge $+2/3$ that decay to a Z boson and a t quark. We search for a final state with a Z boson decaying to electrons or muons, and a t quark producing jets via the decay $t \rightarrow Wb \rightarrow q'\bar{q}b$. An example of a leading-order (LO) Feynman diagram for the single production of a T quark in association with either a b quark, denoted T(b), or a t quark, denoted T(t), is shown in Fig. 1 (left). The three decay channels of the T quark into SM particles are bW, tZ, and tH. If the T is a singlet of the SM, the equivalence theorem [31] implies that the branching fractions for the three decay modes of the T quark are approximately 0.5, 0.25, and 0.25, respectively. If the T is a doublet of the SM, the decay modes are tZ and tH, each with a branching fraction of 0.5.

The T quark could be singly produced in association with either a t or a b quark and an additional quark would be produced in the forward region of the detector. The coupling coefficients of the T quark to SM particles are denoted $C(bW)$ for the T(b) process, and $C(tZ)$ for the T(t) process. The production cross section of the T quark depends on its mass and width, as well as on these couplings. The T quark can have both left-handed (LH) and right-handed (RH) couplings to SM particles. In the case of a singlet T quark, the RH chirality is suppressed by a factor proportional to the SM quark mass divided by the T quark mass. In the case of a doublet T quark, it is the LH chirality that is suppressed [32].

The present search is also sensitive to the production of a T quark together with a t quark in the decay of a heavy neutral spin-1 Z' boson [33–35]. A LO Feynman diagram for this production mode is shown in Fig. 1 (right). This channel was also considered in Refs. [18, 36].

This search follows a strategy similar to that used by Ref. [18]. However, significant improvements to the sensitivity of the method have been made by employing a categorization based

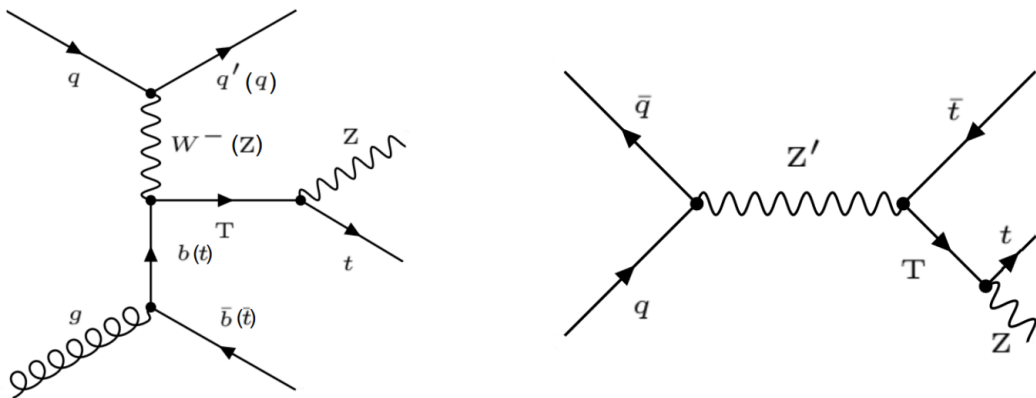


Figure 1: Leading-order Feynman diagrams for the production of a single vector-like T quark and its decay to a Z boson and a t quark, either in association with a b quark or a t quark (left), or in the decay of a Z' boson to Tt (right).

on the presence of forward jets, and by analyzing the mass spectrum of reconstructed T quark candidates, m_{tZ} , in events where the t quark products are highly Lorentz-boosted and therefore are reconstructed as a single, large-radius jet. The present analysis also benefits from the much larger data sample recorded in 2016. This paper also includes the first results assuming a T quark with a nonnegligible decay width that varies between 10 and 30% of the T quark mass.

2 The CMS detector, data, and simulation

The general-purpose CMS detector operates at one of the four interaction points of the LHC. Its central feature is a 3.8 T superconducting solenoid magnet with an inner diameter of 6 m. The following subdetectors are found within the magnet volume: a silicon tracker, a crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL). Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. In addition, the CMS detector has extensive forward calorimetry: two steel and quartz-fiber hadron forward calorimeters that extend the HCAL coverage to regions close to the beam pipe, and cover the pseudorapidity range $3.0 < |\eta| < 5.2$. A more detailed description of the CMS detector, together with a definition of the coordinate system and kinematic variables, can be found in Ref. [37].

This analysis is based on the data collected by the CMS experiment in proton-proton collisions at a center-of-mass energy of 13 TeV in 2016, corresponding to an integrated luminosity of 35.9 fb^{-1} . Events with a Z boson decaying to muons are selected online by requiring the presence of an isolated muon with transverse momentum $p_T > 24 \text{ GeV}$. Events with the Z boson decaying to electrons are selected online if an electron is reconstructed with $p_T > 115 \text{ GeV}$. It is possible to use this relatively high p_T threshold without losing signal efficiency, since the electrons of interest arise from the decay of a heavy resonance.

Background events are generated using the next-to-LO (NLO) generator MADGRAPH5_aMC@NLO 2.2.2 [38] for $Z/\gamma^* + \text{jets}$, $t\bar{t} + V$, and tZq processes, and the NLO generator POWHEG 2.0 [39–42] for $t\bar{t}$ and single t quark production. They are interfaced with PYTHIA 8.212 [43], with the tune CUETP8M2T4 [44] used for the description of parton hadronization and fragmentation. Events for diboson production are generated at LO using MADGRAPH 5.2 and at NLO with POWHEG 2.0. Simulated events are normalized to NLO cross sections for all processes except for $t\bar{t}$, single t quark production and diboson (WW only) processes, where next-to-NLO values are used.

Signal events with the T quark produced either directly or in the decay of a Z' boson are generated at LO using MADGRAPH 5.2 interfaced to PYTHIA 8.212. For the single production of the T quark, different T quark width hypotheses are considered: negligibly small and larger widths (10, 20, and 30% of the T quark mass). Spin correlations are treated in the decay with MADSPIN [45].

In the case where the T and Z' particles are generated with narrow widths, i.e., negligibly small with respect to the experimental reconstructed mass resolution, T quark masses m_T between 0.7 and 1.7 TeV in steps of 0.1 TeV, and Z' masses $m_{Z'}$ of 1.5, 2.0, and 2.5 TeV are considered. The singlet T(b) signal process with LH couplings to SM particles, and doublet T(t) signal process with RH couplings, are generated. Theoretical cross sections for the narrow-width T quark assumption are listed in Table 1, calculated following the procedures described in Ref. [4], where a simplified approach is used to provide a model-independent interpretation of experimental results. The width of the VLQ is negligible compared to the experimental mass resolution for C(bW) and C(tZ) couplings ≤ 0.5 .

Table 1: Theoretical cross sections at next-to-leading order for single production of a T quark in association with a b or t quark for the benchmark masses considered in the analysis, with the couplings set to 0.5 and using the narrow-width T quark assumption, calculated following the procedures described in Ref. [4]. The cross sections do not depend on the chirality of the T quark. The narrow-width assumption is valid for any value of the couplings less than or equal to 0.5.

m_T [TeV]	$\sigma(pp \rightarrow T b q \rightarrow t Z b q)$ [pb]	$\sigma(pp \rightarrow T t q \rightarrow t Z t q)$ [pb]
0.7	0.364	0.063
0.8	0.241	0.046
0.9	0.170	0.034
1.0	0.122	0.026
1.1	0.085	0.019
1.2	0.062	0.015
1.3	0.045	0.011
1.4	0.034	0.009
1.5	0.026	0.007
1.6	0.019	0.006
1.7	0.015	0.004

Signals for T quarks with larger widths (10, 20, and 30% of the T quark mass) are generated in the same mass range but in steps of 0.2 TeV. The effect of the finite-width approximation is evaluated using a modified version of the model constructed by the authors of Refs. [5, 46, 47]. Modifications of the published versions were necessary to provide a simulation of the full $2 \rightarrow 4$ process, i.e., $pp \rightarrow T b q / T t q \rightarrow t Z b q / t Z t q$, in the finite-width hypothesis. It has been verified that the interference of the $2 \rightarrow 4$ process with the SM background processes is negligible.

In the general case, the total production cross section for a T quark with a finite width (FW) can be written as:

$$\sigma_{FW}(C_1, C_2, m_T, \Gamma(C_1, C_2, C_i, m_T, m_j)) = C_1^2 C_2^2 \tilde{\sigma}_{FW}(m_T, \Gamma(C_1, C_2, C_i, m_T, m_j)), \quad (1)$$

where $\Gamma(C_1, C_2, C_i, m_T, m_j)$ is the width of the T quark, C_1 and C_2 are its couplings to SM quarks and bosons in the specific single-production process under consideration, C_i summarizes other possible couplings that allow the T to decay to other final states, and the quantities m_j represent the masses of the decay products of the T quark. The $\tilde{\sigma}_{FW}$ is the “reduced cross section” and it corresponds to the physical cross section after factorizing the production cross section and the decay couplings. For the process $pp \rightarrow T t q \rightarrow t Z t q$ the couplings are $C_1 = C_2 = (g_w/2) C(tZ)$, while for $pp \rightarrow T b q \rightarrow t Z b q$ the couplings are $C_1 = (g_w/2) C(bW)$ and $C_2 = (g_w/2) C(tZ)$. The normalisation factor $g_w/2$ has been introduced to properly compare the couplings as defined in Ref. [4] and in Eq. (1). In Table 2, the values for $\tilde{\sigma}_{FW}$ are shown together with the cross sections for the singlet T(b) and doublet T(t) signals used to interpret the results. These cross sections are calculated by fixing the branching fractions of the T to the expected values in the narrow-width approximation, as described above and in Ref. [4]. This choice corresponds to different sets of couplings than the ones used in the narrow width approximation.

The generated events are passed through a simulation of the CMS detector based on GEANT4 [48, 49]. The number of additional interactions in the same or adjacent bunch crossings (pileup) is included in simulation with a distribution of the number of additional interactions matching that observed in data. Samples are generated using the NNPDF 3.0 [50] parton distribution function (PDF) sets, matching the perturbative order used in simulation.

