EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2018-230
2019/02/05

CMS-B2G-17-018

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

The CMS Collaboration*

arXiv:1809.08597v2 [hep-ex] 1 Feb 2019

Abstract

A search is presented for the single production of vector-like quarks in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$. The data, corresponding to an integrated luminosity of $35.9\,\text{fb}^{-1}$, were recorded with the CMS experiment at the LHC. The analysis focuses on the vector-like quark decay into a top quark and a W boson, with one muon or electron in the final state. The mass of the vector-like quark candidate is reconstructed from hadronic jets, the lepton, and the missing transverse momentum. Methods for the identification of b quarks and of highly Lorentz boosted hadronically decaying top quarks and W bosons are exploited in this search. No significant deviation from the standard model background expectation is observed. Exclusion limits at 95% confidence level are set on the product of the production cross section and branching fraction as a function of the vector-like quark mass, which range from 0.3 to 0.03 pb for vector-like quark masses of 700 to 2000 GeV. Mass exclusion limits up to 1660 GeV are obtained, depending on the vector-like quark type, coupling, and decay width. These represent the most stringent exclusion limits for the single production of vector-like quarks in this channel.

Published in the European Physical Journal C as `doi:10.1140/epjc/s10052-019-6556-3.`

© 2019 CERN for the benefit of the CMS Collaboration. CC-BY-4.0 license

*See Appendix A for the list of collaboration members

1 Introduction

The discovery of the Higgs boson (H) [1, 2] with a mass of 125 GeV completes the particle content of the standard model (SM). Even though the SM yields numerous accurate predictions, there are several open questions, among them the origin of the H mass stability at the electroweak scale. Various models beyond the SM have been proposed that stabilise the H mass at the measured value; some examples are Little Higgs [3–5] or Composite Higgs models [6], in which additional top quark partners with masses at the TeV scale are predicted. Since the left- (LH) and right-handed (RH) chiral components of these particles transform in the same way under the SM electroweak symmetry group, they are often referred to as "vector-like quarks" (VLQs). In contrast to a fourth chiral quark generation, their impact on the H properties is small, such that VLQs have not been excluded by the measurements of H mediated cross sections [7–9].

Several searches for VLQs have been performed at the CERN LHC, setting lower exclusion limits on the VLQ mass m_{VLQ} [10–31]. Many of these analyses study the pair production of VLQs via the strong interaction. In contrast, the analysis presented here searches for the single VLQ production via the weak interaction, where a hadronic jet is emitted at a low angle with respect to the beam direction. Furthermore, VLQs with enhanced couplings to the third generation quarks (i.e. VLQ B and $X_{5/3}$ quarks with an electric charge of $1/3$ and $5/3$ respectively) are produced in association with a bottom (b) or top (t) quark, leading to the B+b, B+t, and $X_{5/3}$+t production modes.

While a VLQ B quark could decay into the Hb, Zb, or tW final state, a VLQ $X_{5/3}$ quark could only decay into the tW final state. This search focuses on the tW final state. In Fig. 1, two leading-order (LO) Feynman diagrams are shown for the single production of B and $X_{5/3}$ quarks and their decay into tW. This paper presents the first search of this signature in proton-proton (pp) collision data recorded at a centre-of-mass energy of 13 TeV. Results at $\sqrt{s} = 8$ TeV have been obtained by the ATLAS collaboration [32].

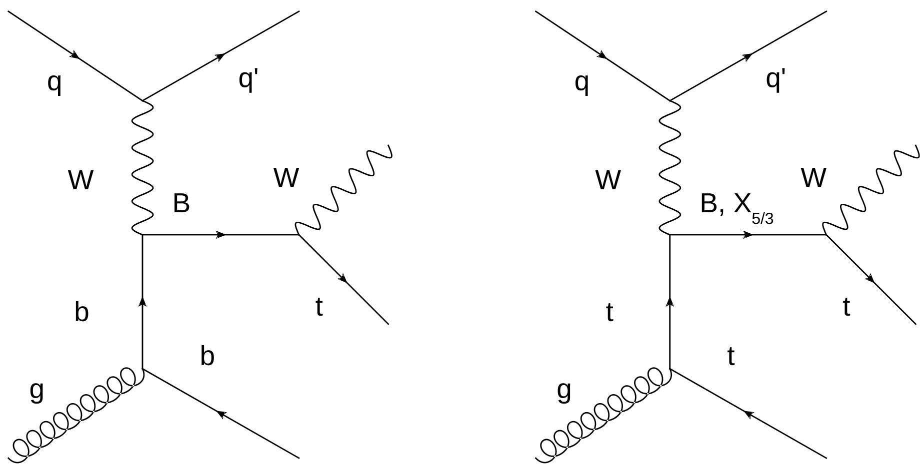

Figure 1: Leading order Feynman diagrams for the production of a single vector-like B or $X_{5/3}$ quark in association with a b (left) or t (right) and a light-flavour quark, and the subsequent decay of the VLQ to tW.

In this analysis, final states with a single muon or electron, several hadronic jets, and missing transverse momenta $p_{\mathrm{T}}^{\mathrm{miss}}$ are studied. Because of the high mass of the VLQ, the t and W can have high Lorentz boosts, leading to highly collimated decays of the W boson, the top quark and non-isolated leptons. For signal events, the mass of the B and $X_{5/3}$ quarks can be reconstructed using hadronic jets, the lepton, and the $p_{\mathrm{T}}^{\mathrm{miss}}$. The associated b and t, as well as the leptons originating from their decay, have much lower transverse momenta p_{T} and are not considered for the reconstruction or selection.

The dominant SM background processes are top quark pair ($\mathrm{t\bar{t}}$) production, W+jets and Z+jets production, single t production, and multijet production via the strong force. All SM backgrounds contributing to this search are predicted from dedicated control regions in data, defined through the absence of a forward jet.

This paper is organised as follows: Section 2 provides a description of the CMS detector. Section 3 introduces the data set and the simulated events. This is followed by the event selection in Section 4, as well as by the description of the reconstruction of the VLQ mass in Section 5. In Section 6, a method to estimate the background is discussed. Systematic uncertainties are detailed in Section 7. The final results of the analysis, as well as the statistical interpretation in terms of exclusion limits, are discussed in Section 8.

2 The CMS detector and physics objects

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionisation chambers embedded in the steel flux-return yoke outside the solenoid.

The particle-flow event algorithm [33] aims to reconstruct and identify each individual particle with an optimised combination of information from the various elements of the CMS detector. The energy of photons is directly obtained from the ECAL measurement, corrected for zero-suppression effects. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track [34]. The energy of muons is obtained from the curvature of the corresponding track [35]. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for zero-suppression effects and for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energy.

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 used are the jets, clustered with the jet finding algorithm [36, 37] with the tracks assigned to the vertex as inputs, and the associated missing transverse momentum, taken as the negative vector sum of the p_{T} of those jets.

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [38].

3 Data and simulated samples

In this analysis, pp collision data at a centre-of-mass energy of 13 TeV taken in 2016 by the CMS experiment are analyzed. The data have been collected with muon and electron triggers [39]. For the muon trigger, a muon candidate with $p_T > 50$ GeV is required. Data events in the electron channel are collected using a logical combination of two triggers: the first requires an electron candidate with $p_T > 45$ GeV and a hadronic jet candidate with $p_T > 165$ GeV, the second requires an electron candidate with $p_T > 115$ GeV. In the trigger selection, reconstructed leptons and jets must be in the central part of the detector, with a pseudorapidity of $|\eta| < 2.4$. No lepton isolation criteria are applied at the trigger level. The collected data correspond to an integrated luminosity of 35.9 fb^{-1} [40].

For the study of dominant SM background processes and for the validation of the background estimation, simulated samples using Monte Carlo (MC) techniques are used. The top quark pair production via the strong interaction and single top quark production in the *t*-channel, and the tW process are generated with the next-to-leading-order (NLO) generator POWHEG [41–43] (version v2 is used for the first two and version v1 for the third). The event generator MADGRAPH5_aMC@NLO (v2.2.2) [44] at NLO is used for single top quark production in the *s*-channel. The W+jets and Z+jets processes are also simulated using MADGRAPH5_aMC@NLO (v2.2.2). The W+jets events are generated at NLO, and the FXFX scheme [45] is used to match the parton shower emission. The Z+jets events are produced at LO with the MLM parton matching scheme [46]. The production of quantum chromodynamics (QCD) multijet events has been simulated at LO using PYTHIA [47]. All generated events are interfaced with PYTHIA for the description of the parton shower and hadronisation. The parton distribution functions (PDFs) are taken from the NNPDF 3.0 [48] sets, with the precision matching that of the matrix element calculations. The underlying event tune is CUETP8M1 [49, 50], except for the simulation of top quark pairs and single top quark production in the *t*-channel, which use CUETP8M2T4 [51].

Signal events are generated at LO using MADGRAPH5_aMC@NLO for B and $X_{5/3}$ with VLQ decay widths relative to the VLQ mass of $(\Gamma/m)_{\mathrm{VLQ}} = 1$, 10, 20, and 30%. The samples with 1% relative VLQ width are simulated in steps of 100 GeV for masses between 700 and 2000 GeV. Samples with 10, 20, and 30% relative VLQ widths are generated in steps of 200 GeV for masses ranging from 800 to 2000 GeV, using a modified version of the model proposed in Refs. [52–54]. Separate signal samples are generated for the two main production modes, in which VLQs are produced in association either with a b quark or with a t quark, viz. pp $\rightarrow$ Bbq and pp $\rightarrow$ Btq. The theoretical cross sections for VLQ production are calculated using Refs. [55–57], where a simplified approach is used to provide a model-independent interpretation of experimental results for narrow and large mass width scenarios, as already used for the interpretation of singly produced vector-like T and B quarks [18, 19]. The MADSPIN package [58, 59] is used to retain the correct spin correlations of the top quark and W boson decay products. Interference effects between signal and SM processes have been found to be negligible in this analysis.

All generated events are passed through a GEANT4 [60] based detector simulation of the CMS detector. Additional pp interactions originating from the same bunch crossing (in-time pileup), as well as from the following or previous bunch crossings (out-of-time pileup) are taken into account in the simulation.

4 Event selection

The physics objects used in this analysis are muons, electrons, hadronic jets, $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$, and $S_{\mathrm{T,lep}}$ (defined as the scalar sum of the lepton p_{T} and $p_{\mathrm{T}}^{\mathrm{miss}}$).

For each event, jets are clustered from reconstructed particles using the infrared and collinear safe anti-k_{T} algorithm [36] with a distance parameter $R = 0.4$ (AK4 jet). Additionally, jets with $R = 0.8$ (AK8 jet) are also clustered in every event with the anti-k_{T} algorithm, which are used for t and W tagging. The jet clustering is performed with the FASTJET [37] package. Jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be within 5–10% of the true momentum over the whole p_{T} spectrum and detector acceptance. Additional pp interactions within the same or nearby bunch crossings can contribute additional tracks and calorimetric energy depositions to the jet momentum. To mitigate this effect, tracks identified to be originating from pileup vertices are discarded, and an offset correction is applied to correct for remaining contributions. Jet energy corrections are derived from simulation studies so that the average measured response of jets becomes identical to that of particle level jets. In situ measurements of the momentum balance in dijet, photon+jet, Z+jet, and multijet events are used to account for any residual differences in the jet energy scale in data and simulation. Additional selection criteria are applied to each jet to remove jets potentially dominated by anomalous contributions from various subdetector components or reconstruction failures [61].

