

# Search for a $W'$ boson decaying to a vector-like quark and a top or bottom quark in the all-jets final state at $\sqrt{s} = 13$ TeV



## The CMS collaboration

*E-mail:* [cms-publication-committee-chair@cern.ch](mailto:cms-publication-committee-chair@cern.ch)

**ABSTRACT:** A search is presented for a heavy  $W'$  boson resonance decaying to a B or T vector-like quark and a t or a b quark, respectively. The analysis is performed using proton-proton collisions collected with the CMS detector at the LHC. The data correspond to an integrated luminosity of  $138 \text{ fb}^{-1}$  at a center-of-mass energy of 13 TeV. Both decay channels result in a signature with a t quark, a Higgs or Z boson, and a b quark, each produced with a significant Lorentz boost. The all-hadronic decays of the Higgs or Z boson and of the t quark are selected using jet substructure techniques to reduce standard model backgrounds, resulting in a distinct three-jet  $W'$  boson decay signature. No significant deviation in data with respect to the standard model background prediction is observed. Upper limits are set at 95% confidence level on the product of the  $W'$  boson cross section and the final state branching fraction. A  $W'$  boson with a mass below 3.1 TeV is excluded, given the benchmark model assumption of democratic branching fractions. In addition, limits are set based on generalizations of these assumptions. These are the most sensitive limits to date for this final state.

**KEYWORDS:** Hadron-Hadron Scattering, Vector-Like Quarks, Vector Boson Production, Beyond Standard Model

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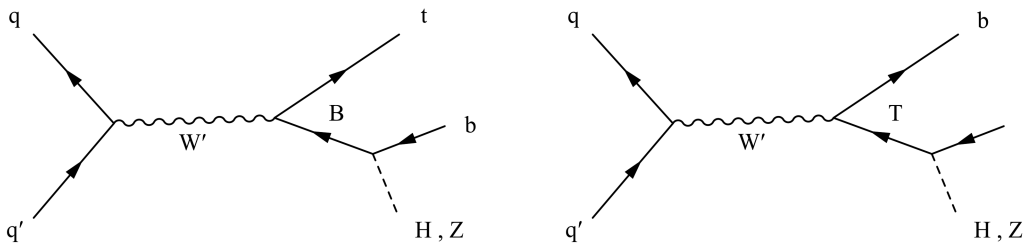
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**1 Introduction**

New massive charged gauge bosons are predicted by various extensions of the standard model (SM) [1–3]. The  $W'$  boson is a hypothetical heavy partner of the SM  $W$  gauge boson that could be produced in proton-proton (pp) collisions at the CERN LHC. Searches for  $W'$  bosons have most recently been performed at a center-of-mass energy of 13 TeV by the CMS and ATLAS collaborations in the lepton-neutrino [4, 5], diboson [6, 7], and diquark [8, 9] final states. The decay of the  $W'$  boson to a heavy B or T vector-like quark (VLQ) and a t or b quark, respectively, is predicted, e.g., in composite Higgs boson models with custodial symmetry protection [10–12]. The VLQs are hypothetical heavy partners of SM quarks that contain left- and right-handed chiralities, which transform identically under the SM gauge groups. These models stabilize the quantum corrections to the Higgs boson mass and preserve naturalness. The  $W'$  branching fraction to a quark and a VLQ depends on the VLQ mass, with a maximum of 50% [13]. Searches for VLQs have been performed by CMS and ATLAS in both the single- [14–18] and pair-production [19–22] channels.

This paper describes a search for the  $W'$  boson in the all-hadronic final state, where the B VLQ decays into a Higgs or Z boson and a b quark, or the T VLQ decays into



**Figure 1.** Dominant Feynman diagrams for the signal model considered.

a Higgs or Z boson and a t quark. The separate studies of the two decay channels are referred to as the tHb analysis and the tZb analysis throughout the paper. Both the B- and T-mediated decays result in the same signature, as shown in figure 1.

Owing to the high  $W'$  boson and VLQ masses considered, the decay products are highly Lorentz boosted, and are combined into large-radius jets with distinct substructure. The challenge is to distinguish between these events and the main background processes, which arise from events comprised of light-quark and gluon jets produced via the strong interaction, referred to as quantum chromodynamics (QCD) multijet events, and t quark pair ( $t\bar{t}$ ) events. These backgrounds are modeled using a combination of Monte Carlo simulation and control regions in data. The invariant mass distribution of the three-jet system ( $m_{tHb}$  or  $m_{tZb}$ ) is used to search for the  $W'$  boson signal. The data correspond to an integrated luminosity of  $138 \text{ fb}^{-1}$  [23–25] of pp collisions at  $\sqrt{s} = 13 \text{ TeV}$ , recorded in the years 2016 to 2018.