Table 2: Theoretical reduced cross sections $\tilde{\sigma}_{\text{FW}}$ for single production of a T quark with a b or a t quark, where the T quark decays to tZ and its width is 10, 20, and 30% of its mass, for the benchmark masses considered in the analysis. The corresponding leading order cross sections σ for the specified production and decay are shown in parentheses.

m_T [TeV]	$\tilde{\sigma}_{\text{FW}} (\sigma)$ for $pp \rightarrow \text{T}bq \rightarrow \text{tZ}bq$ [pb]			$\tilde{\sigma}_{\text{FW}} (\sigma)$ for $pp \rightarrow \text{T}tq \rightarrow \text{tZ}tq$ [pb]		
	10%	20%	30%	10%	20%	30%
0.8	226 (0.675)	108 (0.650)	70 (0.631)	19 (0.144)	9.3 (0.139)	6.0 (0.135)
1.0	183 (0.314)	87 (0.299)	55 (0.284)	17 (0.075)	7.9 (0.072)	5.0 (0.069)
1.2	145 (0.158)	68 (0.149)	43 (0.141)	14 (0.042)	6.4 (0.039)	4.1 (0.037)
1.4	112 (0.084)	52 (0.079)	33 (0.074)	11 (0.024)	5.0 (0.022)	3.2 (0.021)
1.6	85 (0.047)	39 (0.043)	29 (0.041)	8.2 (0.014)	3.8 (0.013)	2.4 (0.012)

3 Object reconstruction

Primary vertices are reconstructed using a deterministic annealing filter algorithm [51]. The reconstructed vertex with the largest value of summed physics-object p_T^2 is taken to be the primary pp interaction vertex. The physics objects are the objects returned by a jet finding algorithm [52, 53] applied to all charged tracks associated with the vertex, plus the corresponding associated missing transverse momentum. Selected events are required to have this primary vertex within 24 cm of the center of the detector along the z-direction, and within 2 cm in the x - y plane.

A particle-flow (PF) algorithm [54] is used to identify and to reconstruct charged and neutral hadrons, photons, muons, and electrons, through an optimal combination of the information from the entire detector.

Electron candidates are reconstructed by combining the information from the ECAL and from the silicon tracker [55]. Electrons are then selected if they are isolated and if they have $p_T > 20$ GeV and pseudorapidity $|\eta| < 2.5$. Additional requirements are applied to the energy distribution in the ECAL, to the geometrical matching of the tracker information to the ECAL energy cluster, on the impact parameters of the charged tracks, and on the ratio of the energies measured in the HCAL and the ECAL in the region around the electron candidate. The leading electron is required to have $p_T > 120$ GeV, in order to be in the region where the trigger is close to 100% efficiency.

Muon candidates are reconstructed by combining in a global fit the information from the silicon tracker and the muon system [56]. Muons are then required to be isolated, to satisfy $p_T > 20$ GeV and $|\eta| < 2.4$, and to pass additional identification criteria based on the track impact parameter, the quality of the track reconstruction, and the number of hits recorded in the tracker and the muon systems. Like the leading electron, the leading muon is required to have $p_T > 120$ GeV.

For both muons and electrons, a lepton isolation variable is used to reduce background from events in which a jet is misidentified as a lepton. This variable is defined as the scalar sum of the p_T of the charged and neutral hadrons and photons in a cone of size $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ around the original lepton track, corrected for the effects of pileup [55, 56], and divided by the lepton p_T . The cone size is 0.4 for muons and 0.3 for electrons.

Jet candidates are clustered from the PF candidates using the anti- k_T clustering algorithm [52] with distance parameters of 0.4 (“AK4 jets”) and 0.8 (“AK8 jets”). The jet energy scale (JES) is calibrated through correction factors dependent on the p_T , η , energy density, and area of the jet. The jet energy resolution (JER) for the simulated jets is degraded to reproduce the resolution

observed in data. The AK4 jet candidates are required to have $p_T > 20 \text{ GeV}$, $|\eta| < 2.4$ and to be separated by $\Delta R > 0.4$ from an identified lepton. The AK8 jet candidates are required to have $p_T > 180 \text{ GeV}$, $|\eta| < 2.4$ and to be separated by $\Delta R > 0.8$ from an identified lepton. The AK8 jets may be tagged as coming from a W boson decaying to $q'\bar{q}$ (denoted “W jets”) or from a t quark decaying fully hadronically (“t jets”). For the W jets, a pruning algorithm [57] is applied. The mass of the jet, after the pruning is performed, is used as a discriminant to select W bosons and reject quark and gluon jets. The discrimination between W jets and jets from quarks and gluons is further improved by requiring the N -subjettiness ratio τ_{21} to be less than 0.6, where $\tau_{21} = \tau_2/\tau_1$ [58], and the mass of the pruned AK8 jet to be within the range 65–105 GeV. In a similar way, AK8 jets may be identified as arising from the all-jets final state of a t quark. These t jets are required to have $p_T > 400 \text{ GeV}$, mass of the jet reconstructed through the modified mass drop tagger algorithm [59, 60] between 105 and 220 GeV, and $\tau_{32} = \tau_3/\tau_2$ less than 0.81. Finally, AK4 jets may be tagged as arising from a b quark (“b jets”) using the combined secondary vertex algorithm [61, 62]. A “medium” working point with an efficiency of 70% for genuine b jets and a rejection of 99% of light-flavor jets is used, together with a “loose” working point that has an 85% identification efficiency and rejects 90% of light-flavored jets. The efficiency for identifying W, t, and b jets in simulation is corrected to match the results found in data.

An interesting feature of the direct production of a single vector-like T quark is the presence of an additional jet that is produced in the forward direction. Forward jets are reconstructed as AK4 jets using the same selections and corrections as defined above, but have $2.4 < |\eta| < 5.0$ and $p_T > 30 \text{ GeV}$.

4 Event selection

Events are required to have two oppositely charged leptons (either muons or electrons) forming a Z boson with an invariant mass between 70 and 110 GeV. A t quark from a T quark decay can be identified in three different ways: fully merged (a t jet is identified), partially merged (a W jet and a b jet are identified), or resolved (three AK4 jets are reconstructed). We therefore define ten event categories, depending on how the Z boson or the t quark candidates are reconstructed and on the number of forward jets present, as summarized in Table 3.

Table 3: Summary of the ten categories of the analysis. For each category the leading lepton must have $p_T > 120 \text{ GeV}$, while at least one b jet has to be present.

Category	Z boson	t quark	$N(\text{forward jets})$	$\Delta R(\ell, \ell)$	$m_{j1,j2}$
1	two muons	fully merged	≥ 0	< 1.4	—
2	two electrons	fully merged	≥ 0	< 1.4	—
3	two muons	partially merged	0	< 0.6	—
4	two muons	partially merged	≥ 1	< 0.6	—
5	two electrons	partially merged	0	< 0.6	—
6	two electrons	partially merged	≥ 1	< 0.6	—
7	two muons	resolved	0	< 0.6	$< 200 \text{ GeV}$
8	two muons	resolved	≥ 1	< 0.6	$< 200 \text{ GeV}$
9	two electrons	resolved	0	< 0.6	$< 200 \text{ GeV}$
10	two electrons	resolved	≥ 1	< 0.6	$< 200 \text{ GeV}$

The hierarchy places the most sensitive categories first. If an event falls into two or more categories it is assigned only to the first. For categories 1 and 2, the t quark candidate is given

by the t jet; for categories 3–6 it is reconstructed by summing the momentum vectors of the W jet and the b jet; while for categories 7–10 the momenta of the three jets are summed. If more than one t quark candidate is found, the one with the largest p_T is selected for the subsequent restoration.

In addition to requiring a Z boson and a t quark in the event, at least one “medium” b jet has to be present (for the partially merged and the resolved categories, it is the one used to reconstruct the t quark), the two leptons from the Z boson decay have to be close to each other ($\Delta R < 0.6$ – 1.4 , depending on the category), and the leading lepton (muon or electron) must have $p_T > 120$ GeV. If more than one medium b jet is present, the one giving the largest t quark p_T is selected for subsequent reconstruction. Furthermore, in the resolved categories, the two jets with the lowest b tagging discriminant of the three jets forming the t quark candidate are required to have a dijet invariant mass $m_{j1,j2}$ below 200 GeV. All these requirements were optimized to increase the sensitivity of the analysis and are summarized in Table 3.

The T quark candidate mass m_{tZ} is obtained by summing the momenta of the Z candidate, given by the two muons or the two electrons, and the t quark candidate, reconstructed for the three scenarios as described above.

5 Background estimate

In this analysis, the signal is searched for as an excess in the mass spectrum of reconstructed T quark candidates, m_{tZ} , which is used as the discriminating variable. The background is largely dominated by $Z/\gamma^* + \text{jets}$ events ($>80\%$), with smaller contributions from other sources ($t\bar{t} + V$, tZq , $t\bar{t}$, single t quark, and VV diboson production, where V represents a W or Z boson).

The background is estimated from data in order to reduce dependence on the simulation. This estimate, which incorporates all of the background processes described above, is obtained by measuring the m_{tZ} distribution in a control region defined by applying the event selection described in Section 4, but instead of requiring the presence of a jet passing the medium b tagging requirements, a veto is applied on the presence of any jet passing the loose b tagging requirements. This veto effectively removes the signal while leaving a substantial fraction of the dominant Z+jets background.

The background expectation in the signal region is then estimated as:

$$N_{\text{bkg}}(m_{tZ}) = N_{\text{CR}}(m_{tZ}) \alpha(m_{tZ}), \quad (2)$$

where $N_{\text{CR}}(m_{tZ})$ is the number of events found in the data in the control region as a function of m_{tZ} , and $\alpha(m_{tZ})$ is the ratio obtained from simulation of the number of background events in the signal region to that in the control region, at each value of m_{tZ} . A closure test is performed to validate the method in an independent signal-free region, defined by considering the resolved categories and inverting the cut on $m_{j1,j2}$. This region has been chosen because it has a negligible signal contamination and yet it preserves the background composition of the signal region. Good agreement is found between the predicted background and the observed data in this region, showing the robustness of the background estimation method. Furthermore a good agreement is also found between the predicted background using the described method and the predicted background from the simulated events.

Comparisons between the background estimates and the observations in data in the m_{tZ} distribution are shown in Figs. 2, 3, and 4. The number of predicted background events and the number of observed events are reported in Tables 4, 5, and 6, together with the number of ex-

pected signal events for two example masses. The numbers of observed events are consistent with SM background predictions.

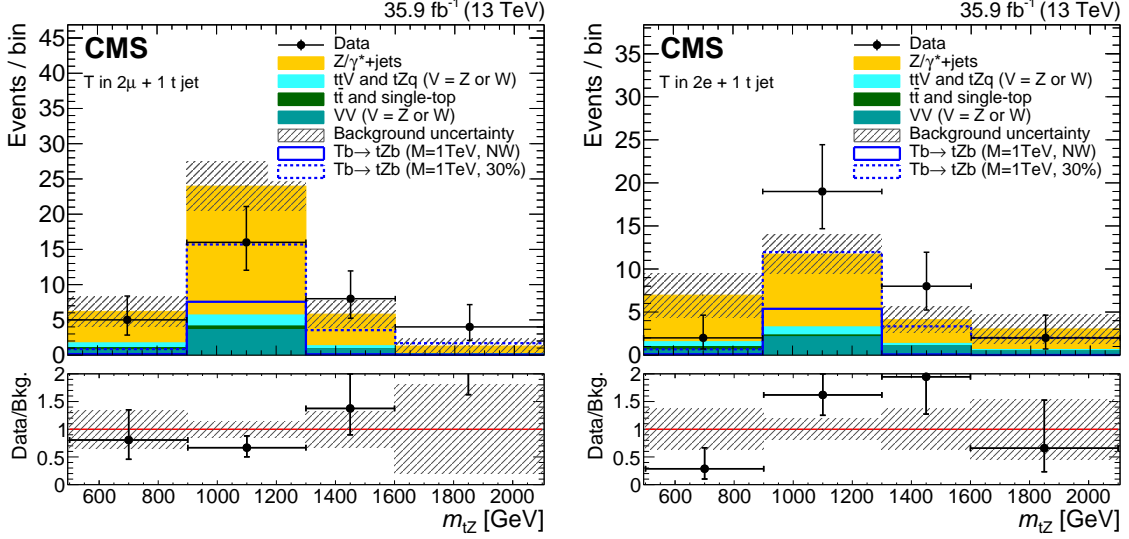


Figure 2: Comparison between the data, the background estimate, and the expected signal for the 2 categories where the T quark is reconstructed in the fully merged topology, for events with the Z boson decaying into muons (left) and electrons (right). The background composition is taken from simulation. The uncertainties in the background estimate include both statistical and systematic components. The expected signal is shown for two benchmark values of the width, for a T quark produced in association with a b, T(b): narrow-width approximation (NW) and 30% of the T quark mass. The lower panel in each plot shows the ratio of the data and the background estimation, with the shaded band representing the uncertainties in the background estimate. The vertical bars for the data points show the Poisson errors associated with each bin, while the horizontal bars indicate the bin width.