From the corrected and reconstructed AK4 jets, those are considered that have $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 4$, while AK8 jets must have $p_{\mathrm{T}} > 170\,\mathrm{GeV}$ and $|\eta| < 2.4$.

Events selected in the analysis are required to have one reconstructed muon or electron with $p_{\mathrm{T}} > 55\,\mathrm{GeV}$ and $|\eta| < 2.4$. Electrons and muons are selected using tight quality criteria with small misidentification probabilities of about 0.1% for muons and 1% for electrons [34, 62]. In the electron channel, a AK4 jet must have $p_{\mathrm{T}} > 185\,\mathrm{GeV}$ and $|\eta| < 2.4$ if the electron has $p_{\mathrm{T}} < 120\,\mathrm{GeV}$, reflecting the trigger selection. Events with more than one muon or electron passing the same tight identification criteria and having $p_{\mathrm{T}} > 40\,\mathrm{GeV}$ and $|\eta| < 2.4$ are discarded. Selected events contain two AK4 jets with $p_{\mathrm{T}} > 50\,\mathrm{GeV}$, which are in the central part of the detector with $|\eta| < 2.4$. Additionally at least one AK8 jet is required. For the reconstruction AK4 jets are used with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 2.4$, while the AK4 jets emitted close to the beam pipe and employed in the background estimation must fulfill $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $2.4 < |\eta| < 4$.

Because of the high Lorentz boosts of the top quarks and W bosons from the heavy VLQ decay, signal events can have leptons in close vicinity to the jets. For this reason, standard lepton isolation would reduce the selection efficiency considerably. Therefore, for the suppression of events originating from QCD mulitjet processes, either the perpendicular component of the lepton momentum relative to the geometrically closest AK4 jet $p_{\mathrm{T,rel}}$, is required to exceed 40 GeV or the angular distance of the lepton to the jet, $\Delta R(\ell, \mathrm{jet}) = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, must be larger than 0.4, where ϕ is the azimuthal angle in radians. Furthermore, for selecting an event, the magnitude of $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ has to be greater than 50 GeV in the muon channel and greater than 60 GeV in the electron channel. This requirement reduces the amount of background from multijet production. The final selection is based on the variable $S_{\mathrm{T,lep}}$, which is required to be larger than 250 GeV in the muon channel and 290 GeV in the electron channel.

Events are separated into categories exploiting the tagging techniques for boosted top quarks and W bosons decaying hadronically, as well as for hadronic jets originating from b quarks. Jets with $R = 0.8$ are used to identify the hadronic decays of highly boosted top quarks and W bosons [63, 64]. For top quark jets $p_{\mathrm{T}} > 400\,\mathrm{GeV}$ is required, and for W boson jets the requirement is $p_{\mathrm{T}} > 200\,\mathrm{GeV}$. The "soft drop" (SD) declustering and grooming algorithm [65, 66] with $z = 0.1$ and $\beta = 0$ is employed to identify subjets and to remove soft and wide-angle radiation. The groomed jet mass, m_{SD}, is used to identify top quark and W boson candidates. Tagged top quark candidates (t tagged) are required to have $105 < m_{\mathrm{SD}} < 220\,\mathrm{GeV}$ and one of the subjets must fulfill the loose b tagging criterion, based on the combined secondary vertex (CSVv2) [67] algorithm. The loose criterion is defined to give a 80% efficiency of correctly identifying b jets, with a 10% probability of incorrectly tagging a light quark jet. Additionally, the jet must have a N-subjettiness [68, 69] ratio $\tau_3/\tau_2 < 0.5$ and its angular distance to the lepton $\Delta R(\ell, \mathrm{t\ tag})$ must be larger than 2. Identified W boson candidates (W tag) must have $65 < m_{\mathrm{SD}} < 95\,\mathrm{GeV}$. The medium b tag criterion is used on AK4 jets, defined to give a 60% efficiency of correctly identifying b jets, with a 1% probability of incorrectly tagging a light quark jet.

Selected events are attributed to different mutually exclusive event categories. Events containing at least one t tag constitute the first category ("t tag"). If no t tag is found, all events with at least one W tag are grouped into a second category ("W tag"). The remaining events are attributed to three further categories based on the multiplicity of b tags found in the event. We distinguish events with at least two ("≥2 b tag"), exactly one ("1 b tag"), and no b tag ("0 b tag"). These five categories are built separately in the muon and in the electron channel leading to a total of ten categories.

5 Mass reconstruction

Hadronic jets, leptons, and $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ are used to reconstruct the mass of the VLQ, denoted m_{reco}. In signal events, the lepton in the final state always originates from the decay of a W boson, either the W boson from the VLQ decay or the W boson from the top quark decay. The neutrino four-momentum can thus be reconstructed from the components of $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$, the W mass constraint, and the assumption of massless neutrinos.

In the case when a hadronic jet with a t tag is found, m_{reco} is calculated from the four-momentum of the t-tagged jet and the four-momentum of the leptonically decaying W boson. If several hadronic jets with t tags are present, the one with the largest angular distance to the reconstructed leptonic W boson decay is used. Once the t-tagged jet has been selected, all overlapping AK4 jet jets in the event are removed in order to avoid double counting of energy. For the shown m_{reco} distributions these events form the t tag category. For events in the other categories the hadronic part of the VLQ decay is reconstructed from combinations of AK4 jets with $|\eta| < 2.4$. Each possible jet assignment for the decays of the W boson and t quark is tested exploiting the following χ^2 quantity

$$\chi^2 = \frac{(m_{\mathrm{t}} - \overline{m}_{\mathrm{t}})^2}{\sigma_{\mathrm{t}}^2} + \frac{(m_{\mathrm{W}} - \overline{m}_{\mathrm{W}})^2}{\sigma_{\mathrm{W}}^2} + \frac{(\Delta R(\mathrm{t}, \mathrm{W}) - \pi)^2}{\sigma_{\Delta R}^2} + \frac{(p_{\mathrm{T,W}}/p_{\mathrm{T,t}} - 1)^2}{\sigma_{p_{\mathrm{T}}}^2}. \quad (1)$$

For each event, the jet assignment with the maximum χ^2 probability is selected. For the χ^2 quantity the p_{T} balance, $p_{\mathrm{T,W}}/p_{\mathrm{T,t}}$, the angular distance, $\Delta R(\mathrm{t}, \mathrm{W})$, and the reconstructed masses of the top quark candidate m_{t} and the W boson candidate m_{W} are used. The expected values $\overline{m}_{\mathrm{t}}$ and $\overline{m}_{\mathrm{W}}$, and their standard deviations σ_{t} and σ_{W} are obtained from simulation for correctly reconstructed events and it is verified that the values are independent of the VLQ mass. Here, correctly reconstructed events are defined by the assignment of jets to generated t quarks and W bosons, where the generated particles from the VLQ decay are unambiguously matched within a distance of $\Delta R < 0.4$ to the reconstructed particles. It was also verified in

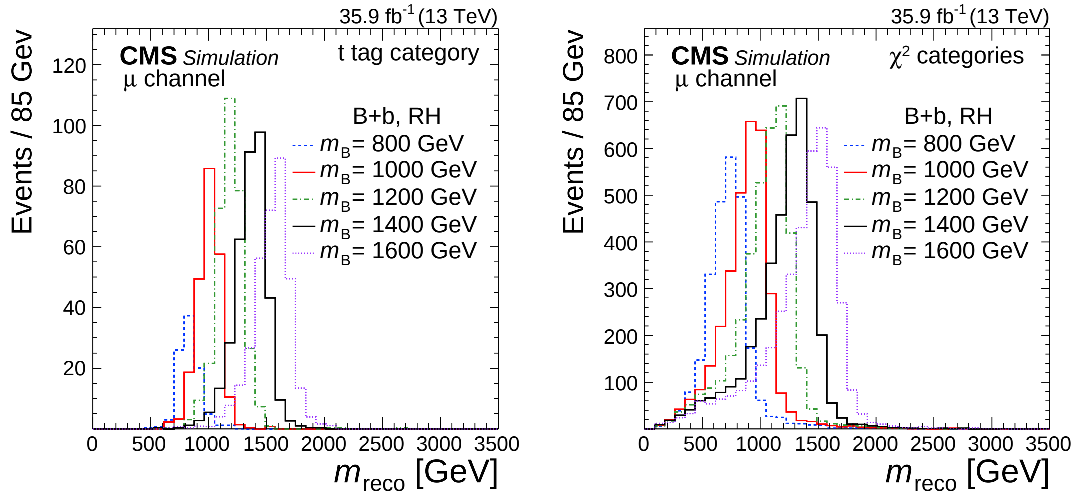

Figure 2: Distributions of m_{reco} for the B+b production mode, obtained for simulated events with a muon in the final state, reconstructed with a t tag (left) and with the χ^2 method (right) for right-handed VLQ couplings and various VLQ masses m_{B}. Signal events are shown assuming a production cross section of 1 pb and a relative VLQ decay width of 1%.

simulation that the expected values of $\Delta R(\text{t}, \text{W})$ and the p_{T} balance are π and 1, with their standard deviations $\sigma_{\Delta R}$ and $\sigma_{p_{\text{T}}}$. In order to account for cases where the W boson from the VLQ decay decays into a lepton and neutrino, the χ^2 is calculated for each permutation with the second term omitted. Cases where the hadronic decay products of the W bosons or the top quark are reconstructed in a single AK4 jet are included by omitting the first or second term in the calculation of the χ^2.

The distributions of m_{reco} in simulation for the B+b production mode with right-handed couplings are shown in Fig. 2 for events with a muon in the final state. The reconstruction of events with a t tag (left) is best suited for high VLQ masses where the decay products of the top quark are highly boosted, while the χ^2 method (right) yields a stable performance for all VLQ masses, where the decay products of the W boson and top quark are reconstructed from several jets. Additionally, the latter method enables the reconstruction of events with a lepton from the top quark decay chain. Mass resolutions between 10–15% are achieved for both reconstruction methods, with peak values of the m_{reco} distributions at the expected values. The VLQs with left-handed couplings (not shown) have a lower selection efficiency by 20–25% because of a smaller lepton p_{T}, on average, but otherwise features a behaviour similar to VLQs with right-handed couplings. Distributions obtained for the final states with an electron are similar to those with a muon.