We consider a theoretical framework where the t quark and  $W'$  boson are superpositions of elementary and composite modes, with the t quark degree of compositeness given by  $s_L$ , and the mixing angle of the elementary and composite  $W'$  states given by  $\theta_2$  [13]. The  $W'$  boson is assumed to be produced in a Drell-Yan process, with a cross section that is inversely proportional to  $\cot^2(\theta_2)$ . Small values of  $\cot(\theta_2)$  tend to be dominated by the leptonic  $W'$  boson decay mode. Large values of the  $s_L$  parameter increase the relative phase space for the decay into two VLQs, whereas small  $s_L$  values enhance the  $W'$  diboson decays. The analysis assumes this theoretical framework as evaluated at  $s_L = 0.5$  and  $\cot(\theta_2) = 3$ , which is chosen to enhance sensitivity to the single VLQ decay channel of the  $W'$  boson. The expected signal cross sections are evaluated at  $\sqrt{s} = 13 \text{ TeV}$ , considering  $W'$  boson masses in the 1.5 to 5.0 TeV range with the assumption that the  $W' \rightarrow \text{VLQ}$  branching fraction is equally distributed between the tB and tT final states. For the benchmark, the VLQ branching fractions for the decays to qH and qZ are both assumed to be 50%. Additionally, we present generalizations of the relative and total branching fraction assumptions for both the  $W'$  and VLQ decays.

Tabulated results are provided in the HEPData record for this analysis [26].

## 2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid 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 ( $\eta$ ) coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid.

Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about  $4\ \mu\text{s}$  [27]. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [28].

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in ref. [29].

The particle-flow algorithm [30] aims to reconstruct and identify each individual particle with an optimized combination of information from the various elements of the CMS detector. The energy of each photon is obtained from the ECAL measurement. The energy of each electron is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of each muon is obtained from the momentum, which is measured by the curvature of the corresponding track. 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 each neutral hadron is obtained from the corresponding corrected ECAL and HCAL energies that are not associated with a charged hadron track.

Jets are clustered with the anti- $k_T$  algorithm [31] using the FASTJET 3.0 [32] software package with distance parameters of 0.8 (AK8 jets) and 0.4 (AK4 jets). Jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be within 5 to 10% of the true momentum over the entire  $p_T$  spectrum and detector acceptance. Additional pp interactions within the same or nearby bunch crossings (pileup) 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.

The candidate 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 for this determination are the jets, clustered using the jet finding algorithm [31, 32] with the tracks assigned to candidate vertices as inputs, and the associated missing transverse momentum, taken as the negative vector sum of the  $p_T$  of those jets.

To account for the neutral pileup component of the AK8 jets, the pileup per particle identification (PUPPI) algorithm [33] is used, which applies weights that rescale the jet  $p_T$  based on the per-particle probability of originating from the primary vertex prior to jet clustering.

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 determine any residual differences between the jet energy scale (JES) in data and in simulation, and appropriate corrections are made [34]. Additional selection criteria are applied to each jet to remove jets potentially dominated by instrumental effects or reconstruction failures. The jet energy resolution (JER) amounts typically to 15% at 10 GeV, 8% at 100 GeV, and 4% at 1 TeV, to be compared to about 40, 12, and 5% obtained when the calorimeters alone are used for jet clustering.

### 3 Simulated samples

The  $t\bar{t}$  and single t quark production backgrounds are estimated from simulation generated at next-to-leading order with POWHEG 2.0 [35–40]. The signal and QCD background events are generated at leading order using the MADGRAPH5\_AMC@NLO 2.3.3 [41, 42] package. Signal events are generated in the mass range from 1.5 to 5.0 TeV in 0.5 TeV increments. Events are generated using either the NNPDF 3.0 [43] or 3.1 [44] parton distribution functions (PDFs), with parton showering and hadronization simulated with PYTHIA 8.212 [45].

The simulated events are produced with either the CUETP8M2T4 [46], CUETP8M1 [47], or CP5 [48] underlying-event tunes. The CMS detector is simulated using GEANT4 [49]. All simulated events include pileup simulation and are weighted such that the distribution of the number of interactions per bunch crossing agrees with that in data assuming a total inelastic cross section of 69.2 mb.