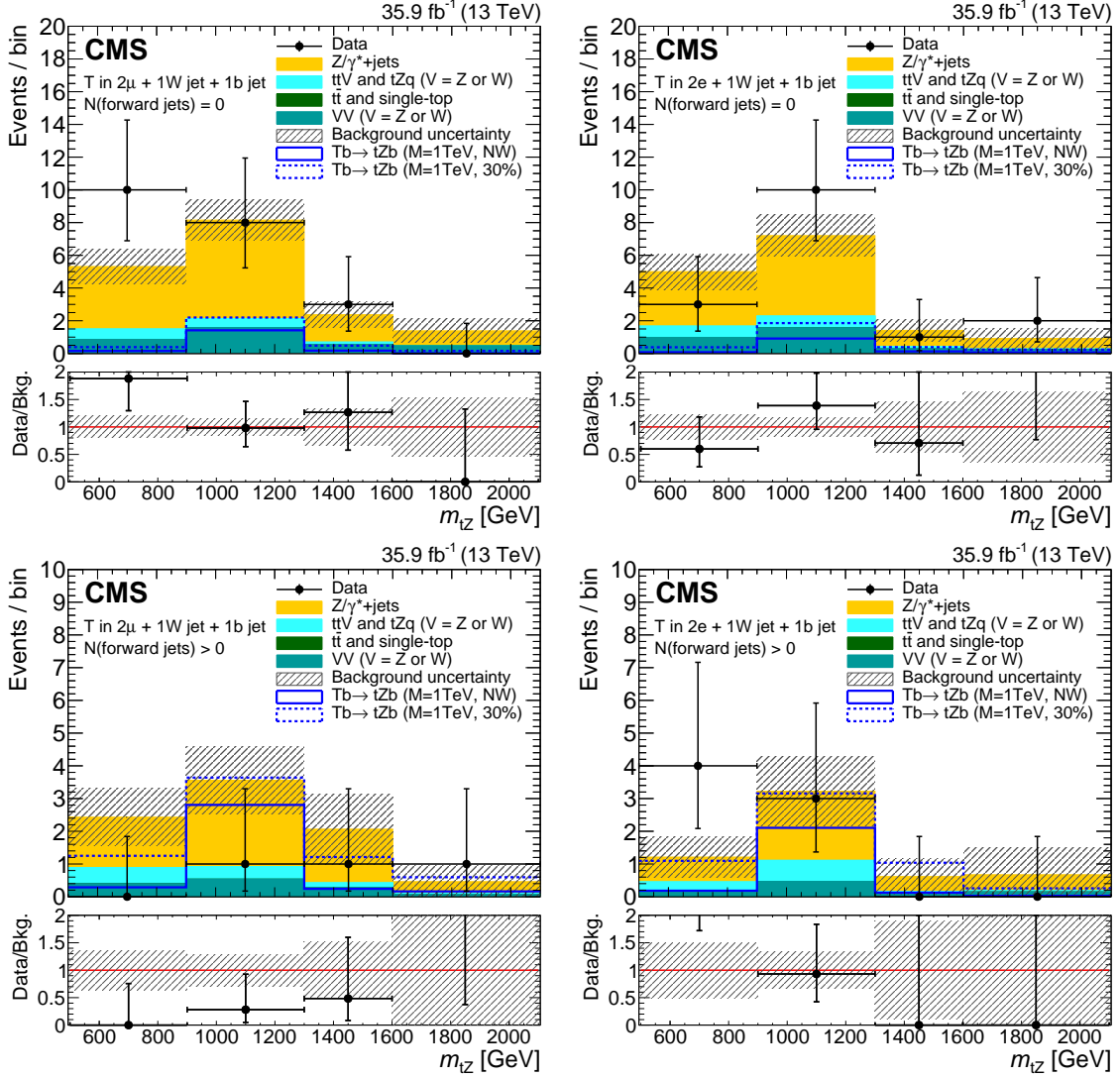


Figure 3: Comparison between the data, the background estimate, and the expected signal for the 4 categories where the T quark is reconstructed in the partially merged topology, for events with the Z boson decaying into muons (left) and electrons (right), and zero (at least one) forward jets in the upper (lower) row. The background composition is taken from simulation. The uncertainties in the background estimate include both statistical and systematic components. The expected signal is shown for two benchmark values of the width, for a T quark produced in association with a b, T(b): narrow-width approximation (NW) and 30% of the T quark mass. The lower panel in each plot shows the ratio of the data and the background estimation, with the shaded band representing the uncertainties in the background estimate. The vertical bars for the data points show the Poisson errors associated with each bin, while the horizontal bars indicate the bin width.

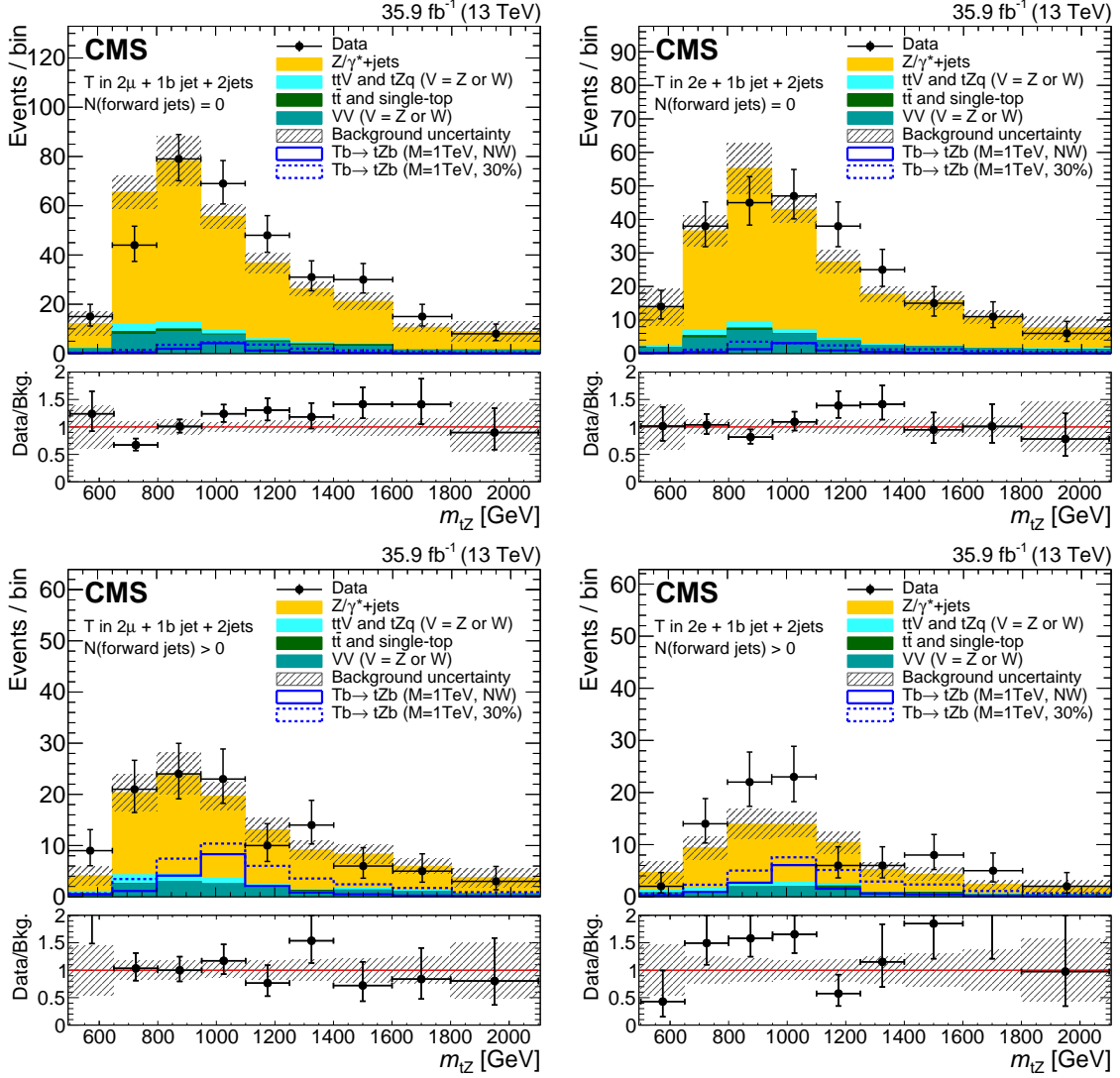


Figure 4: Comparison between the data, the background estimate, and the expected signal for the 4 categories where the T quark is reconstructed in the resolved topology, for events with the Z boson decaying into muons (left) and electrons (right), and zero (at least one) forward jets in the upper (lower) row. The background composition is taken from simulation. The uncertainties in the background estimate include both statistical and systematic components. The expected signal is shown for two benchmark values of the width, for a T quark produced in association with a b, T(b): narrow-width approximation (NW) and 30% of the T quark mass. The lower panel in each plot shows the ratio of the data and the background estimation, with the shaded band representing the uncertainties in the background estimate. The vertical bars for the data points show the Poisson errors associated with each bin, while the horizontal bars indicate the bin width.

Table 4: The number of estimated background events compared to the observed number of events for the two fully merged categories. The quoted uncertainties in the background estimates include both statistical and systematic components, as described in Section 6. Expected signal yields and their respective efficiencies in parentheses are given for two benchmark masses and two values of the width “ Γ ”, for a T quark produced in association with a b, T(b), and a T quark produced in association with a t, T(t). The signal efficiencies are calculated for events with the Z boson decaying to electrons or muons. Background, data, and signal yields are shown for the range in m_{tZ} between 500 and 2100 GeV.