6 Background estimation

The data sample obtained after the selection is then divided into a signal region with a jet in the forward region of the detector with $2.4 < |\eta| < 4.0$ and a control region without such a jet. The distribution of background processes in the signal region is estimated using the shape of the m_{reco} distribution in the control region. Residual differences in the shapes of the m_{reco} distributions between signal and control regions are investigated in each of the signal categories by using simulated SM events. Differences can arise from different background compositions in signal and control regions due to the presence of a forward jet. The observed differences are small, with average values of 10%, and are corrected for by multiplicative factors applied

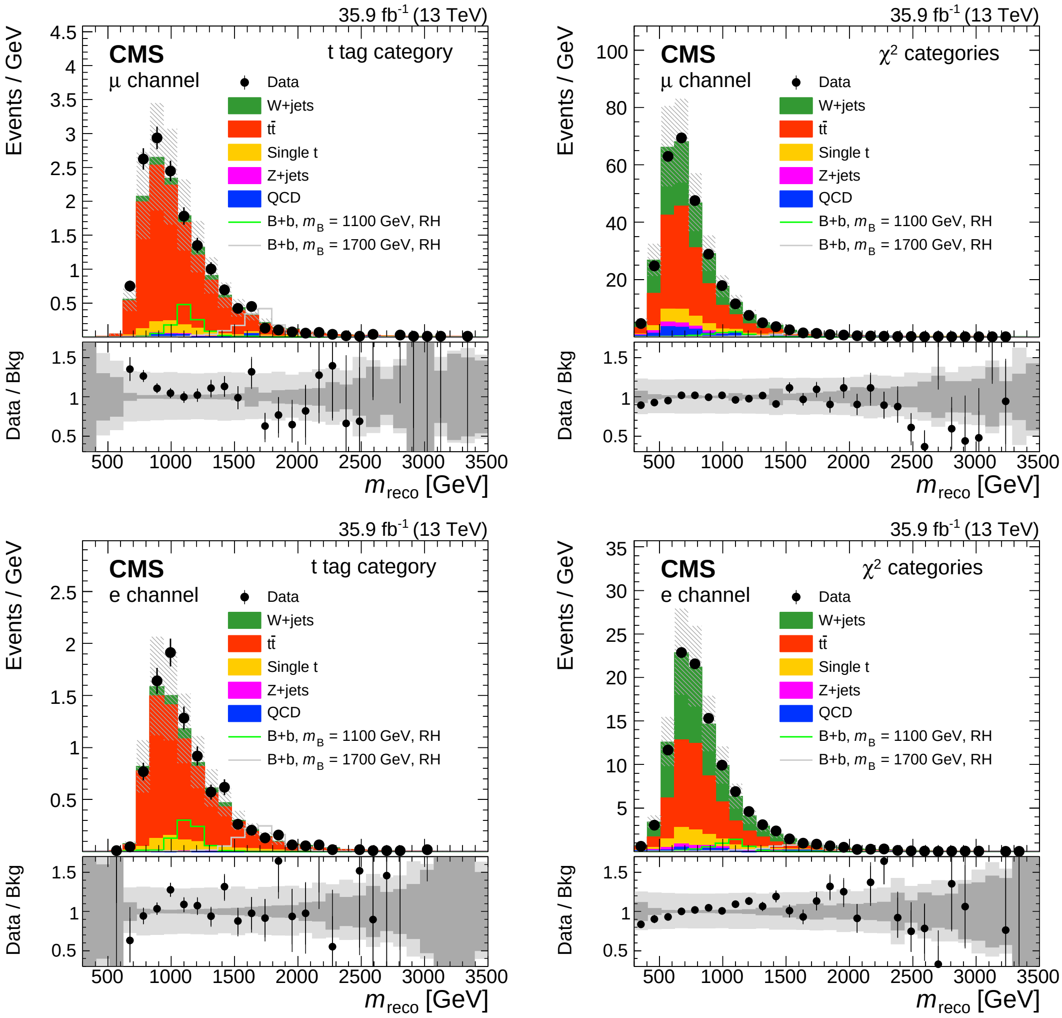

Figure 3: Distributions of m_{reco} in data and simulation in the control region for the muon (upper) and electron (lower) channels for events reconstructed with a t tag (left) and with the χ^2 method (right). The VLQ signal is shown for the B+b production mode and right-handed VLQ couplings. The vertical bars illustrate the statistical uncertainties on the data, while the shaded area shows the total uncertainties for the background simulation. The lower panels show the ratio of data to the background prediction. The dark and light gray bands correspond to the statistical and total uncertainties, respectively.

to the background predictions in the validation and signal regions. The largest differences are observed for m_{reco} values below 800 GeV, with values no larger than about 20%.

In order to validate the VLQ mass reconstruction, data are compared to simulation in the control region. In Fig. 3 the distributions of m_{reco} are shown in the muon (upper) and electron (lower) channels for events with a t tag (left) and events reconstructed with the χ^2 method (right). The $\text{t}\bar{\text{t}}$ and tW standard model processes provide irreducible backgrounds in the reconstructed VLQ mass distributions, showing good agreement between the data and simulation. The contribution of signal events in the control region is small and is taken into account by a simultaneous fit to signal and control regions in the statistical extraction of the results.

In order to validate the background estimation, a validation region is constructed from requiring events with reconstruction p-values smaller than 0.08. The p-values are calculated as the probability of obtaining the χ^2 as given by Eq. (1), where the number of degrees of freedom of

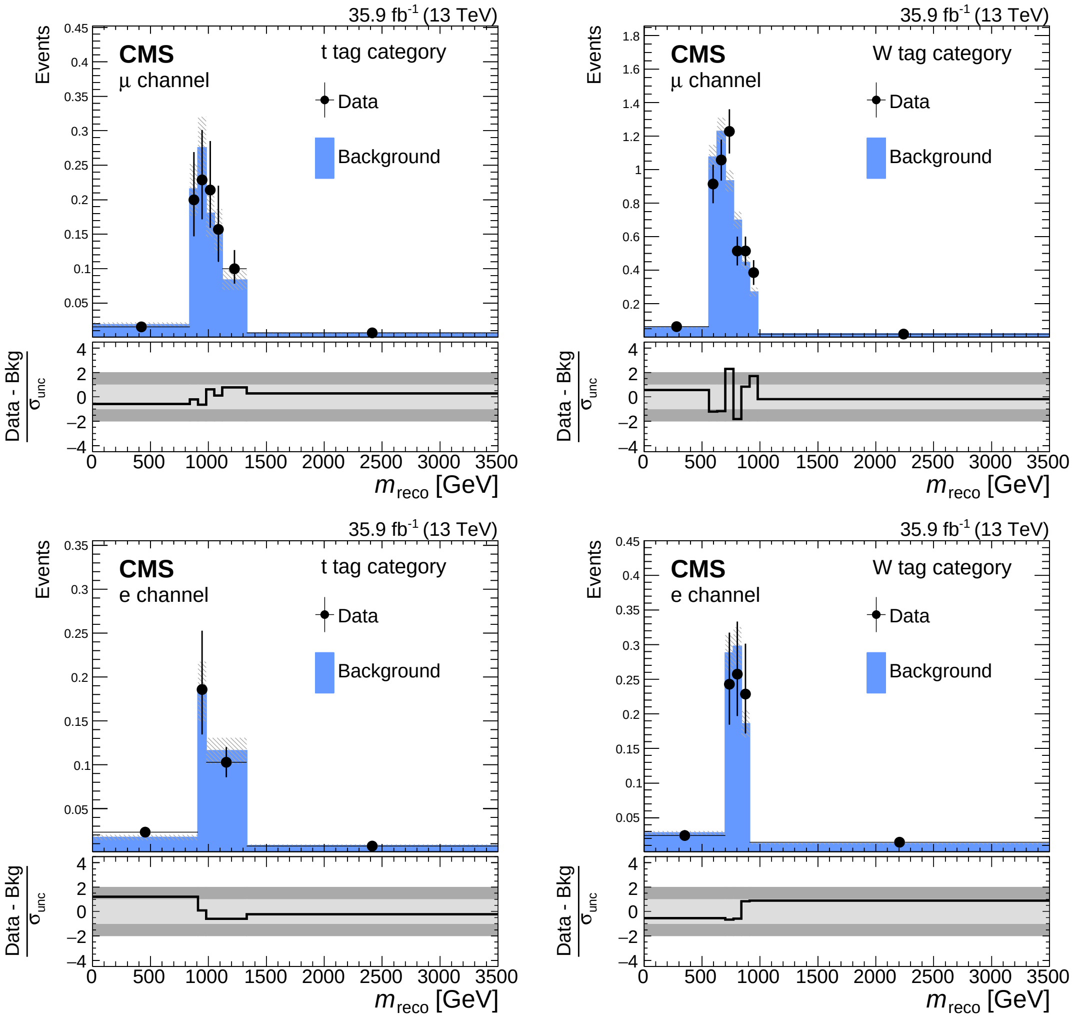

Figure 4: Distributions of m_{reco} in the validation region of the two most sensitive categories in the muon channel (upper) and electron channel (lower). The lower panels show the difference of data and background expectations in units of the total (stat. and sys.) uncertainty on the background estimate.

the selected hypothesis are taken into account. For events with a t tag, the same χ^2 quantity is evaluated for the selected hypothesis. The validation region has an order of magnitude fewer events than the signal region and a negligible amount of signal contamination. The m_{reco} distributions for the two most sensitive categories are shown in Fig. 4 for the muon (upper) and electron (lower) channels. The observed number of events is found to be in good agreement with the predicted number of events from the background estimation in the validation region, with no statistically significant deviations. Similar observations are made for the other signal categories.

7 Systematic uncertainties

Systematic uncertainties can affect both the overall normalisation of background components and the shapes of the m_{reco} distributions for signal and background processes. The main uncertainty in the shape of the m_{reco} distribution from the background estimation based on a control region in data is related to the kinematic difference between the signal and control regions. Correction factors are applied to account for this difference, obtained from SM simulations. These uncertainties have a size of 10% on average, with maximum values of 20% at small values of m_{reco}. Compared to these uncertainties, the effects from uncertainties in the SM simulations are negligible on the background estimation, as these cancel to a large degree when building the ratios between signal and control regions. The uncertainties in the overall normalisation of the background predictions are obtained from a fit to the data in the signal region.

Uncertainties in the MC simulation are applied to all simulated signal events. In the following, the systematic uncertainties are summarized.

- The uncertainty in the integrated luminosity measurement recorded with the CMS detector in the 2016 run at $\sqrt{s} = 13\,\mathrm{TeV}$ is 2.5% [40].
- The estimation of pileup effects is based on the total inelastic cross section. This cross section is determined to be 69.2 mb. The uncertainty is taken into account by varying the total inelastic cross section by 4.6% [70].
- Simulated events are corrected for lepton identification, trigger, and isolation efficiencies. The corresponding corrections are applied as functions of $|\eta|$ and p_{T}. The systematic uncertainties due to these corrections are taken into account by varying each correction factor within its uncertainty.
- The scale factors for the jet energy scale and resolution are determined as functions of $|\eta|$ and p_{T} [61]. The effect of the uncertainties in these scale factors are considered by varying the scale factors within their uncertainties. Jets with distance parameters of 0.4 and 0.8 are modified simultaneously. The results of variations for AK4 jets are propagated to the measurement of $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$.
- The uncertainties due to the PDFs are evaluated by considering 100 replicas of the NNPDF 3.0 set according to the procedure described in Ref. [71]. The associated PDF uncertainties in the signal acceptance are estimated following the prescription for the LHC [71].
- Uncertainties associated with variations of the factorisation μ_{f} and renormalisation scales μ_{r} are evaluated by varying the respective scales independently, by factors of 0.5 and 2.
- Corrections for the b tagging efficiencies and misidentification rates for AK4 jets, and subjets of AK8 jets are applied. These are measured as a function of the jet p_{T} [67]. The corresponding uncertainties are taken into account by varying the corrections within their uncertainties for heavy- and light-flavour jets separately.
- An uncertainty on the t tagging efficiency of $+7$ and -4% is applied to signal events with a t tag [64]. The uncertainty on the W tagging efficiency is determined from jet mass resolution (JMR) and scale (JMS) uncertainties, which are added in quadrature. An additional JMR uncertainty is derived from the differences in the hadronisation and shower models of PYTHIA and HERWIG++ [72]. The uncertainty depends on the p_{T} of the W boson; for VLQs with a mass of 700 GeV it is around 2% and for a mass of 1800 GeV it is around 6%. An uncertainty of 1% is assigned to the JMS, as obtained from studies of the jet mass in fully merged hadronic W boson decays.

In Table 1, a summary of the uncertainties considered for signal events is shown, where the largest uncertainties come from the jet energy scale and the jet tagging. For the uncertainties connected to the PDF, μ_{f} and μ_{r} only the signal acceptance and shape differences are propagated. The uncertainties with the largest impact on the analysis are the uncertainties associated with the data-driven background estimation, being more than two times larger than the jet

Table 1: Uncertainties considered for simulated signal events in the B+b production mode ($m_B = 900\,\text{GeV}$) for right-handed VLQ couplings for the t tag and W tag categories. The uncertainties in the b tag categories are of comparable size to those in the W tag category.

Uncertainty		t tag [%]	W tag [%]
W tagging	Rate	—	3.3
t tagging	Rate	$^{+7}_{-4}$	—
Luminosity	Rate	2.5	2.5
Pileup	Shape	1–3	0.2
Lepton reconstruction	Shape	2–3	2–3
b tagging	Shape	2.5	2.5
Jet energy scale	Shape	2–6	1–5
Jet energy resolution	Shape	1–2	1–2
PDF	Shape	2–3	0.5
μ_f and μ_r	Shape	0.3	0.2

energy scale uncertainties in the signal.

8 Results

The m_{reco} distributions in the ten categories are measured in the signal and control region, which are defined by the presence or absence of a forward jet with $|\eta| > 2.4$. For the background estimate in the signal regions, a simultaneous binned maximum likelihood fit of both regions is performed using the THETA [73] package. In these fits, the signal cross section and the background normalisations in the different signal categories are free parameters. The shapes of the m_{reco} distributions for the SM background in the signal regions are taken from the corresponding control regions. Systematic uncertainties are taken into account as additional nuisance parameters. A common nuisance parameter is used for uncertainties in the muon and electron channels if a similar effect is expected on the shape or normalisation of the m_{reco} distribution in both channels similarly. The nuisance parameters for the shape uncertainties are taken to be Gaussian distributed. For the uncertainties on the normalisation log-normal prior distributions are assumed.

The measured distributions of m_{reco} for the signal categories are shown in Figs. 5 and 6 for the muon and electron channels, together with the background predictions obtained from the control regions. The signal m_{reco} distributions for a vector-like B quark with right-handed couplings produced in association with a b quark are shown for illustration, for two different VLQ masses with an assumed production cross section of 1 pb and a relative VLQ width of 1%. No significant deviation from the background expectation is observed in any of the categories.

Exclusion limits on the product of the VLQ production cross section and branching fraction are calculated at 95% confidence level (CL) for VLQ masses between 700 and 2000 GeV by using a Bayesian statistical method [73, 74]. Pseudo-experiments are performed to extract expected upper limits under the background-only hypothesis. For the signal cross section parameter an uniform prior distribution, and for the nuisance parameters log-normal prior distributions are used. The nuisance parameters are randomly varied within their ranges of validity to estimate the 68 and 95% CL expected limits. Correlations between the systematic uncertainties across all channels are taken into account through a common nuisance parameter. The statistical uncertainties of the background predictions are treated as an additional Poisson nuisance parameter in each bin of the m_{reco} distribution.

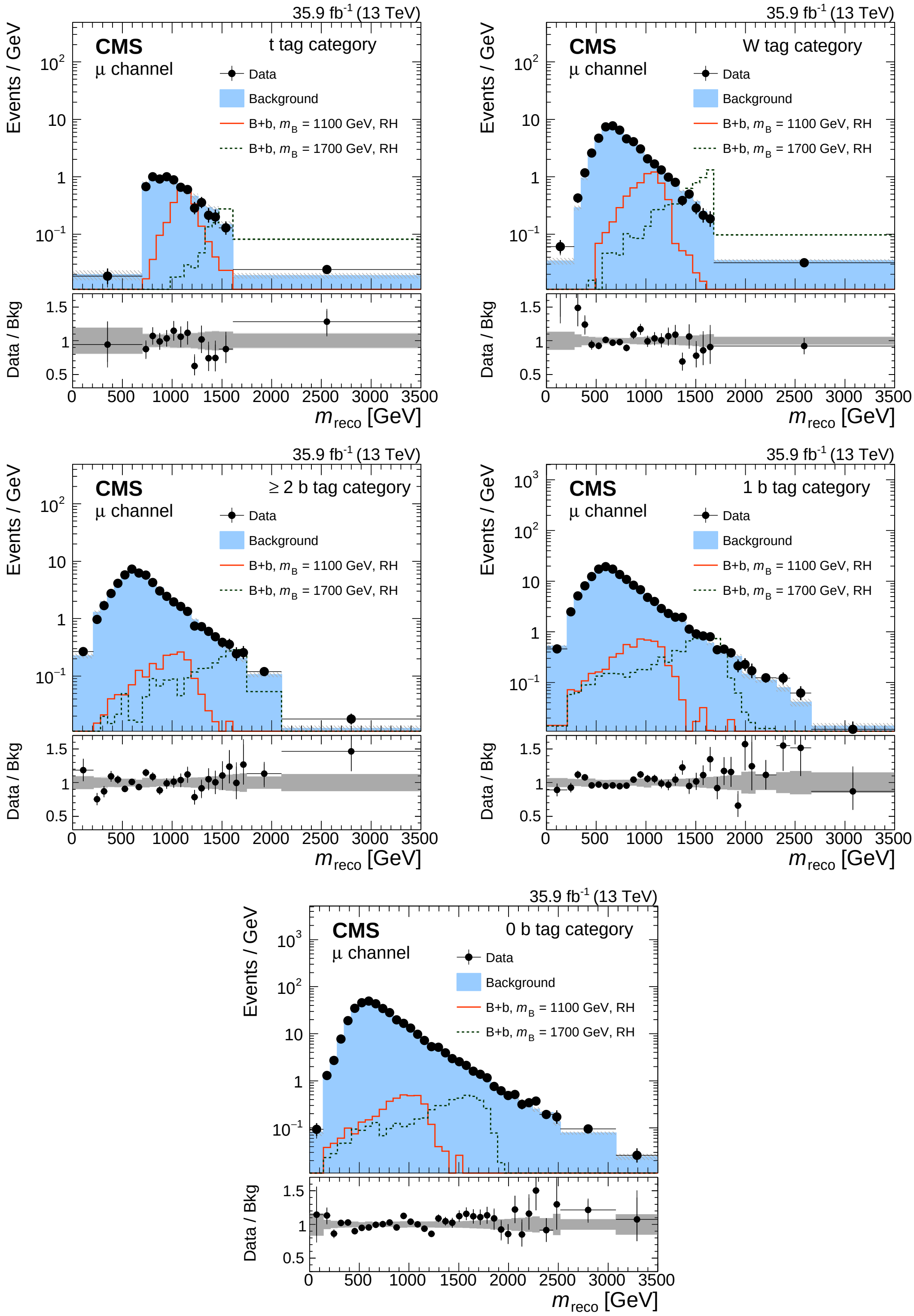

Figure 5: Distributions of m_{reco} measured in the signal region for events with a jet in the forward direction with $|\eta| > 2.4$ in the muon channel. Shown are the sensitive categories: t tag (upper left), W tag (upper right), ≥2 b tag (middle left), 1 b tag (middle right) and 0 b tag (lower). The background prediction is obtained from control regions as detailed in the main text. The distributions from two example signal samples for the B+b production mode with right-handed VLQ couplings with a cross section of 1 pb and a relative width of 1% are shown for illustration.

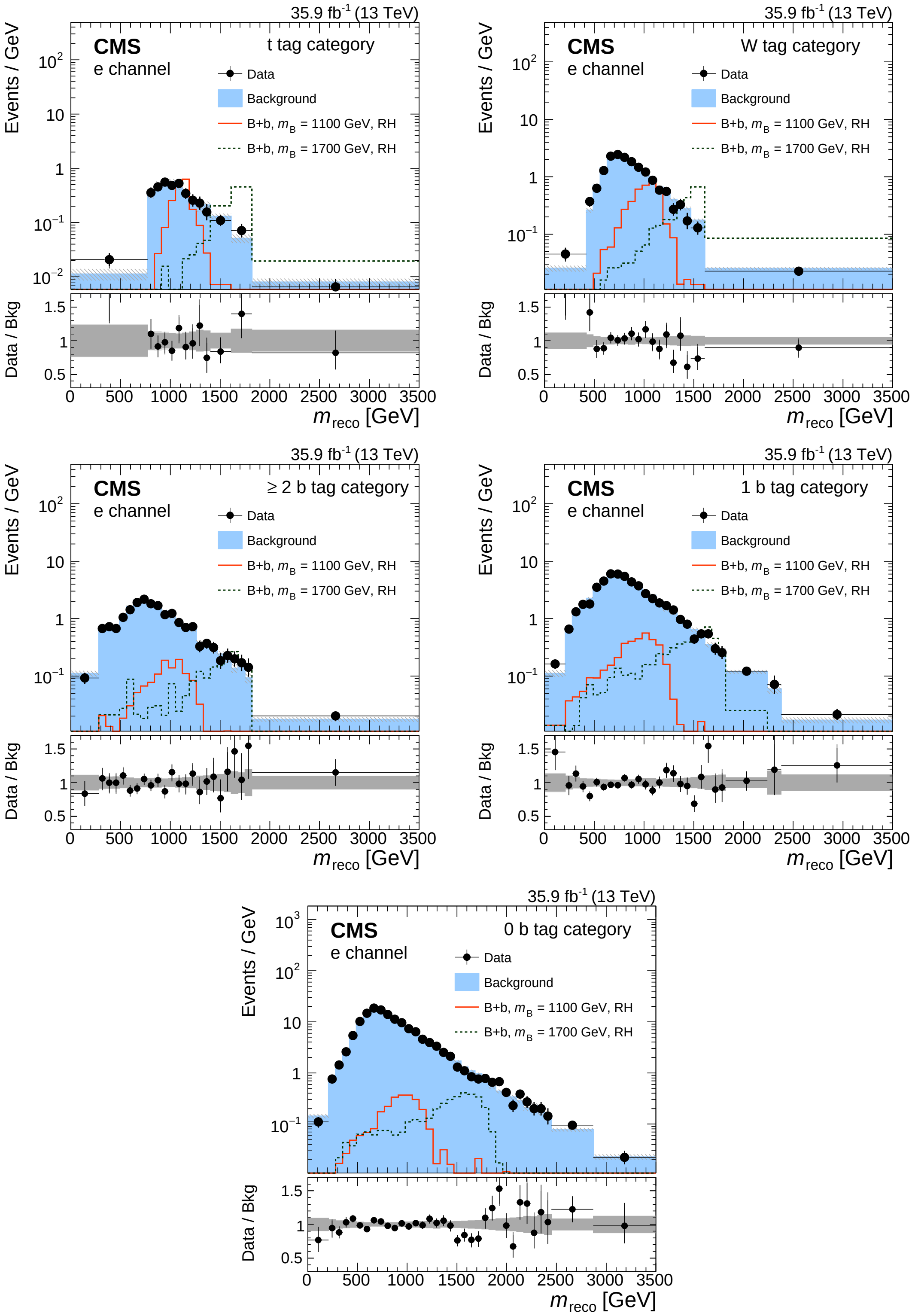

Figure 6: Distributions of m_{reco} measured in the signal region for events with a jet in the forward direction with $|\eta| > 2.4$ in the electron channel. Shown are the sensitive categories: t tag(upper left), W tag(upper right), ≥2 b tag (middle left), 1 b tag (middle right) and 0 b tag (lower). The background prediction is obtained from control regions as detailed in the main text. The distributions from two example signal samples for the B+b production mode with right-handed VLQ couplings with a cross section of 1 pb and a relative VLQ width of 1% are shown for illustration.