Channel	$2\mu+1$ t-jet	$2e+1$ t-jet
Estimated background	37.3 ± 4.6	25.8 ± 4.1
Data events	33	31
T(b), $m_T = 0.8$ TeV, $\Gamma \simeq 0$	1.2 (0.2%)	0.9 (0.1%)
T(b), $m_T = 0.8$ TeV, $\Gamma = 0.3m_T$	22.9 (1%)	17.1 (1%)
T(t), $m_T = 0.8$ TeV, $\Gamma \simeq 0$	1.3 (1%)	1.0 (1%)
T(t), $m_T = 0.8$ TeV, $\Gamma = 0.3m_T$	6.3 (2%)	5.4 (2%)
T(b), $m_T = 1.6$ TeV, $\Gamma \simeq 0$	2.9 (6%)	2.6 (6%)
T(b), $m_T = 1.6$ TeV, $\Gamma = 0.3m_T$	5.3 (5%)	4.8 (5%)
T(t), $m_T = 1.6$ TeV, $\Gamma \simeq 0$	0.8 (6%)	0.7 (6%)
T(t), $m_T = 1.6$ TeV, $\Gamma = 0.3m_T$	1.5 (5%)	1.4 (5%)

Table 5: The number of estimated background events compared to the observed number of events for the four partially merged categories. The quoted uncertainties in the background estimates include both statistical and systematic components, as described in Section 6. Expected signal yields and their respective efficiencies in parentheses are given for two benchmark masses and two values of the width “ Γ ”, for a T quark produced in association with a b, T(b), and a T quark produced in association with a t, T(t). The signal efficiencies are calculated for events with the Z boson decaying to electrons or muons. Background, data, and signal yields are shown for the range in m_{tZ} between 500 and 2100 GeV.

Channel	$2\mu+1$ W-jet+1 b-jet	$2e+1$ W-jet+1 b-jet	$2\mu+1$ W-jet+1 b-jet	$2e+1$ W-jet+1 b-jet
	$N(\text{forward jets}) = 0$		$N(\text{forward jets}) > 0$	
Estimated background	17.2 ± 2.0	14.5 ± 1.9	8.5 ± 1.8	5.7 ± 1.6
Data events	21	16	3	7
T(b), $m_T = 0.8$ TeV, $\Gamma \simeq 0$	2.7 (0.5%)	1.7 (0.3%)	5.4 (0.9%)	4.3 (0.7%)
T(b), $m_T = 0.8$ TeV, $\Gamma = 0.3m_T$	8.2 (0.5%)	5.0 (0.3%)	12.2 (0.8%)	9.5 (0.6%)
T(t), $m_T = 0.8$ TeV, $\Gamma \simeq 0$	0.9 (0.8%)	0.8 (0.7%)	2.0 (2%)	1.5 (1%)
T(t), $m_T = 0.8$ TeV, $\Gamma = 0.3m_T$	2.8 (0.9%)	2.1 (0.6%)	4.7 (1%)	3.9 (1%)
T(b), $m_T = 1.6$ TeV, $\Gamma \simeq 0$	0.2 (0.3%)	0.2 (0.3%)	0.4 (0.9%)	0.3 (0.6%)
T(b), $m_T = 1.6$ TeV, $\Gamma = 0.3m_T$	0.4 (0.4%)	0.3 (0.3%)	0.7 (0.7%)	0.6 (0.6%)
T(t), $m_T = 1.6$ TeV, $\Gamma \simeq 0$	0.1 (0.7%)	0.1 (0.5%)	0.2 (1%)	0.2 (1%)
T(t), $m_T = 1.6$ TeV, $\Gamma = 0.3m_T$	0.2 (0.7%)	0.2 (0.6%)	0.4 (1%)	0.4 (1%)

Table 6: The number of estimated background events compared to the observed number of events for the four resolved categories. The quoted uncertainties in the background estimates include both statistical and systematic components, as described in Section 6. Expected signal yields and their respective efficiencies in parentheses are given for two benchmark masses and two values of the width “ Γ ”, for a T quark produced in association with a b, T(b), and a T quark produced in association with a t, T(t). The signal efficiencies are calculated for events with the Z boson decaying to electrons or muons. Background, data, and signal yields are shown for the range in m_{tZ} between 500 and 2100 GeV.

Channel	$2\mu+1\text{ b-jet}+2\text{ jets}$	$2e+1\text{ b-jet}+2\text{ jets}$	$2\mu+1\text{ b-jet}+2\text{ jets}$	$2e+1\text{ b-jet}+2\text{ jets}$
	$N(\text{forward jets}) = 0$		$N(\text{forward jets}) > 0$	
Estimated background	315 ± 16	228 ± 13	108.3 ± 7.5	66.2 ± 5.7
Data events	339	239	115	88
T(b), $m_T = 0.8\text{ TeV}$, $\Gamma \simeq 0$	13.7 (2%)	10.0 (2%)	25.7 (4%)	18.5 (3%)
T(b), $m_T = 0.8\text{ TeV}$, $\Gamma = 0.3m_T$	35.9 (2%)	29.7 (2%)	66.5 (4%)	52.7 (3%)
T(t), $m_T = 0.8\text{ TeV}$, $\Gamma \simeq 0$	2.5 (2%)	2.0 (2%)	5.0 (5%)	4.0 (4%)
T(t), $m_T = 0.8\text{ TeV}$, $\Gamma = 0.3m_T$	8.9 (3%)	6.7 (2%)	15.8 (5%)	12.0 (4%)
T(b), $m_T = 1.6\text{ TeV}$, $\Gamma \simeq 0$	1.0 (2%)	0.9 (2%)	2.5 (5%)	2.0 (4%)
T(b), $m_T = 1.6\text{ TeV}$, $\Gamma = 0.3m_T$	2.2 (2%)	1.9 (2%)	4.7 (5%)	3.9 (4%)
T(t), $m_T = 1.6\text{ TeV}$, $\Gamma \simeq 0$	0.3 (3%)	0.3 (2%)	0.8 (6%)	0.7 (5%)
T(t), $m_T = 1.6\text{ TeV}$, $\Gamma = 0.3m_T$	0.8 (3%)	0.7 (2%)	1.7 (6%)	1.5 (5%)

6 Systematic uncertainties

Systematic effects have been evaluated by propagating the uncertainties in the input quantities. Unless explicitly stated, the impact of these uncertainties are evaluated both in the normalization and in the shape of the distribution of m_{tZ} .

Five main sources of uncertainty contribute to the estimated background. The dominant ones are the statistical uncertainties in the control regions used to estimate the background, both in data, giving an uncertainty of 10–46% depending on the category, and in the simulation, with an uncertainty of 3–34%. The small differences between the observation and the prediction for the closure test described previously are taken as systematic uncertainties (6%). An uncertainty due to possible mismodelling of the Z+light quark and Z+b quark fractions in the simulation is evaluated. This systematic uncertainty is evaluated by observing the effect of changing the Z+b fraction by 10% [63], yielding a contribution to the uncertainty in the background estimation of between 2 and 4%. Finally, the uncertainty from the b tagging for the b, c, and light-flavor jets is evaluated by changing the b tagging corrections by their uncertainties [61, 62], yielding a change in the normalization of 2% for the b tagging efficiency and 2% for the misidentification probability. Other systematic uncertainties related to the simulation modelling have been studied and found negligible, because of the data-driven method used to estimate the background.

The systematic uncertainty in the signal is estimated from the corrections applied to the simulation to match distributions in data. The corrections for lepton identification and lepton trigger efficiency are obtained from dedicated analyses, using the “tag-and-probe” method [55, 56]. Changing these corrections by their uncertainties provides an estimate of the uncertainties in the signal yield of 3% for muons and electrons for a mass hypothesis of 1.0 TeV, and 1% for the trigger. The jet four-momenta are varied by the JES and JER uncertainties, which provide respective changes in the signal yield of 1% (JES) and 0.5% (JER), while for forward jets a change of 8% is observed. For W and t jet tagging, the same procedure of varying the corrections is applied, yielding an uncertainty of 4 and 8%, respectively. The uncertainty in the b tagging efficiency is evaluated, as for the background; the change in yield of the signal is found to be 2.5%. The uncertainties from the choice of PDF are evaluated using the NNPDF 3.0 PDF eigenvectors [64], considering only the change in the shape of the m_{tZ} distribution. The uncertainty in the simulation of pileup is obtained by changing the inelastic cross section, which controls the average pileup multiplicity, by 5% [65], resulting in a signal yield uncertainty of 1%. Additional sources of systematic uncertainty are the integrated luminosity (2.5%, normalization only) [66] and the factorization and renormalization scales used in simulation (shape only).

7 Results

No significant deviations from the expected background are observed in any of the search channels. We set upper limits on the product of the cross section and branching fraction of a T quark decaying to tZ . The exclusion limits at a confidence level (CL) of 95% are obtained using the asymptotic CL_s criterion [67–70], with templates for background and signal given by the binned distributions in Figs. 2, 3, and 4. Systematic uncertainties are treated as nuisance parameters, assuming a log-normal distribution for normalization parameters and a Gaussian distribution for systematic uncertainties that affect the m_{tZ} shape.

In Fig. 5, the observed and expected limits from the ten categories of the T quark search are shown combined together, for the singlet LH T(b) (left) and doublet RH T(t) (right) production modes. The ten categories have different sensitivities to different values of m_T , and the final result benefits from this behavior: the resolved categories drive the limit at low m_T , the fully

merged categories, at higher values, while at intermediate values the limit takes advantage of all the three topologies. Limits on $\sigma(\text{pp} \rightarrow \text{Tbq} \rightarrow \text{tZbq})$ for the singlet LH T(b) exclude values greater than 0.26–0.04 pb at 95% CL, for masses in the range 0.7–1.7 TeV. For an RH T(t) signal, the region above 0.14–0.04 pb is excluded for the same mass range. Upper limits are compared with theoretical cross sections calculated at NLO in Ref. [4]. For this model, a singlet LH T quark with $C(\text{bW}) = 0.5$ is excluded at 95% CL for masses in the range 0.7–1.2 TeV.