Table 2: Observed (expected) upper limits at 95% CL on the product of the cross section and branching fraction for the B+b and $X_{5/3}$+t production modes, for a set of VLQ masses, for VLQs widths of 1% and 10%, and for left-handed and right-handed couplings. The exclusion limits for the B+t production mode (not shown) are very similar to those for the $X_{5/3}$+t mode.

		B+b			$X_{5/3}$+t	
m_{VLQ} [TeV]	1% LH	10% LH	1% RH	1% LH	10% LH	1% RH
0.8	0.29 (0.36)	0.27 (0.36)	0.25 (0.29)	0.31 (0.27)	0.32 (0.25)	0.21 (0.18)
1	0.29 (0.17)	0.29 (0.19)	0.21 (0.12)	0.25 (0.15)	0.25 (0.16)	0.15 (0.10)
1.2	0.10 (0.10)	0.11 (0.11)	0.07 (0.07)	0.10 (0.09)	0.10 (0.10)	0.06 (0.06)
1.4	0.07 (0.07)	0.06 (0.08)	0.03 (0.05)	0.05 (0.06)	0.05 (0.07)	0.03 (0.05)
1.6	0.05 (0.05)	0.05 (0.06)	0.03 (0.04)	0.04 (0.04)	0.05 (0.05)	0.03 (0.03)
1.8	0.04 (0.04)	0.05 (0.04)	0.03 (0.03)	—	0.05 (0.04)	—

Figure 7 shows the 95% CL upper limits on the product of the cross section and branching fraction for the B+b production mode for left- and right-handed VLQ couplings and a relative VLQ width of 1% (upper left and upper right), for the left-handed VLQ couplings and a relative VLQ width of 10% (lower left), as well as a comparison of the observed exclusion limits for relative VLQ widths between 10 and 30% (lower right). In Fig. 8, the 95% CL upper limits on the product of the cross section and branching fraction for the production modes B+t (upper left) and $X_{5/3}$+t (upper right) and right-handed VLQ couplings are shown. The figure also shows the $X_{5/3}$+t exclusion limits for left-handed VLQ couplings with a 10% relative VLQ width (lower left) and a comparison of the observed exclusion limits for VLQ widths between 10 and 30% for left-handed couplings (lower right). The predicted cross sections for variations of the relative VLQ mass width (dashed lines) are taken from Refs. [55–57]. For a set of VLQ masses the expected and observed 95% CL upper limits for the B+b and the $X_{5/3}$+t production modes are also given in Table 2 for VLQs with widths of 1% and 10% and left-handed couplings, as well as for widths of 1% and right-handed couplings. The exclusion limits for the B+t production mode are similar to those for the $X_{5/3}$+t production mode.

The obtained exclusion limits range from 0.3 to 0.03 pb for VLQ masses between 700 and 2000 GeV. For VLQs with a relative width of 1% and purely left-handed couplings an increase of about 25% of the 95% CL upper limits is observed because of the reduced signal acceptance, in comparison to the right-handed couplings. The expected limits for VLQ with relative widths of 10–30% and left-handed couplings only show small differences. Although the predicted cross sections for the SM backgrounds are considerably larger at 13 TeV, similar exclusion limits on the product of cross section and branching fraction are achieved compared to the results obtained at 8 TeV in the more restricted mass range considered in Ref. [32]. However, because of the increase of the VLQ signal cross section at 13 TeV, with this analysis, the existence of VLQ B ($X_{5/3}$) quarks with left-handed couplings and a relative width of 10, 20, and 30% can be excluded for masses below 1490, 1590, and 1660 GeV (920, 1300, and 1450 GeV) respectively. The results represent the most stringent exclusion limits for singly produced VLQ in this channel.

9 Summary

A search for singly produced vector-like quarks decaying into a top quark and a W boson has been performed using the 2016 data set recorded by the CMS experiment at the CERN LHC. The selection is optimised for high vector-like quark masses, with a single muon or electron, significant missing transverse momentum, and two jets with high p_{T} in the final state. Vector-like quarks in the single production mode can be produced in association with a t or a b quark

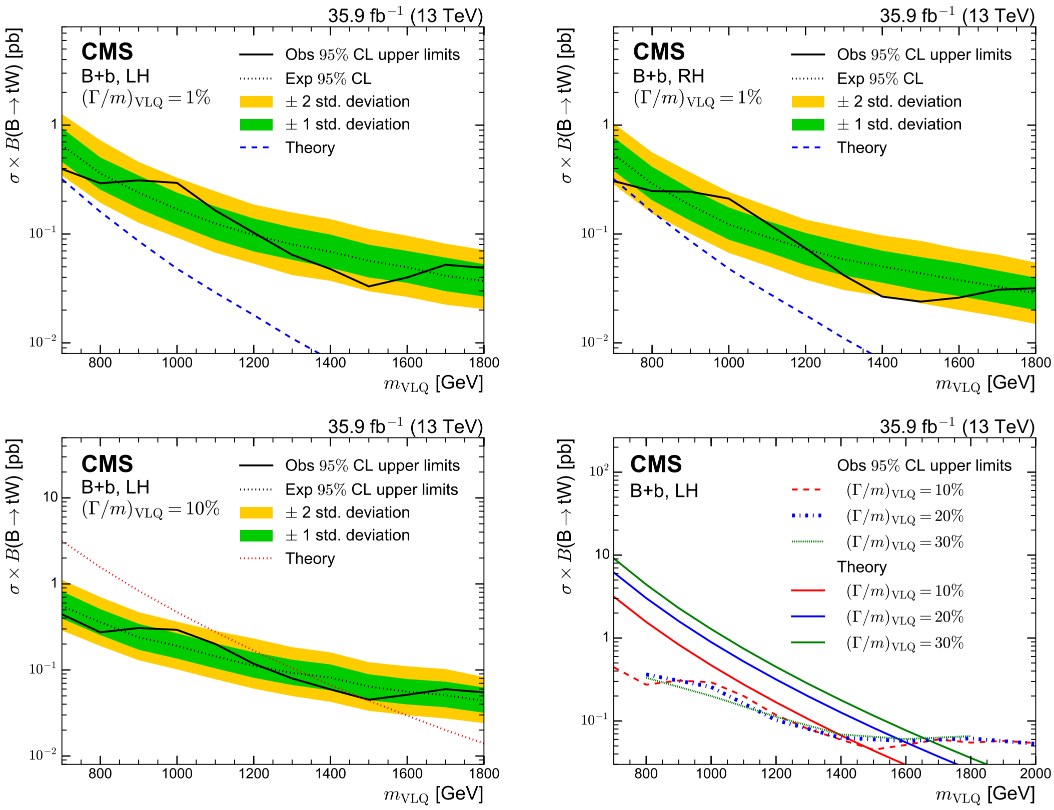

Figure 7: Upper limits at 95% CL on the product of the VLQ production cross section and branching fraction for the B+b production mode for a relative VLQ width of 1% and left- and right-handed VLQ couplings (upper left and right), for 10% relative VLQ width and left-handed VLQ couplings (lower left), and a comparison of the observed exclusion limits for relative VLQ widths of 10, 20, and 30% for left-handed couplings (lower right). The dashed lines show the theoretical predictions.

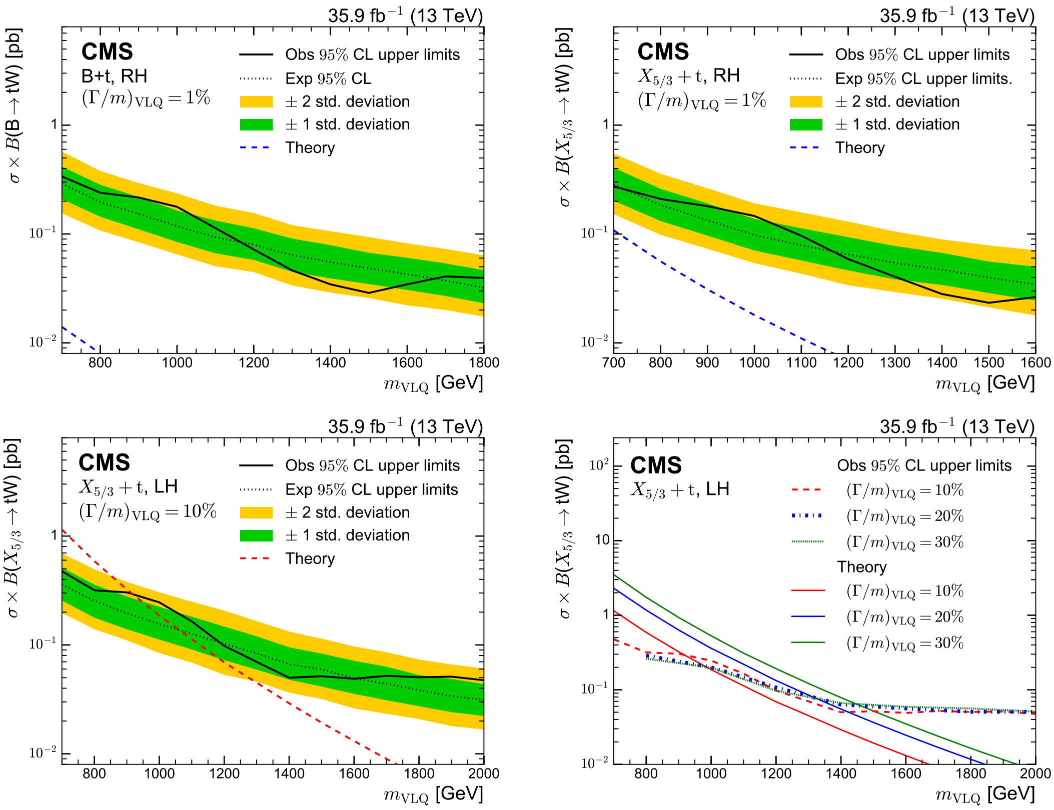

Figure 8: Upper limits at 95% CL on the product of the VLQ production cross section and branching fraction for the B+t and $X_{5/3}$+t production modes for right-handed VLQ couplings assuming a relative VLQ width of 1% (upper left and right), for the $X_{5/3}$+t production mode with left-handed VLQ couplings and a 10% relative width (lower left) and a comparison of the observed exclusion limits for left-handed couplings for relative widths of 10, 20, and 30% (lower right). The dashed lines show the theoretical predictions.

and a forward jet. The latter feature is used to obtain the background prediction in the signal regions from data. The mass of the vector-like quark is reconstructed from the hadronic jets, the missing transverse momentum, and the lepton in the event. Different decay possibilities of the t and W are considered. The reach of the search is enhanced by t, W, and b tagging methods. No significant deviation from the standard model prediction is observed. Upper exclusion limits at 95% confidence level on the product of the production cross section and branching fraction range from around 0.3–0.03 pb for vector-like quark masses between 700 and 2000 GeV. Depending on the vector-like quark type, coupling, and decay width to tW, mass exclusion limits up to 1660 GeV are obtained. These represent the most stringent exclusion limits for the single production of vector-like quarks in this channel.

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 centres 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, FAPERGS, 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); NKFIA (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); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MOSTR (Sri Lanka); 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 programme and the European Research Council and Horizon 2020 Grant, contract No. 675440 (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science - EOS" - be.h project n. 30820817; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Lendület ("Momentum") Programme and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFIA research grants 123842, 123959, 124845, 124850 and 125105 (Hungary); the Council of Science and Industrial Research, India; the HOMING PLUS programme of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus programme 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 Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant

MDM-2015-0509 and the Programa Severo Ochoa del Principado de Asturias; the Thalis and Aristeia programmes 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); the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

[1] ATLAS Collaboration, "Observation of a new particle in the search for the standard model Higgs boson with the ATLAS detector at the LHC", *Phys. Lett. B* **716** (2012) 1, doi:10.1016/j.physletb.2012.08.020, arXiv:1207.7214.

[2] CMS Collaboration, "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC", *Phys. Lett. B* **716** (2012) 30, doi:10.1016/j.physletb.2012.08.021, arXiv:1207.7235.

[3] N. Arkani-Hamed, A. G. Cohen, E. Katz, and A. E. Nelson, "The littlest Higgs", *JHEP* **07** (2002) 034, doi:10.1088/1126-6708/2002/07/034, arXiv:hep-ph/0206021.

[4] M. Schmaltz, "Physics beyond the standard model (theory): Introducing the little Higgs", *Nucl. Phys. Proc. Suppl.* **117** (2003) 40, doi:10.1016/S0920-5632(03)01409-9, arXiv:hep-ph/0210415.

[5] M. Schmaltz and D. Tucker-Smith, "Little Higgs review", *Ann. Rev. Nucl. Part. Sci.* **55** (2005) 229, doi:10.1146/annurev.nucl.55.090704.151502, arXiv:hep-ph/0502182.

[6] D. Marzocca, M. Serone, and J. Shu, "General composite Higgs models", *JHEP* **08** (2012) 013, doi:10.1007/JHEP08(2012)013, arXiv:1205.0770.

[7] A. Djouadi and A. Lenz, "Sealing the fate of a fourth generation of fermions", *Phys. Lett. B* **715** (2012) 310, doi:10.1016/j.physletb.2012.07.060, arXiv:1204.1252.

[8] J. A. Aguilar-Saavedra, R. Benbrik, S. Heinemeyer, and M. Pérez-Victoria, "Handbook of vectorlike quarks: Mixing and single production", *Phys. Rev. D* **88** (2013) 094010, doi:10.1103/PhysRevD.88.094010, arXiv:1306.0572.

[9] ATLAS and CMS Collaborations, "Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s} = 7$ and 8 TeV", *JHEP* **08** (2016) 045, doi:10.1007/JHEP08(2016)045, arXiv:1606.02266.

[10] CMS Collaboration, "Inclusive search for a vector-like T quark with charge $\frac{2}{3}$ in pp collisions at $\sqrt{s}$ = 8 TeV", *Phys. Lett. B* **729** (2014) 149, doi:10.1016/j.physletb.2014.01.006, arXiv:1311.7667.

[11] CMS Collaboration, "Search for vector-like T quarks decaying to top quarks and Higgs bosons in the all-hadronic channel using jet substructure", *JHEP* **06** (2015) 080, doi:10.1007/JHEP06(2015)080, arXiv:1503.01952.

[12] 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.

[13] 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.

[14] 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.

[15] CMS Collaboration, "Search for top quark partners with charge 5/3 in proton-proton collisions at $\sqrt{s} = 13$ TeV", *JHEP* **08** (2017) 073, doi:10.1007/JHEP08(2017)073, arXiv:1705.10967.

[16] 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.

[17] CMS Collaboration, "Search for pair production of vector-like quarks in the $\mathrm{bW\bar{b}W}$ channel from proton-proton collisions at $\sqrt{s} = 13$ TeV", *Phys. Lett. B* **779** (2018) 82, doi:10.1016/j.physletb.2018.01.077, arXiv:1710.01539.

[18] CMS Collaboration, "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", *Phys. Lett. B* **781** (2018) 574, doi:10.1016/j.physletb.2018.04.036, arXiv:1708.01062.

[19] CMS Collaboration, "Search for single production of vector-like quarks decaying to a b quark and a Higgs boson", *JHEP* **06** (2018) 031, doi:10.1007/JHEP06(2018)031, arXiv:1802.01486.

[20] ATLAS Collaboration, "Search for heavy vector-like quarks coupling to light quarks in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector", *Phys. Lett. B* **712** (2012) 22, doi:10.1016/j.physletb.2012.03.082, arXiv:1112.5755.

[21] ATLAS Collaboration, "Search for pair production of a new quark that decays to a Z boson and a bottom quark with the ATLAS detector", *Phys. Rev. Lett.* **109** (2012) 071801, doi:10.1103/PhysRevLett.109.071801, arXiv:1204.1265.

[22] 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.

[23] ATLAS Collaboration, "Analysis of events with b-jets and a pair of leptons of the same charge in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector", *JHEP* **10** (2015) 150, doi:10.1007/JHEP10(2015)150, arXiv:1504.04605.

[24] 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.

[25] 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.

[26] ATLAS Collaboration, "Search for top squarks in final states with one isolated lepton, jets, and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector", *Phys. Rev. D* **94** (2016) 052009, doi:10.1103/PhysRevD.94.052009, arXiv:1606.03903.

[27] 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.

[28] 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) 249, doi:10.1016/j.physletb.2016.04.061, arXiv:1602.06034.

[29] 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.

[30] ATLAS Collaboration, "Search for pair production of heavy vector-like quarks decaying to high-p_{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.

[31] ATLAS Collaboration, "Search for pair production of up-type vector-like quarks and for four-top-quark events in final states with multiple b-jets with the ATLAS detector", *JHEP* **07** (2018) 089, doi:10.1007/JHEP07(2018)089, arXiv:1803.09678.

[32] 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.

[33] CMS Collaboration, "Particle-flow reconstruction and global event description with the CMS detector", *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.

[34] 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.

[35] 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.

[36] 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.

[37] 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.

[38] CMS Collaboration, "The CMS experiment at the CERN LHC", *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

[39] CMS Collaboration, "The CMS trigger system", *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.

[40] CMS Collaboration, "CMS luminosity measurements for the 2016 data taking period", Technical Report CMS-PAS-LUM-17-001, 2017.

[41] 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.

[42] 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.

[43] 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.

[44] 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.

[45] R. Frederix and S. Frixione, "Merging meets matching in MC@NLO", *JHEP* **12** (2012) 061, doi:10.1007/JHEP12(2012)061, arXiv:1209.6215.

[46] J. Alwall et al., "Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions", *Eur. Phys. J. C* **53** (2008) 473, doi:10.1140/epjc/s10052-007-0490-5, arXiv:0706.2569.

[47] 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.

[48] NNPDF Collaboration, "Parton distributions for the LHC run II", *JHEP* **04** (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849.

[49] CMS Collaboration, "Event generator tunes obtained from underlying event and multiparton scattering measurements", *Eur. Phys. J. C* **76** (2016) 155, doi:10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.

[50] P. Skands, S. Carrazza, and J. Rojo, "Tuning PYTHIA 8.1: the Monash 2013 tune", *Eur. Phys. J. C* **74** (2014) 3024, doi:10.1140/epjc/s10052-014-3024-y, arXiv:1404.5630.

[51] 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", Technical Report CMS-PAS-TOP-16-021, CERN, Geneva, 2016.

[52] 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.

[53] 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.

[54] A. Carvalho, "Gravity particles from warped extra dimensions, predictions for LHC", (2014). arXiv:1404.0102.

[55] J. M. Campbell, R. K. Ellis, and F. Tramontano, "Single top production and decay at next-to-leading order", *Phys. Rev. D* **70** (2004) 094012, doi:10.1103/PhysRevD.70.094012, arXiv:hep-ph/0408158.

[56] 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.

[57] A. Carvalho et al., "Single production of vector-like quarks with large width at the Large Hadron Collider", *Phys. Rev. D* **98** (2018) 015029, doi:10.1103/PhysRevD.98.015029, arXiv:1805.06402.

[58] S. Frixione, E. Laenen, P. Motylinski, and B. R. Webber, "Angular correlations of lepton pairs from vector boson and top quark decays in Monte Carlo simulations", *JHEP* **04** (2007) 081, doi:10.1088/1126-6708/2007/04/081, arXiv:hep-ph/0702198.

[59] 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.

[60] GEANT4 Collaboration, "GEANT4–a simulation toolkit", *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.

[61] CMS Collaboration, "Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV", *JINST* **12** (2017) P02014, doi:10.1088/1748-0221/12/02/P02014, arXiv:1607.03663.

[62] CMS Collaboration, "Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV", *JINST* **13** (2018) P06015, doi:10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.

[63] CMS Collaboration, "Top tagging with new approaches", Technical Report CMS-PAS-JME-15-002, CERN, Geneva, 2016.

[64] CMS Collaboration, "Jet algorithms performance in 13 TeV data", Technical Report CMS-PAS-JME-16-003, 2017.

[65] 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.

[66] 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.

[67] CMS Collaboration, "Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV", *JINST* **13** (2018) P05011, doi:10.1088/1748-0221/13/05/P05011, arXiv:1712.07158.

[68] J. Thaler and K. Van Tilburg, "Identifying boosted objects with N-subjettiness", *JHEP* **03** (2011) 015, doi:10.1007/JHEP03(2011)015, arXiv:1011.2268.

[69] J. Thaler and K. Van Tilburg, "Maximizing boosted top identification by minimizing N-subjettiness", *JHEP* **02** (2012) 093, doi:10.1007/JHEP02(2012)093, arXiv:1108.2701.

[70] CMS Collaboration, "Measurement of the inelastic proton-proton cross section at $\sqrt{s} = 7$ TeV", *Phys. Lett. B* **722** (2013) 5, doi:10.1016/j.physletb.2013.03.024, arXiv:1210.6718.

[71] 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.

[72] M. Bähr et al., "Herwig++ physics and manual", *Eur. Phys. J. C* **58** (2008) 639, doi:10.1140/epjc/s10052-008-0798-9, arXiv:0803.0883.

[73] J. Ott, "THETA — A framework for template-based modeling and inference" (2010), http://www-ekp.physik.uni-karlsruhe.de/~ott/theta/theta-auto.