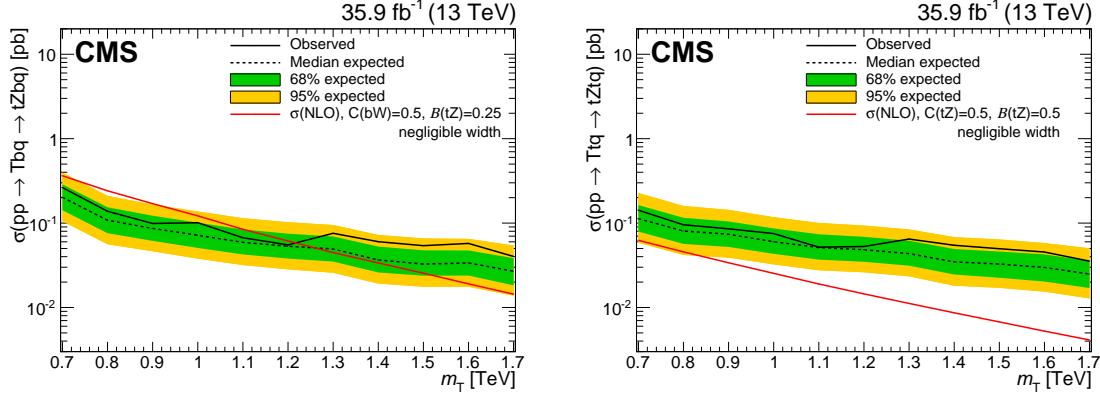


Figure 5: Observed and expected limits at 95% CL on the product of the single production cross section and branching fraction for the singlet LH T quark produced in association with a b quark (left) and for the doublet RH T quark produced in association with a t quark (right), where the T quark has a narrow width and decays to tZ. The inner green and outer yellow bands represent the 1 and 2 standard deviation uncertainties in the expected limit. The red lines indicate theoretical cross sections, as calculated at next-to-leading order in Ref. [4]. The branching fraction $\mathcal{B}(\text{T} \rightarrow \text{tZ})$ is 0.25 (0.5) for the left (right) plot.

In Fig. 6, the observed and expected upper limits at 95% CL are shown as a function of the T quark width and T quark mass in the ranges from 10 to 30% and 0.8 to 1.6 TeV, respectively. A sensitivity similar to that obtained assuming a narrow-width T quark is observed. In this case the experimental results are compared with the theoretical cross sections calculated at LO using a modified version of the model constructed by the authors of [5, 46, 47] and reported in Table 2. For this model, the data exclude a singlet LH T quark produced in association with a b quark, for masses below values in the range 1.34 and 1.42 TeV depending on the width. A doublet RH T quark produced in association with a t quark is excluded for masses below values in the range 0.82 and 0.94 TeV.

In addition to being singly produced directly, as diagrammed in Fig. 1 (left), the T quark may also appear singly in events where a single Z' is produced that decays $Z' \rightarrow \text{Tt}$, as illustrated in Fig. 1 (right). Observed and expected limits for the production of a T quark via the decay of a Z' boson, $Z' \rightarrow \text{Tt}$ and $\text{T} \rightarrow \text{tZ}$, are shown in Table 7. We assume negligible widths for both the Z' boson and the T quark. The product of cross section and branching fractions is excluded above 0.13–0.06 pb, for a Z' boson mass in the range from 1.5 to 2.5 TeV and for a T quark mass from 0.7 to 1.5 TeV.

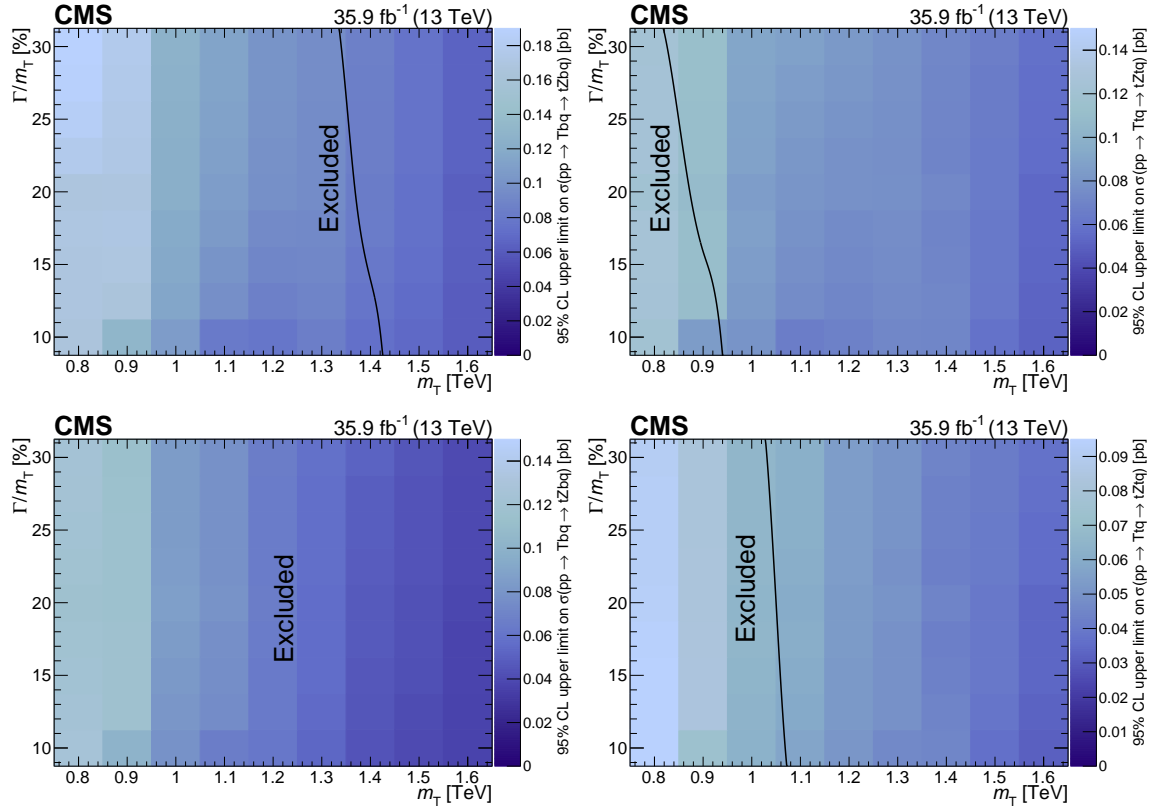


Figure 6: Observed (upper) and expected (lower) limits at 95% CL on the product of the single production cross section and branching fraction for the singlet LH T quark produced in association with a b quark (left) and for the doublet RH T quark produced in association with a t quark (right), where the T quark has a width from 10% to 30% of its mass and decays to tZ . The solid black lines indicate theoretical cross sections, as calculated at leading order using a modified version of the model constructed by the authors of Refs. [5, 46, 47] and reported in Table 2. In each plot, the excluded region lies to the left of the line, except in the lower-left plot where the entire region shown is excluded.

Table 7: Observed and expected 95% CL upper limit on $\sigma(pp \rightarrow Z') \mathcal{B}(Z' \rightarrow Tt) \mathcal{B}(T \rightarrow tZ)$. The ± 1 and ± 2 standard deviation (s.d.) expected limits are also given. The limits are given in pb.

$m_{Z'}$ [TeV]	m_T [TeV]	Observed	Expected	Expected $-1(2)$ s.d.	Expected $+1(2)$ s.d.
1.5	0.7	0.13	0.10	0.07 (0.05)	0.14 (0.19)
1.5	0.9	0.11	0.08	0.06 (0.05)	0.12 (0.16)
1.5	1.2	0.09	0.05	0.04 (0.03)	0.07 (0.10)
2.0	0.9	0.08	0.06	0.04 (0.03)	0.08 (0.11)
2.0	1.2	0.08	0.05	0.04 (0.03)	0.07 (0.09)
2.0	1.5	0.06	0.04	0.03 (0.02)	0.05 (0.07)
2.5	1.2	0.06	0.05	0.03 (0.02)	0.06 (0.09)
2.5	1.5	0.06	0.04	0.03 (0.02)	0.05 (0.07)

8 Summary

This paper has presented results of a search for the single production of a T quark with a charge of $+2/3$, decaying to a Z boson and a t quark. No deviations were observed relative to the expected standard model background. Upper limits on the product of the cross section and branching fraction range between 0.26 and 0.04 pb at 95% confidence level for a left-handed T quark produced in association with a b quark, T(b), and between 0.14 and 0.04 pb for a right-handed T quark produced in association with a t quark, T(t), for the range of masses between 0.7 and 1.7 TeV. This result was obtained under the hypothesis of a narrow-width T quark, providing an interpretation of results through the simplified approach of Ref. [4]. In this case, left-handed T quarks produced in association with a b quark and with a coupling $C(bW)$ of 0.5 were excluded for masses in the range 0.7–1.2 TeV. A large gain in the search sensitivity was found relative to previous results [18] because of improvements introduced in the analysis as well as the increase in the integrated luminosity. The effect of a nonnegligible width was also studied; values of the width between 10 and 30% of the T quark mass were considered, and similar sensitivities were observed. The results were interpreted using a modified version of the model constructed by the authors of Refs. [5, 46, 47], and a left-handed T(b) signal was excluded for masses below values in the range 1.34–1.42 TeV, depending on the width, while a right-handed T(t) signal was excluded for masses below values in the range 0.82–0.94 TeV. Finally, the production of a Z' boson that decays to Tt was excluded for values of the product of cross section and branching fractions between 0.13–0.06 pb, for Z' boson and T quark masses in the respective ranges of 1.5 to 2.5 TeV and 0.7 to 1.5 TeV. The results presented in this paper are the most-stringent limits to date on the single production of heavy vector-like T quarks, the first to set limits for a variety of resonance widths, and the most-stringent limits for the production of a Z' boson decaying to Tt .

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 for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR and RAEP (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI and FEDER (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract No. 675440 (European Union); the Leventis Foun-

dation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa Clarín-COFUND del Principado de Asturias; the Thalís and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); and the Welch Foundation, contract C-1845.

References

- [1] J. A. Aguilar-Saavedra, R. Benbrik, S. Heinemeyer, and M. Perez-Victoria, "Handbook of vectorlike quarks: Mixing and single production", *Phys. Rev. D* **88** (2013) 094010, doi:10.1103/PhysRevD.88.094010, arXiv:1306.0572.
- [2] J. A. Aguilar-Saavedra, "Identifying top partners at LHC", *JHEP* **11** (2009) 030, doi:10.1088/1126-6708/2009/11/030, arXiv:0907.3155.
- [3] A. De Simone, O. Matsedonskyi, R. Rattazzi, and A. Wulzer, "A first top partner hunter's guide", *JHEP* **04** (2013) 004, doi:10.1007/JHEP04(2013)004, arXiv:1211.5663.
- [4] O. Matsedonskyi, G. Panico, and A. Wulzer, "On the interpretation of top partners searches", *JHEP* **12** (2014) 097, doi:10.1007/JHEP12(2014)097, arXiv:1409.0100.
- [5] M. Buchkremer, G. Cacciapaglia, A. Deandrea, and L. Panizzi, "Model independent framework for searches of top partners", *Nucl. Phys. B* **876** (2013) 376, doi:10.1016/j.nuclphysb.2013.08.010, arXiv:1305.4172.
- [6] O. Eberhardt et al., "Joint analysis of Higgs decays and electroweak precision observables in the standard model with a sequential fourth generation", *Phys. Rev. D* **86** (2012) 013011, doi:10.1103/PhysRevD.86.013011, arXiv:1204.3872.
- [7] ATLAS Collaboration, "Search for production of vector-like quark pairs and of four top quarks in the lepton-plus-jets final state in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector", *JHEP* **08** (2015) 105, doi:10.1007/JHEP08(2015)105, arXiv:1505.04306.
- [8] ATLAS Collaboration, "Search for vector-like B quarks in events with one isolated lepton, missing transverse momentum and jets at $\sqrt{s} = 8$ TeV with the ATLAS detector", *Phys. Rev. D* **91** (2015) 112011, doi:10.1103/PhysRevD.91.112011, arXiv:1503.05425.
- [9] ATLAS Collaboration, "Search for pair and single production of new heavy quarks that decay to a Z boson and a third-generation quark in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector", *JHEP* **11** (2014) 104, doi:10.1007/JHEP11(2014)104, arXiv:1409.5500.