[74] A. O'Hagan and J. J. Forster, "Kendall's advanced theory of statistics. Vol. 2B: Bayesian Inference". Arnold, London, 2004. ISBN 978-0470685693.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria
W. Adam, F. Ambrogi, E. Asilar, T. Bergauer, J. Brandstetter, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth[1], V.M. Ghete, J. Hrubec, M. Jeitler[1], N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, H. Rohringer, J. Schieck[1], R. Schöfbeck, M. Spanring, D. Spitzbart, A. Taurok, W. Waltenberger, J. Wittmann, C.-E. Wulz[1], 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, M. Pieters, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium
S. Abu Zeid, F. Blekman, J. D'Hondt, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskyi, S. Lowette, I. Marchesini, 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
D. Beghin, B. Bilin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, A.K. Kalsi, T. Lenzi, J. Luetic, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, Q. Wang

Ghent University, Ghent, Belgium
T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov[2], D. Poyraz, C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, A. Giammanco, G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, K. Piotrzkowski, A. Saggio, M. Vidal Marono, S. Wertz, J. Zobec

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
F.L. Alves, G.A. Alves, M. Correa Martins Junior, G. Correia Silva, 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. Chinellato[3], E. Coelho, E.M. Da Costa, G.G. Da Silveira[4], D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, D. Matos Figueiredo, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote[3], F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista [a], Universidade Federal do ABC [b], São Paulo, Brazil
S. Ahuja[a], C.A. Bernardes[a], L. Calligaris[a], T.R. Fernandez Perez Tomei[a], E.M. Gregores[b], P.G. Mercadante[b], S.F. Novaes[a], SandraS. Padula[a]

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

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

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

Beihang University, Beijing, China
W. Fang[5], X. Gao[5], L. Yuan

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[6], A. Spiezia, J. Tao, Z. Wang, E. Yazgan, H. Zhang, S. Zhang[6], J. Zhao

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

Tsinghua University, Beijing, China
Y. Wang

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, M.A. Segura Delgado

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
B. Courbon, N. Godinovic, D. Lelas, I. Puljak, 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. Starodumov[7], T. Susa

University of Cyprus, Nicosia, Cyprus
M.W. Ather, A. Attikis, M. Kolosova, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

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

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
M.A. Mahmoud[9,10], A. Mahrous[11], Y. Mohammed[9]

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

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

Helsinki Institute of Physics, Helsinki, Finland
J. Havukainen, J.K. Heikkilä, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland
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, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, 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[12], C. Amendola, I. Antropov, F. Beaudette, P. Busson, C. Charlot, R. Granier de Cassagnac, I. Kucher, A. Lobanov, J. Martin Blanco, C. Martin Perez, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[13], J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, V. Cherepanov, C. Collard, E. Conte[13], J.-C. Fontaine[13], 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, France
S. Beauceron, C. Bernet, G. Boudoul, N. Chanon, 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, H. Lattaud, M. Lethuillier, L. Mirabito, S. Perries, A. Popov[14], V. Sordini, G. Touquet, M. Vander Donckt, S. Viret

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

Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze[8]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, M.P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
A. Albert, D. Duchardt, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, S. Ghosh, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, T. Pook, M. Radziej, H. Reithler, M. Rieger, A. Schmidt, D. Teyssier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
G. Flügge, O. Hlushchenko, T. Kress, A. Künsken, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl[15]

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, I. Babounikau, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, D. Bertsche, A.A. Bin Anuar, K. Borras[16], V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, V. Danilov, A. De Wit, M.M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, T. Eichhorn, A. Elwood, E. Eren, E. Gallo[17], A. Geiser, J.M. Grados Luyando, A. Grohsjean, M. Guthoff, M. Haranko, A. Harb, J. Hauk, H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, A. Lelek, T. Lenz, J. Leonard, K. Lipka, W. Lohmann[18], R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, G. Mittag, J. Mnich, V. Myronenko, S.K. Pflitsch, D. Pitzl, A. Raspereza, M. Savitskyi, P. Saxena, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, H. Tholen, O. Turkot, A. Vagnerini, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

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

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
M. Akbiyik, C. Barth, M. Baselga, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, B. Freund, M. Giffels, M.A. Harrendorf, F. Hartmann[15], S.M. Heindl, U. Husemann, I. Katkov[14], S. Kudella, S. Mitra, M.U. Mozer, Th. Müller, M. Musich, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, C. Wöhrmann, R. Wolf

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki, I. Topsis-Giotis

National and Kapodistrian University of Athens, Athens, Greece
G. Karathanasis, S. Kesisoglou, P. Kontaxakis, A. Panagiotou, I. Papavergou, N. Saoulidou, E. Tziaferi, K. Vellidis

National Technical University of Athens, Athens, Greece
K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

University of Ioánnina, Ioánnina, Greece
I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F.A. Triantis, D. Tsitsonis

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Bartók[19], M. Csanad, N. Filipovic, P. Major, M.I. Nagy, G. Pasztor, O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, D. Horvath[20], Á. Hunyadi, F. Sikler, T.Á. Vámi, V. Veszpremi, G. Vesztergombi[†]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi[21], A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, Z.L. Trocsanyi, B. Ujvari

Indian Institute of Science (IISc), Bangalore, India
S. Choudhury, J.R. Komaragiri, P.C. Tiwari

National Institute of Science Education and Research, HBNI, Bhubaneswar, India
S. Bahinipati[22], C. Kar, P. Mal, K. Mandal, A. Nayak[23], D.K. Sahoo[22], S.K. Swain

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

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

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
R. Bhardwaj[24], M. Bharti[24], R. Bhattacharya, S. Bhattacharya, U. Bhawandeep[24], D. Bhowmik, S. Dey, S. Dutt[24], S. Dutta, S. Ghosh, K. Mondal, S. Nandan, A. Purohit, P.K. Rout, A. Roy, S. Roy Chowdhury, G. Saha, S. Sarkar, M. Sharan, B. Singh[24], S. Thakur[24]

Indian Institute of Technology Madras, Madras, India
P.K. Behera

Bhabha Atomic Research Centre, Mumbai, India
R. Chudasama, D. Dutta, V. Jha, V. Kumar, P.K. Netrakanti, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, B. Sutar, RavindraKumar Verma

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Karmakar, S. Kumar, M. Maity[25], G. Majumder, K. Mazumdar, N. Sahoo, T. Sarkar[25]

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

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani[26], E. Eskandari Tadavani, S.M. Etesami[26], M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi, B. Safarzadeh[27], 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], A. Colaleo[a], D. Creanza[a,c], L. Cristella[a,b], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,b], F. Errico[a,b], L. Fiore[a], A. Gelmi[a,b], G. Iaselli[a,c], M. Ince[a,b], S. Lezki[a,b], G. Maggi[a,c], M. Maggi[a], G. Miniello[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a], A. Ranieri[a], G. Selvaggi[a,b], A. Sharma[a], L. Silvestris[a], R. Venditti[a], P. Verwilligen[a], G. Zito[a]

INFN Sezione di Bologna [a], Università di Bologna [b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], L. Borgonovi[a,b], S. Braibant-Giacomelli[a,b], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], S.S. Chhibra[a,b], C. Ciocca[a], G. Codispoti[a,b], M. Cuffiani[a,b], G.M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], E. Fontanesi, P. Giacomelli[a], C. Grandi[a], L. Guiducci[a,b], S. Lo Meo[a], S. Marcellini[a], G. Masetti[a], A. Montanari[a], F.L. Navarria[a,b], A. Perrotta[a], F. Primavera[a,b,15], 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], A. Di Mattia[a], 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], G. Latino, P. Lenzi[a,b], M. Meschini[a], S. Paoletti[a], L. Russo[a,28], G. Sguazzoni[a], D. Strom[a], L. Viliani[a]

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

INFN Sezione di Genova [a], Università di Genova [b], Genova, Italy
F. Ferro[a], R. Mulargia[a,b], F. Ravera[a,b], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca [a], Università di Milano-Bicocca [b], Milano, Italy
A. Benaglia[a], A. Beschi[b], F. Brivio[a,b], V. Ciriolo[a,b,15], S. Di Guida[a,d,15], 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], A. Massironi[a,b], D. Menasce[a], F. Monti, L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], S. Ragazzi[a,b], T. Tabarelli de Fatis[a,b], D. Zuolo[a,b]

INFN Sezione di Napoli [a], Università di Napoli 'Federico II' [b], Napoli, Italy, Università della Basilicata [c], Potenza, Italy, Università G. Marconi [d], Roma, Italy
S. Buontempo[a], N. Cavallo[a,c], A. De Iorio[a,b], A. Di Crescenzo[a,b], F. Fabozzi[a,c], F. Fienga[a], G. Galati[a], A.O.M. Iorio[a,b], W.A. Khan[a], L. Lista[a], S. Meola[a,d,15], P. Paolucci[a,15], C. Sciacca[a,b], E. Voevodina[a,b]

INFN Sezione di Padova [a], Università di Padova [b], Padova, Italy, Università di Trento [c], Trento, Italy
P. Azzi[a], N. Bacchetta[a], A. Boletti[a,b], A. Bragagnolo, R. Carlin[a,b], P. Checchia[a], M. Dall'Osso[a,b], P. De Castro Manzano[a], T. Dorigo[a], U. Dosselli[a], F. Gasparini[a,b], U. Gasparini[a,b], A. Gozzelino[a], S.Y. Hoh, S. Lacaprara[a], P. Lujan, M. Margoni[a,b], A.T. Meneguzzo[a,b], J. Pazzini[a,b], N. Pozzobon[a,b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], A. Tiko, E. Torassa[a], M. Tosi[a,b], S. Ventura[a], M. Zanetti[a,b], P. Zotto[a,b]

INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy
A. Braghieri[a], A. Magnani[a], P. Montagna[a,b], S.P. Ratti[a,b], V. Re[a], M. Ressegotti[a,b], C. Riccardi[a,b], P. Salvini[a], I. Vai[a,b], P. Vitulo[a,b]

INFN Sezione di Perugia [a], Università di Perugia [b], Perugia, Italy
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], G. Bagliesi[a], L. Bianchini[a], T. Boccali[a], L. Borrello, R. Castaldi[a], M.A. Ciocci[a,b], R. Dell'Orso[a], G. Fedi[a], F. Fiori[a,c], L. Giannini[a,c], A. Giassi[a], M.T. Grippo[a],

F. Ligabue[a,c], E. Manca[a,c], G. Mandorli[a,c], A. Messineo[a,b], F. Palla[a], A. Rizzi[a,b], G. Rolandi[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], D. Del Re[a,b], E. Di Marco[a,b], M. Diemoz[a], S. Gelli[a,b], E. Longo[a,b], B. Marzocchi[a,b], P. Meridiani[a], G. Organtini[a,b], F. Pandolfi[a], 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], S. Cometti[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], B. Kiani[a,b], C. Mariotti[a], S. Maselli[a], E. Migliore[a,b], V. Monaco[a,b], E. Monteil[a,b], M. Monteno[a], M.M. Obertino[a,b], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], G.L. Pinna Angioni[a,b], A. Romero[a,b], M. Ruspa[a,c], R. Sacchi[a,b], K. Shchelina[a,b], V. Sola[a], A. Solano[a,b], D. Soldi[a,b], A. Staiano[a]

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

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.I. Pak, S. Sekmen, D.C. Son, Y.C. Yang

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
H. Kim, D.H. Moon, G. Oh

Hanyang University, Seoul, Korea
B. Francois, J. Goh[30], T.J. Kim

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

Sejong University, Seoul, Korea
H.S. Kim

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

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 Ali[31], F. Mohamad Idris[32], W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castilla-Valdez, E. De La Cruz-Burelo, M.C. Duran-Osuna, I. Heredia-De La Cruz[33], R. Lopez-Fernandez, J. Mejia Guisao, R.I. Rabadan-Trejo, M. Ramirez-Garcia, G. Ramirez-Sanchez, R. Reyes-Almanza, A. Sanchez-Hernandez

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
J. Eysermans, 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
S. Bheesette, P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M. Ahmad, M.I. Asghar, 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, M. Szleper, P. Traczyk, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, A. Byszuk[34], 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
M. Araujo, P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, J. Seixas, G. Strong, O. Toldaiev, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, A. Lanev, A. Malakhov, V. Matveev[35,36], P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
V. Golovtsov, Y. Ivanov, V. Kim[37], E. Kuznetsova[38], P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, 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. Stepennov, V. Stolin, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia
T. Aushev

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
M. Chadeeva[39], P. Parygin, D. Philippov, S. Polikarpov[39], E. Popova, V. Rusinov

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin[36], M. Kirakosyan, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin[40], L. Dudko, A. Ershov, V. Klyukhin, N. Korneeva, I. Lokhtin, I. Miagkov, S. Obraztsov, M. Perfilov, V. Savrin, P. Volkov

Novosibirsk State University (NSU), Novosibirsk, Russia
A. Barnyakov[41], V. Blinov[41], T. Dimova[41], L. Kardapoltsev[41], Y. Skovpen[41]