- [10] ATLAS Collaboration, “Search for single production of a vector-like quark via a heavy gluon in the $4b$ final state with the ATLAS detector in pp collisions at $\sqrt{s} = 8$ TeV”, *Phys. Lett. B* **758** (2016) doi:10.1016/j.physletb.2016.04.061, arXiv:1602.06034.
- [11] ATLAS Collaboration, “Search for single production of vector-like quarks decaying into Wb in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector”, *Eur. Phys. J. C* **76** (2016) 442, doi:10.1140/epjc/s10052-016-4281-8, arXiv:1602.05606.
- [12] ATLAS Collaboration, “Search for the production of single vector-like and excited quarks in the Wt final state in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector”, *JHEP* **02** (2016) 110, doi:10.1007/JHEP02(2016)110, arXiv:1510.02664.
- [13] ATLAS Collaboration, “Search for pair production of vector-like top quarks in events with one lepton, jets, and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector”, *JHEP* **08** (2017) 052, doi:10.1007/JHEP08(2017)052, arXiv:1705.10751.
- [14] ATLAS Collaboration, “Search for pair production of heavy vector-like quarks decaying to high- $p_{\text{mathrm{T}}$ W bosons and b quarks in the lepton-plus-jets final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *JHEP* **10** (2017) 141, doi:10.1007/JHEP10(2017)141, arXiv:1707.03347.
- [15] CMS Collaboration, “Search for vector-like charge $2/3$ T quarks in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *Phys. Rev. D* **93** (2016) 012003, doi:10.1103/PhysRevD.93.012003, arXiv:1509.04177.
- [16] CMS Collaboration, “Search for pair-produced vector-like B quarks in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *Phys. Rev. D* **93** (2016) 112009, doi:10.1103/PhysRevD.93.112009, arXiv:1507.07129.
- [17] CMS Collaboration, “Search for top-quark partners with charge $5/3$ in the same-sign dilepton final state”, *Phys. Rev. Lett.* **112** (2014) 171801, doi:10.1103/PhysRevLett.112.171801, arXiv:1312.2391.
- [18] CMS Collaboration, “Search for single production of vector-like quarks decaying to a Z boson and a top or a bottom quark in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **05** (2017) 029, doi:10.1007/JHEP05(2017)029, arXiv:1701.07409.
- [19] CMS Collaboration, “Search for single production of a heavy vector-like T quark decaying to a Higgs boson and a top quark with a lepton and jets in the final state”, *Phys. Lett. B* **771** (2017) 80, doi:10.1016/j.physletb.2017.05.019, arXiv:1612.00999.
- [20] CMS Collaboration, “Search for electroweak production of a vector-like quark decaying to a top quark and a Higgs boson using boosted topologies in fully hadronic final states”, *JHEP* **04** (2017) 136, doi:10.1007/JHEP04(2017)136, arXiv:1612.05336.
- [21] CMS Collaboration, “Search for single production of vector-like quarks decaying into a b quark and a W boson in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Lett. B* **772** (2017) 634, doi:10.1016/j.physletb.2017.07.022, arXiv:1701.08328.
- [22] CMS Collaboration, “Search for pair production of vector-like T and B quarks in single-lepton final states using boosted jet substructure in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **11** (2017) 085, doi:10.1007/JHEP11(2017)085, arXiv:1706.03408.

-
- [23] D0 Collaboration, “Search for single vector-like quarks in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV”, *Phys. Rev. Lett.* **106** (2011) 081801, doi:10.1103/PhysRevLett.106.081801, arXiv:1010.1466.
- [24] D0 Collaboration, “Search for a fourth generation t' quark in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV”, *Phys. Rev. Lett.* **107** (2011) 082001, doi:10.1103/PhysRevLett.107.082001, arXiv:1104.4522.
- [25] CDF Collaboration, “Search for new particles leading to Z+jets final states in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV”, *Phys. Rev. D* **76** (2007) 072006, doi:10.1103/PhysRevD.76.072006, arXiv:0706.3264.
- [26] CDF Collaboration, “Search for new bottomlike quark pair decays $q\bar{Q} \rightarrow (tW^+)(\bar{t}W^\pm)$ in same-charge dilepton events”, *Phys. Rev. Lett.* **104** (2010) 091801, doi:10.1103/PhysRevLett.104.091801, arXiv:0912.1057.
- [27] CDF Collaboration, “Search for New T' Particles in Final States with Large Jet Multiplicities and Missing Transverse Energy in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV”, *Phys. Rev. Lett.* **107** (2011) 191803, doi:10.1103/PhysRevLett.107.191803, arXiv:1107.3574.
- [28] CDF Collaboration, “Search for Production of Heavy Particles Decaying to Top Quarks and Invisible Particles in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV”, *Phys. Rev. Lett.* **106** (2011) 191801, doi:10.1103/PhysRevLett.106.191801, arXiv:1103.2482.
- [29] CDF Collaboration, “Search for Heavy Bottomlike Quarks Decaying to an Electron or Muon and Jets in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV”, *Phys. Rev. Lett.* **106** (2011) 141803, doi:10.1103/PhysRevLett.106.141803, arXiv:1101.5728.
- [30] CDF Collaboration, “Search for a Heavy Top-Like Quark in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV”, *Phys. Rev. Lett.* **107** (2011) 261801, doi:10.1103/PhysRevLett.107.261801, arXiv:1107.3875.
- [31] B. W. Lee, C. Quigg, and H. B. Thacker, “Weak interactions at very high-energies: The role of the Higgs boson mass”, *Phys. Rev. D* **16** (1977) 1519, doi:10.1103/PhysRevD.16.1519.
- [32] G. Cacciapaglia et al., “Heavy vector-like top partners at the LHC and flavour constraints”, *JHEP* **03** (2012) 070, doi:10.1007/JHEP03(2012)070, arXiv:1108.6329.
- [33] C. Bini, R. Contino, and N. Vignaroli, “Heavy-light decay topologies as a new strategy to discover a heavy gluon”, *JHEP* **01** (2012) 157, doi:10.1007/JHEP01(2012)157, arXiv:1110.6058.
- [34] E. Accomando et al., “Z’ physics with early LHC data”, *Phys. Rev. D* **83** (2011) 075012, doi:10.1103/PhysRevD.83.075012, arXiv:1010.6058.
- [35] D. Greco and D. Liu, “Hunting composite vector resonances at the LHC: naturalness facing data”, *JHEP* **12** (2014) 126, doi:10.1007/JHEP12(2014)126, arXiv:1410.2883.
- [36] CMS Collaboration, “Search for a heavy resonance decaying to a top quark and a vector-like top quark at $\sqrt{s} = 13$ TeV”, *JHEP* **09** (2017) 53, doi:10.1007/JHEP09(2017)053, arXiv:1703.06352.

- [37] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [38] 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.
- [39] 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.
- [40] 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.
- [41] 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.
- [42] S. Alioli, S.-O. Moch, and P. Uwer, “Hadronic top-quark pair-production with one jet and parton showering”, *JHEP* **01** (2012) 137, doi:10.1007/JHEP01(2012)137, arXiv:1110.5251.
- [43] 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.
- [44] 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.
- [45] P. Artoisenet, R. Frederix, O. Mattelaer, and R. Rietkerk, “Automatic spin-entangled decays of heavy resonances in Monte Carlo simulations”, *JHEP* **03** (2013) 015, doi:10.1007/JHEP03(2013)015, arXiv:1212.3460.
- [46] B. Fuks and H.-S. Shao, “QCD next-to-leading-order predictions matched to parton showers for vector-like quark models”, *Eur. Phys. J. C* **77** (2017) 135, doi:10.1140/epjc/s10052-017-4686-z, arXiv:1610.04622.
- [47] A. Oliveira, “Gravity particles from warped extra dimensions, predictions for LHC”, (2014). arXiv:1404.0102.
- [48] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [49] J. Allison et al., “GEANT4 developments and applications”, *IEEE Trans. Nucl. Sci.* **53** (2006) 270, doi:10.1109/TNS.2006.869826.
- [50] NNPDF Collaboration, “Parton distributions for the LHC Run II”, *JHEP* **04** (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849.
- [51] CMS Collaboration, “Description and performance of track and primary-vertex reconstruction with the CMS tracker”, *JINST* **9** (2014) P10009, doi:10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.

-
- [52] 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.
- [53] 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.
- [54] CMS Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, *JINST* **12** (2017), no. 10, P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.
- [55] CMS Collaboration, “Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *JINST* **10** (2015) P06005, doi:10.1088/1748-0221/10/06/P06005, arXiv:1502.02701.
- [56] CMS Collaboration, “Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV”, *JINST* **7** (2012) P10002, doi:10.1088/1748-0221/7/10/P10002, arXiv:1206.4071.
- [57] S. D. Ellis, C. K. Vermilion, and J. R. Walsh, “Techniques for improved heavy particle searches with jet substructure”, *Phys. Rev. D* **80** (2009) 051501, doi:10.1103/PhysRevD.80.051501, arXiv:0903.5081.
- [58] CMS Collaboration, “Identification techniques for highly boosted W bosons that decay into hadrons”, *JHEP* **12** (2014) 017, doi:10.1007/JHEP12(2014)017, arXiv:1410.4227.
- [59] M. Dasgupta, A. Fregoso, S. Marzani, and G. P. Salam, “Towards an understanding of jet substructure”, *JHEP* **09** (2013) 029, doi:10.1007/JHEP09(2013)029, arXiv:1307.0007.
- [60] A. J. Larkoski, S. Marzani, G. Soyez, and J. Thaler, “Soft Drop”, *JHEP* **05** (2014) 146, doi:10.1007/JHEP05(2014)146, arXiv:1402.2657.
- [61] CMS Collaboration, “Identification of b-quark jets with the CMS experiment”, *JINST* **8** (2013) P04013, doi:10.1088/1748-0221/8/04/P04013, arXiv:1211.4462.
- [62] CMS Collaboration, “Identification of b quark jets at the CMS experiment in the LHC Run 2”, CMS Physics Analysis Summary CMS-PAS-BTV-15-001, 2016.
- [63] CMS Collaboration, “Measurement of the production cross sections for a Z boson and one or more b jets in pp collisions at $\sqrt{s} = 7$ TeV”, *JHEP* **06** (2014) 120, doi:10.1007/JHEP06(2014)120, arXiv:1402.1521.
- [64] J. Butterworth et al., “PDF4LHC recommendations for LHC Run II”, *J. Phys. G* **43** (2016) 023001, doi:10.1088/0954-3899/43/2/023001, arXiv:1510.03865.
- [65] ATLAS Collaboration, “Measurement of the Inelastic Proton-Proton Cross Section at $\sqrt{s} = 13$ TeV with the ATLAS Detector at the LHC”, *Phys. Rev. Lett.* **117** (2016) 182002, doi:10.1103/PhysRevLett.117.182002, arXiv:1606.02625.
- [66] CMS Collaboration, “CMS luminosity measurements for the 2016 data taking period”, CMS Physics Analysis Summary CMS-PAS-LUM-17-001, 2017.
- [67] 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.

-
- [68] 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.
- [69] 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].
- [70] ATLAS and CMS Collaborations, “Procedure for the LHC Higgs boson search combination in summer 2011”, Technical Report CMS-NOTE-2011/005, ATL-PHYS-PUB-2011-011, CERN, 2011.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria

W. Adam, F. Ambrogio, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth¹, V.M. Ghete, J. Grossmann, J. Hrubec, M. Jeitler¹, A. König, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, E. Pree, D. Rabady, N. Rad, H. Rohringer, J. Schieck¹, R. Schöfbeck, M. Spanring, D. Spitzbart, W. Waltenberger, J. Wittmann, C.-E. Wulz¹, M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus

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

Universiteit Antwerpen, Antwerpen, Belgium

E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, I. De Bruyn, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskyi, S. Lowette, S. Moortgat, L. Moreels, 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, J. Luetic, T. Maerschalk, A. Marinov, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, D. Vannerom, R. Yonamine, F. Zenoni, F. Zhang²

Ghent University, Ghent, Belgium

A. Cimmino, T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov, D. Poyraz, C. Roskas, S. Salva, M. Tytgat, W. Verbeke, N. Zaganidis

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

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

Université de Mons, Mons, Belgium

N. Bely

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

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

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

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato³, A. Custódio, E.M. Da Costa, G.G. Da Silveira⁴, D. De Jesus Damiao, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, A. Santoro, A. Sznajder, E.J. Tonelli Manganote³, F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista ^a, Universidade Federal do ABC ^b, São Paulo, Brazil

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

Institute for Nuclear Research and Nuclear Energy of Bulgaria Academy of Sciences

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

University of Sofia, Sofia, Bulgaria

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

Beihang University, Beijing, China

W. Fang⁵, X. Gao⁵

Institute of High Energy Physics, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, E. Yazgan, 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, C.F. González Hernández, J.D. Ruiz Alvarez

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

B. Courbon, 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, A. Starodumov⁶, T. Susa

University of Cyprus, Nicosia, Cyprus

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

Charles University, Prague, Czech Republic

M. Finger⁷, M. Finger Jr.⁷

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

Y. Assran^{8,9}, S. Elgammal⁹, A. Mahrous¹⁰

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

R.K. Dewanjee, 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, E. Tuominen, J. Tuominiemi, E. Tuovinen

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

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

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

Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, FranceJ.-L. Agram¹¹, J. Andrea, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte¹¹, X. Coubez, J.-C. Fontaine¹¹, D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, 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, FranceS. Beauceron, C. Bernet, G. Boudoul, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov¹², V. Sordini, M. Vander Donckt, S. Viret**Georgian Technical University, Tbilisi, Georgia**A. Khvedelidze⁷**Tbilisi State University, Tbilisi, Georgia**Z. Tsamalaidze⁷**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, 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, D. Teyssier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut B, Aachen, GermanyG. Flügge, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, T. Müller, A. Nehr Korn, A. Nowack, C. Pistone, O. Pooth, A. Stahl¹³**Deutsches Elektronen-Synchrotron, Hamburg, Germany**M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras¹⁴, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Eckerlin, D. Eckstein, T. Eichhorn,

E. Eren, E. Gallo¹⁵, J. Garay Garcia, A. Geiser, A. Gizhko, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, M. Guthoff, A. Harb, J. Hauk, M. Hempel¹⁶, H. Jung, A. Kalogeropoulos, M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, T. Lenz, J. Leonard, K. Lipka, W. Lohmann¹⁶, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, A. Raspereza, B. Roland, M. Savitskyi, P. Saxena, R. Shevchenko, S. Spannagel, N. Stefaniuk, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

University of Hamburg, Hamburg, Germany

S. Bein, V. Blobel, M. Centis Vignali, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, A. Hinzmann, M. Hoffmann, A. Karavdina, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, T. Lapsien, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo¹³, T. Peiffer, A. Perieanu, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

M. Akbiyik, C. Barth, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, B. Freund, R. Friese, M. Giffels, A. Gilbert, D. Haitz, F. Hartmann¹³, S.M. Heindl, U. Husemann, F. Kassel¹³, S. Kudella, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

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

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

National and Kapodistrian University of Athens, Athens, Greece

G. Karathanasis, S. Kesisoglou, A. Panagiotou, N. Saoulidou

University of Ioánnina, Ioánnina, Greece

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

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

M. Csanad, N. Filipovic, G. Pasztor

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath¹⁷, Á. Hunyadi, F. Sikler, V. Veszpremi, G. Vesztergombi¹⁸, A.J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi¹⁹, A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary

M. Bartók¹⁸, P. Raics, Z.L. Trocsanyi, B. Ujvari

Indian Institute of Science (IISc), Bangalore, India

S. Choudhury, J.R. Komaragiri

National Institute of Science Education and Research, Bhubaneswar, India

S. Bahinipati²⁰, S. Bhowmik, P. Mal, K. Mandal, A. Nayak²¹, D.K. Sahoo²⁰, N. Sahoo, S.K. Swain

Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India

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

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

R. Bhardwaj, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep, 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

Bhabha Atomic Research Centre, Mumbai, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty¹³, P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research-A, Mumbai, India

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

Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Kumar, M. Maity²², G. Majumder, K. Mazumdar, T. Sarkar²², N. Wickramage²³

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. Chenarani²⁴, E. Eskandari Tadavani, S.M. Etesami²⁴, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi²⁵, F. Rezaei Hosseinabadi, B. Safarzadeh²⁶, 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}, F. Errico^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, S. Lezki^{a,b}, G. Maggi^{a,c}, M. Maggi^a, G. Miniello^{a,b}, S. My^{a,b}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^{a,b}, A. Ranieri^a, G. Selvaggi^{a,b}, A. Sharma^a, L. Silvestris^{a,13}, 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}, S. Braibant-Giacomelli^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, S.S. Chhibra^a, 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

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, K. Chatterjee^{a,b}, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, L. Russo^{a,27}, G. Sguazzoni^a, D. Strom^a, L. Viliani^{a,b,13}

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera¹³

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

V. Calvelli^{a,b}, F. Ferro^a, L. Panizzi, E. Robutti^a, S. Tosi^{a,b}

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

L. Brianza^{a,b}, F. Brivio^{a,b}, V. Ciriolo^{a,b}, M.E. Dinardo^{a,b}, S. Fiorendi^{a,b}, S. Gennai^a, A. Ghezzi^{a,b}, P. Govoni^{a,b}, M. Malberti^{a,b}, S. Malvezzi^a, R.A. Manzoni^{a,b}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, K. Pauwels^{a,b}, D. Pedrini^a, S. Pigazzini^{a,b,28}, 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}, S. Di Guida^{a,d,13}, F. Fabozzi^{a,c}, F. Fienga^{a,b}, A.O.M. Iorio^{a,b}, W.A. Khan^a, L. Lista^a, S. Meola^{a,d,13}, P. Paolucci^{a,13}, 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,13}, N. Bacchetta^a, L. Benato^{a,b}, D. Bisello^{a,b}, A. Boletti^{a,b}, R. Carlin^{a,b}, A. Carvalho Antunes De Oliveira^{a,b}, 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}, F. Montecassiano^a, D. Pantano^a, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, R. Rossin^{a,b}, E. Torassa^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, M. Ressegotti, 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}, M. Biasini^{a,b}, G.M. Bilei^a, C. Cecchi^{a,b}, D. Ciangottini^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,b}, R. Leonardi^{a,b}, E. Manoni^a, G. Mantovani^{a,b}, V. Mariani^{a,b}, M. Menichelli^a, A. Rossi^{a,b}, A. Santocchia^{a,b}, D. Spiga^a

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

K. Androsov^a, P. Azzurri^{a,13}, G. Bagliesi^a, J. Bernardini^a, T. Boccali^a, L. Borrello, R. Castaldi^a, M.A. Ciocci^{a,b}, R. Dell'Orso^a, G. Fedi^a, L. Giannini^{a,c}, A. Giassi^a, M.T. Grippo^{a,27}, F. Ligabue^{a,c}, T. Lomtadze^a, E. Manca^{a,c}, G. Mandorli^{a,c}, L. Martini^{a,b}, A. Messineo^{a,b}, F. Palla^a, A. Rizzi^{a,b}, A. Savoy-Navarro^{a,29}, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P.G. Verdini^a

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

L. Barone^{a,b}, F. Cavallari^a, M. Cipriani^{a,b}, N. Daci^a, D. Del Re^{a,b,13}, M. Diemoz^a, S. Gelli^{a,b}, E. Longo^{a,b}, F. Margaroli^{a,b}, B. Marzocchi^{a,b}, P. Meridiani^a, G. Organtini^{a,b}, R. Paramatti^{a,b}, F. Preiato^{a,b}, S. Rahatlou^{a,b}, C. Rovelli^a, F. Santanastasio^{a,b}

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}, C. Biino^a, N. Cartiglia^a, F. Cenna^{a,b}, M. Costa^{a,b}, R. Covarelli^{a,b}, A. Degano^{a,b}, N. Demaria^a, B. Kiani^{a,b}, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, E. Monteil^{a,b}, M. Monteno^a

M.M. Obertino^{a,b}, L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a, G.L. Pinna Angioni^{a,b}, F. Ravera^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, K. Shchelina^{a,b}, V. Sola^a, A. Solano^{a,b}, A. Staiano^a, P. Traczyk^{a,b}

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, J. Lee, S. Lee, S.W. Lee, C.S. Moon, 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, D.H. Moon, G. Oh

Hanyang University, Seoul, Korea

J.A. Brochero Cifuentes, J. Goh, 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, J.S. Kim, H. Lee, K. Lee, K. Nam, 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

Sungkyunkwan University, Suwon, Korea

Y. Choi, 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, M.A.B. Md Ali³⁰, F. Mohamad Idris³¹, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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

Duran-Osuna, M. C., H. Castilla-Valdez, E. De La Cruz-Burelo, Ramirez-Sanchez, G., I. Heredia-De La Cruz³², Rabadan-Trejo, R. I., R. Lopez-Fernandez, J. Mejia Guisao, Reyes-Almanza, R, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

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, 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. Byszuk³³, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

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

P. Bargassa, C. Beirão Da Cruz E Silva, B. Calpas³⁴, A. Di Francesco, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Seixas, O. Toldaiev, D. Vadrucio, J. Varela