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, D. Elumakhov, A. Godizov, V. Kachanov, A. Kalinin, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

National Research Tomsk Polytechnic University, Tomsk, Russia
A. Babaev, S. Baidali, V. Okhotnikov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic[42], P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, J.A. Brochero Cifuentes, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, M.S. Soares, A. Triossi

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain
J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, V. Rodríguez Bouza, S. Sanchez Cruz, 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, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, A. García Alonso, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

University of Ruhuna, Department of Physics, Matara, Sri Lanka
N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, C. Botta, E. Brondolin, T. Camporesi, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, G. Cucciati, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, A. De Roeck, N. Deelen, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita[43], D. Fasanella, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, M. Gruchala, M. Guilbaud, D. Gulhan, J. Hegeman, C. Heidegger, V. Innocente, A. Jafari, P. Janot, O. Karacheban[18], J. Kieseler, A. Kornmayer, M. Krammer[1], C. Lange, P. Lecoq, C. Lourenço, L. Malgeri, M. Mannelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic[44], F. Moortgat, M. Mulders, J. Ngadiuba, S. Nourbakhsh, S. Orfanelli, L. Orsini, F. Pantaleo[15], L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabady, A. Racz, T. Reis, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas[45], A. Stakia, J. Steggemann, D. Treille, A. Tsirou, V. Veckalns[46], M. Verzetti, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
L. Caminada[47], K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
M. Backhaus, L. Bäni, P. Berger, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T.A. Gómez Espinosa, C. Grab, D. Hits, T. Klijnsma, W. Lustermann, R.A. Manzoni, M. Marionneau, M.T. Meinhard, F. Micheli, P. Musella, F. Nessi-Tedaldi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, S. Pigazzini, M. Quittnat, C. Reissel, D. Ruini, D.A. Sanz Becerra, 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. Amsler[48], D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, S. Leontsinis, I. Neutelings, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, A. Zucchetta

National Central University, Chung-Li, Taiwan
Y.H. Chang, K.y. Cheng, T.H. Doan, 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, W.-S. Hou, Arun Kumar, Y.F. Liu, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
M.N. Bakirci[49], A. Bat, F. Boran, S. Damarseckin, Z.S. Demiroglu, F. Dolek, C. Dozen, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos[50], C. Isik, E.E. Kangal[51], O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir[52], S. Ozturk[49], D. Sunar Cerci[53], B. Tali[53], U.G. Tok, H. Topakli[49], S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey
B. Isildak[54], G. Karapinar[55], M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey
I.O. Atakisi, E. Gülmez, M. Kaya[56], O. Kaya[57], S. Ozkorucuklu[58], S. Tekten, E.A. Yetkin[59]

Istanbul Technical University, Istanbul, Turkey
M.N. Agaras, A. Cakir, K. Cankocak, Y. Komurcu, S. Sen[60]

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

University of Bristol, Bristol, United Kingdom
F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, D.M. Newbold[61], S. Paramesvaran, B. Penning, T. Sakuma, D. Smith, V.J. Smith, J. Taylor, A. Titterton

Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, A. Belyaev[62], C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley

Imperial College, London, United Kingdom
R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, D. Colling, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, G. Hall, G. Iles, T. James, M. Komm, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, J. Nash[63], A. Nikitenko[7], V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, G. Singh, M. Stoye, T. Strebler, S. Summers, A. Tapper, K. Uchida, T. Virdee[15], N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

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

Baylor University, Waco, USA
K. Call, J. Dittmann, K. Hatakeyama, H. Liu, C. Madrid, B. McMaster, 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, T. Bose, D. Gastler, D. Pinna, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Brown University, Providence, USA
G. Benelli, X. Coubez, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan[64], K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, S. Sagir[65], R. Syarif, E. Usai, D. Yu

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

University of California, Los Angeles, USA
M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, S. Regnard, D. Saltzberg, C. Schnaible, V. Valuev

University of California, Riverside, Riverside, USA
E. Bouvier, K. Burt, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, W. Si, L. Wang, H. Wei, S. Wimpenny, B.R. Yates

University of California, San Diego, La Jolla, USA
J.G. Branson, P. Chang, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech[66], 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, M. Citron, A. Dishaw, V. Dutta, M. Franco Sevilla, L. Gouskos, R. Heller, J. Incandela, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, S. Wang, J. Yoo

California Institute of Technology, Pasadena, USA
D. Anderson, A. Bornheim, J.M. Lawhorn, N. Lu, H.B. Newman, T.Q. Nguyen, M. Spiropulu, J.R. Vlimant, R. Wilkinson, S. Xie, Z. Zhang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

University of Colorado Boulder, Boulder, USA
J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, USA
J. Alexander, J. Chaves, Y. Cheng, J. Chu, A. Datta, K. Mcdermott, N. Mirman, J.R. Patterson, D. Quach, 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, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, C. Pena, O. Prokofyev, G. Rakness, L. Ristori, A. Savoy-Navarro[67], 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, L. Cadamuro, A. Carnes, D. Curry, R.D. Field, S.V. Gleyzer, B.M. Joshi, J. Konigsberg, A. Korytov, K.H. Lo, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, D. Rosenzweig, K. Shi, D. Sperka, J. Wang, S. Wang, X. Zuo

Florida International University, Miami, USA
Y.R. Joshi, S. Linn

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, C. Schiber, R. Yohay

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, M. Rahmani, 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, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, C. Mills, I.D. Sandoval Gonzalez, M.B. Tonjes, H. Trauger, N. Varelas, H. Wang, X. Wang, Z. Wu, J. Zhang

The University of Iowa, Iowa City, USA
M. Alhusseini, B. Bilki[68], W. Clarida, K. Dilsiz[69], S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul[70], Y. Onel, F. Ozok[71], A. Penzo, C. Snyder, E. Tiras, J. Wetzel

Johns Hopkins University, Baltimore, USA
B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, W.T. Hung, 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, A. Bylinkin, J. Castle, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, C. Rogan, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang

Kansas State University, Manhattan, USA
S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi, L.K. Saini, N. Skhirtladze

Lawrence Livermore National Laboratory, Livermore, USA
F. Rebassoo, D. Wright

University of Maryland, College Park, USA
A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, S. Nabili, F. Ricci-Tam, Y.H. Shin, A. Skuja, S.C. Tonwar, K. Wong

Massachusetts Institute of Technology, Cambridge, USA
D. Abercrombie, B. Allen, V. Azzolini, A. Baty, G. Bauer, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.-J. Lee, P.D. Luckey, B. Maier, A.C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch, S. Zhaozhong

University of Minnesota, Minneapolis, USA
A.C. Benvenuti[†], R.M. Chatterjee, A. Evans, P. Hansen, J. Hiltbrand, Sh. Jain, S. Kalafut, Y. Kubota, Z. Lesko, J. Mans, N. Ruckstuhl, R. Rusack, M.A. Wadud

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, F. Golf, 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
A. Godshalk, C. Harrington, I. Iashvili, A. Kharchilava, C. Mclean, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA
G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, D.M. Morse, T. Orimoto, R. Teixeira De Lima, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, USA
S. Bhattacharya, J. Bueghly, O. Charaf, K.A. Hahn, N. Mucia, N. Odell, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA
R. Bucci, N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, W. Li, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko[35], M. Planer, A. Reinsvold, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA
J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, C. Hill, W. Ji, T.Y. Ling, W. Luo, B.L. Winer

Princeton University, Princeton, USA
S. Cooperstein, P. Elmer, J. Hardenbrook, S. Higginbotham, A. Kalogeropoulos, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, J. Salfeld-Nebgen, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, USA
S. Malik, S. Norberg

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

Purdue University Northwest, Hammond, USA
T. Cheng, J. Dolen, N. Parashar

Rice University, Houston, USA
Z. Chen, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, W. Li, B.P. Padley, J. Roberts, J. Rorie, W. Shi, Z. Tu, A. Zhang

University of Rochester, Rochester, USA
A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, E. Ranken, P. Tan, R. Taus

Rutgers, The State University of New Jersey, Piscataway, USA
A. Agapitos, J.P. Chou, Y. Gershtein, E. Halkiadakis, A. Hart, 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, J. Heideman, G. Riley, S. Spanier

Texas A&M University, College Station, USA
O. Bouhali[72], A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[73], S. Luo, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, USA
N. Akchurin, J. Damgov, F. De Guio, P.R. Dudero, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, 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, K. Padeken, J.D. Ruiz Alvarez, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij, Q. Xu

University of Virginia, Charlottesville, USA
M.W. Arenton, P. Barria, B. Cox, R. Hirosky, M. Joyce, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, USA
R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

University of Wisconsin - Madison, Madison, WI, USA
M. Brodski, J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, I. De Bruyn, L. Dodd, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, K. Long, R. Loveless, T. Ruggles, A. Savin, V. Sharma, N. Smith, W.H. Smith, N. Woods

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
3: Also at Universidade Estadual de Campinas, Campinas, Brazil
4: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
5: Also at Université Libre de Bruxelles, Bruxelles, Belgium
6: Also at University of Chinese Academy of Sciences, Beijing, China
7: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
8: Also at Joint Institute for Nuclear Research, Dubna, Russia
9: Also at Fayoum University, El-Fayoum, Egypt
10: Now at British University in Egypt, Cairo, Egypt
11: Now at Helwan University, Cairo, Egypt
12: Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia
13: Also at Université de Haute Alsace, Mulhouse, France
14: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
15: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
16: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
17: Also at University of Hamburg, Hamburg, Germany
18: Also at Brandenburg University of Technology, Cottbus, Germany
19: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
20: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
21: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
22: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India

23: Also at Institute of Physics, Bhubaneswar, India
24: Also at Shoolini University, Solan, India
25: Also at University of Visva-Bharati, Santiniketan, India
26: Also at Isfahan University of Technology, Isfahan, Iran
27: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
28: Also at Università degli Studi di Siena, Siena, Italy
29: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
30: Also at Kyunghee University, Seoul, Korea
31: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
32: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
33: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
34: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
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 Pavia [a], Università di Pavia [b], Pavia, Italy
44: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
45: Also at National and Kapodistrian University of Athens, Athens, Greece
46: Also at Riga Technical University, Riga, Latvia
47: Also at Universität Zürich, Zurich, Switzerland
48: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
49: Also at Gaziosmanpasa University, Tokat, Turkey
50: Also at Istanbul Aydin University, Istanbul, Turkey
51: Also at Mersin University, Mersin, Turkey
52: Also at Piri Reis University, Istanbul, Turkey
53: Also at Adiyaman University, Adiyaman, Turkey
54: Also at Ozyegin University, Istanbul, Turkey
55: Also at Izmir Institute of Technology, Izmir, Turkey
56: Also at Marmara University, Istanbul, Turkey
57: Also at Kafkas University, Kars, Turkey
58: Also at Istanbul University, Faculty of Science, Istanbul, Turkey
59: Also at Istanbul Bilgi University, Istanbul, Turkey
60: Also at Hacettepe University, Ankara, 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 Monash University, Faculty of Science, Clayton, Australia
64: Also at Bethel University, St. Paul, USA
65: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
66: Also at Utah Valley University, Orem, USA
67: Also at Purdue University, West Lafayette, USA

68: Also at Beykent University, Istanbul, Turkey
69: Also at Bingol University, Bingol, Turkey
70: Also at Sinop University, Sinop, Turkey
71: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
72: Also at Texas A&M University at Qatar, Doha, Qatar
73: Also at Kyungpook National University, Daegu, Korea