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^{35,36}, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

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

Y. Ivanov, V. Kim³⁷, E. Kuznetsova³⁸, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, 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, A. Stepenov, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia

T. Aushev, A. Bylinkin³⁶

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

R. Chistov³⁹, M. Danilov³⁹, P. Parygin, D. Philippov, S. Polikarpov, E. Tarkovskii

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin³⁶, I. Dremin³⁶, M. Kirakosyan³⁶, A. Terkulov

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

A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin⁴⁰, L. Dudko, A. Ershov, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, M. Perfilov, V. Savrin, A. Snigirev

Novosibirsk State University (NSU), Novosibirsk, Russia

V. Blinov⁴¹, D. Shtol⁴¹, Y. Skovpen⁴¹

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. Krychkin, 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. Adzic⁴², P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic

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

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

Universidad Autónoma de Madrid, Madrid, Spain

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

Universidad de Oviedo, Oviedo, Spain

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

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

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

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, E. Auffray, P. Baillon, A.H. Ball, D. Barney, M. Bianco, P. Bloch, A. Bocci, C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, A. De Roeck, E. Di Marco⁴³, M. Dobson, B. Dorney, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, F. Glege, D. Gulhan, S. Gundacker, P. Harris, J. Hegeman, V. Innocente, P. Janot, O. Karacheban¹⁶, J. Kieseler, H. Kirschenmann, V. Knünz, A. Kornmayer¹³, M.J. Kortelainen, M. Krammer¹, 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. Milenovic⁴⁴, F. Moortgat, M. Mulders, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, A. Racz, T. Reis, G. Rolandi⁴⁵, M. Rove, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas⁴⁶, A. Stakia, J. Steggemann, M. Stoye, M. Tosi, D. Treille, A. Triossi, A. Tsiros, V. Veckals⁴⁷, G.I. Veres¹⁸, M. Verweij, N. Wardle, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

W. Bertl[†], L. Caminada⁴⁸, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

F. Bachmair, L. Bäni, P. Berger, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, T. Klijnsma, W. Lustermann, B. Mangano, M. Marionneau, 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. Reichmann, M. Schönenberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler⁴⁹, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, C. Seitz, Y. Takahashi, A. Zucchetta

National Central University, Chung-Li, Taiwan

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

National Taiwan University (NTU), Taipei, Taiwan

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

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

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

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

A. Adiguzel⁵⁰, F. Boran, S. Cerci⁵¹, S. Damarseckin, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, I. Hos⁵², E.E. Kangal⁵³, O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut⁵⁴, K. Ozdemir⁵⁵, D. Sunar Cerci⁵¹, B. Tali⁵¹, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

B. Bilin, G. Karapinar⁵⁶, K. Ocalan⁵⁷, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

E. Gülmez, M. Kaya⁵⁸, O. Kaya⁵⁹, S. Tekten, E.A. Yetkin⁶⁰

Istanbul Technical University, Istanbul, Turkey

M.N. Agaras, S. Atay, A. Cakir, K. Cankocak

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, O. Davignon, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, D.M. Newbold⁶¹, 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. Belyaev⁶², C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, D. O'Brien, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom

G. Auzinger, R. Bainbridge, S. Breeze, O. Buchmuller, A. Bundock, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, R. Di Maria, A. Elwood, Y. Haddad, G. Hall, G. Iles, T. James, R. Lane, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, T. Matsushita, J. Nash, A. Nikitenko⁶, V. Palladino, M. Pesaresi,

D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta⁶³, T. Virdee¹³, D. Winterbottom, J. Wright, S.C. Zenz

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, USA

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

Catholic University of America, Washington DC, USA

R. Bartek, A. Dominguez

The University of Alabama, Tuscaloosa, USA

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

Boston University, Boston, USA

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

Brown University, Providence, USA

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

University of California, Davis, Davis, USA

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

University of California, Los Angeles, USA

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

University of California, Riverside, Riverside, USA

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

University of California, San Diego, La Jolla, USA

J.G. Branson, S. Cittolin, M. Derdzinski, R. Gerosa, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, I. Macneill, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech⁶⁴, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

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

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

California Institute of Technology, Pasadena, USA

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

Carnegie Mellon University, Pittsburgh, USA

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

University of Colorado Boulder, Boulder, USA

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

Cornell University, Ithaca, USA

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

Fermi National Accelerator Laboratory, Batavia, USA

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

University of Florida, Gainesville, USA

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

Florida International University, Miami, USA

Y.R. Joshi, S. Linn, P. Markowitz, J.L. Rodriguez

Florida State University, Tallahassee, USA

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

Florida Institute of Technology, Melbourne, USA

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

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

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

The University of Iowa, Iowa City, USA

B. Bilki⁶⁵, W. Clarida, K. Dilsiz⁶⁶, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya⁶⁷, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul⁶⁸, Y. Onel, F. Ozok⁶⁹, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, USA

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

The University of Kansas, Lawrence, USA

A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, J. Castle, S. Khalil, A. Kropivnitskaya,

D. Majumder, W. Mcbrayer, M. Murray, C. Royon, S. Sanders, E. Schmitz, R. Stringer, J.D. Tapia Takaki, Q. Wang

Kansas State University, Manhattan, USA

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

Lawrence Livermore National Laboratory, Livermore, USA

F. Rebassoo, D. Wright

University of Maryland, College Park, USA

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

Massachusetts Institute of Technology, Cambridge, USA

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

University of Minnesota, Minneapolis, USA

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

University of Mississippi, Oxford, USA

J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA

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

State University of New York at Buffalo, Buffalo, USA

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

Northeastern University, Boston, USA

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

Northwestern University, Evanston, USA

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

University of Notre Dame, Notre Dame, USA

N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko³⁵, M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, M. Wayne, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA

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

Princeton University, Princeton, USA

A. Benaglia, S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S. Higginbotham,

D. Lange, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, USA

S. Malik, S. Norberg

Purdue University, West Lafayette, USA

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

Purdue University Northwest, Hammond, USA

T. Cheng, N. Parashar, J. Stupak

Rice University, Houston, USA

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

University of Rochester, Rochester, USA

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

The Rockefeller University, New York, USA

R. Ciesielski, K. Goulianos, C. Mesropian

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

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

University of Tennessee, Knoxville, USA

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

Texas A&M University, College Station, USA

O. Bouhali⁷⁰, A. Castaneda Hernandez⁷⁰, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁷¹, R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov, K.A. Ulmer

Texas Tech University, Lubbock, USA

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

Vanderbilt University, Nashville, USA

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, USA

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

Wayne State University, Detroit, USA

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

University of Wisconsin - Madison, Madison, WI, USA

M. Brodski, J. Buchanan, C. Caillol, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe,

M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, G.A. Pierro, G. Polese, T. Ruggles, A. Savin, N. Smith, W.H. Smith, D. Taylor, N. Woods

†: 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 Universidade Estadual de Campinas, Campinas, Brazil
- 4: Also at Universidade Federal de Pelotas, Pelotas, Brazil
- 5: Also at Université Libre de Bruxelles, Bruxelles, Belgium
- 6: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 7: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 8: Also at Suez University, Suez, Egypt
- 9: Now at British University in Egypt, Cairo, Egypt
- 10: Now at Helwan University, Cairo, Egypt
- 11: Also at Université de Haute Alsace, Mulhouse, France
- 12: Also at Skobeltsyn Institute of Nuclear Physics; Lomonosov Moscow State University, Moscow, Russia
- 13: Also at CERN; European Organization for Nuclear Research, Geneva, Switzerland
- 14: Also at RWTH Aachen University; III. Physikalisches Institut A, Aachen, Germany
- 15: Also at University of Hamburg, Hamburg, Germany
- 16: Also at Brandenburg University of Technology, Cottbus, Germany
- 17: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 18: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group; Eötvös Loránd University, Budapest, Hungary
- 19: Also at Institute of Physics; University of Debrecen, Debrecen, Hungary
- 20: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
- 21: Also at Institute of Physics, Bhubaneswar, India
- 22: Also at University of Visva-Bharati, Santiniketan, India
- 23: Also at University of Ruhuna, Matara, Sri Lanka
- 24: Also at Isfahan University of Technology, Isfahan, Iran
- 25: Also at Yazd University, Yazd, Iran
- 26: Also at Plasma Physics Research Center; Science and Research Branch; Islamic Azad University, Tehran, Iran
- 27: Also at Università degli Studi di Siena, Siena, Italy
- 28: Also at INFN Sezione di Milano-Bicocca; Università di Milano-Bicocca, Milano, Italy
- 29: Also at Purdue University, West Lafayette, USA
- 30: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
- 31: Also at Malaysian Nuclear Agency; MOSTI, Kajang, Malaysia
- 32: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
- 33: Also at Warsaw University of Technology; Institute of Electronic Systems, Warsaw, Poland
- 34: Also at Czech Technical University, Praha, Czech Republic
- 35: Also at Institute for Nuclear Research, Moscow, Russia
- 36: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
- 37: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 38: Also at University of Florida, Gainesville, USA
- 39: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 40: Also at California Institute of Technology, Pasadena, USA
- 41: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia

- 42: Also at Faculty of Physics; University of Belgrade, Belgrade, Serbia
- 43: Also at INFN Sezione di Roma; Sapienza Università di Roma, Rome, Italy
- 44: Also at University of Belgrade; Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 45: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 46: Also at National and Kapodistrian University of Athens, Athens, Greece
- 47: Also at Riga Technical University, Riga, Latvia
- 48: Also at Universität Zürich, Zurich, Switzerland
- 49: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
- 50: Also at Istanbul University; Faculty of Science, Istanbul, Turkey
- 51: Also at Adiyaman University, Adiyaman, Turkey
- 52: Also at Istanbul Aydin University, Istanbul, Turkey
- 53: Also at Mersin University, Mersin, Turkey
- 54: Also at Cag University, Mersin, Turkey
- 55: Also at Piri Reis University, Istanbul, Turkey
- 56: Also at Izmir Institute of Technology, Izmir, Turkey
- 57: Also at Necmettin Erbakan University, Konya, Turkey
- 58: Also at Marmara University, Istanbul, Turkey
- 59: Also at Kafkas University, Kars, Turkey
- 60: Also at Istanbul Bilgi University, Istanbul, Turkey
- 61: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 62: Also at School of Physics and Astronomy; University of Southampton, Southampton, United Kingdom
- 63: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
- 64: Also at Utah Valley University, Orem, USA
- 65: Also at Beykent University, Istanbul, Turkey
- 66: Also at Bingol University, Bingol, Turkey
- 67: Also at Erzincan University, Erzincan, Turkey
- 68: Also at Sinop University, Sinop, Turkey
- 69: Also at Mimar Sinan University; Istanbul, Istanbul, Turkey
- 70: Also at Texas A&M University at Qatar, Doha, Qatar
- 71: Also at Kyungpook National University, Daegu, Korea