For each  $W'$  boson mass ( $m_{W'}$ ) point, three characteristic VLQ mass points are generated, corresponding to low ( $1/2 m_{W'}$ ), medium ( $2/3 m_{W'}$ ), and high ( $3/4 m_{W'}$ ) mass ratios, in order to allow the full sensitive phase space of the boosted  $W'$  boson decay products to be explored.

The generated  $W'$  boson and VLQ widths are chosen to be narrow (less than 10%) relative to the experiment resolution, as required by the theoretical predictions for the region of phase space under investigation [13].

### 4 Event reconstruction

The final state is characterized by three high- $p_T$  jets from the decay of the t and b quarks, and from either the Higgs or Z boson. Because the signal of interest corresponds to a high mass resonance decaying to multiple high- $p_T$  jets, data events are triggered by the presence of either a large value of  $H_T$  (the scalar sum of all AK4 jet  $p_T$  in the event), an AK8 jet with a large  $p_T$ , or an AK8 jet with a large jet mass.

The efficiency of the trigger selection is studied using a sample of events that are triggered by at least one high- $p_T$  muon. The fraction of these events that pass the full trigger selection is defined as the trigger efficiency. The offline event selection requires that the  $H_T$  is larger than 1 TeV and the maximum jet mass is larger than 140 GeV, which ensures that the trigger is close to fully efficient. The small inefficiency (less than 1%) due

to the trigger selection is taken into account as an event weight when processing simulated events.

The jets from the t quark (t jet) and from the Higgs or Z boson (Higgs or Z jet) decay tend to be wide, massive, and have a distinct substructure, whereas the jet from the b quark (b jet) tends to be narrower and have a lower mass. Therefore, an AK8 jet with  $p_T > 400$  GeV is required for the Higgs or Z boson candidate, and similarly for the t quark candidate, together with an AK4 jet with  $p_T > 200$  GeV for the b candidate. The angular separation  $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ , where  $\phi$  is the azimuthal angle, between the two AK8 jets is required to be at least 1.6 to reduce the confusion of jet shapes arising from the abutment of jet boundaries, which can bias the background estimate. The AK8 jets are then selected as being consistent with a t quark or a Higgs or Z boson decay using the jet identification (“tagging”) procedures defined below. The jet considered for the b quark candidate is the leading AK4 jet with a  $\Delta R$  of at least 1.2 from the tagged AK8 jets. All jets are required to be within the tracker acceptance ( $|\eta| < 2.4$ ). The high- $p_T$  requirement for the AK8 jets provides a strong reduction in the background for the selection of boosted resonances. However, for the lowest mass  $W'$  boson signal hypothesis considered, it results in a small kinematic acceptance, thus this mass region would also benefit from nonboosted techniques that are beyond the scope of this paper.

#### 4.1 Tagging t jets

For t quarks with  $p_T > 400$  GeV, the decay products, one b quark and two light quarks, can merge into a single AK8 jet. The t quark jets are identified by a novel algorithm designed to separate t jets from jets arising from light quarks and gluons using a deep convolutional neural network called imageTop [50]. The network uses the particle momentum and particle-flow identification category as an analogy to the pixel intensity and color that would be used as inputs to a conventional image-classification algorithm. Additionally, the algorithm includes b tagging information simultaneously in the training in order to identify the b quark from the t quark decay.

The version used in this analysis includes a network that is trained on QCD jets that are drawn from a mass distribution that is constrained to be identical to the top mass distribution, so as to decorrelate the discriminator from the jet mass, and is referred to as the mass-decorrelated imageTop or imageTop<sub>MD</sub>. This analysis is the first application of the imageTop<sub>MD</sub> tagger, which is the most sensitive decorrelated t tagger developed by the CMS collaboration, and the mass decorrelation is valid over a large range of t jet mass and  $p_T$ . This tagger shows an improvement of approximately a factor of six in background rejection at a constant efficiency when compared to the best t quark taggers used previously. The imageTop<sub>MD</sub> tagger is used to select t quark jets at an operating point with  $\approx 60\%$  efficiency and a mistag probability of  $\approx 2\%$  in QCD multijet events.

Owing to the decorrelated nature of the t tagging algorithm, we also apply a selection on the mass of the t jet. The modified mass-drop tagger algorithm [51], also known as the “soft-drop” (SD) algorithm [52], with  $\beta = 0$  and  $z = 0.1$ , is used to calculate the mass variable  $m_{\text{SD}}(t)$  to discriminate between t jets and the typically lighter background jets. This variable is corrected by applying AK4 jet energy corrections to the subjets identified

by the algorithm. For events in the signal region, we require  $140 < m_{\text{SD}}(t) < 220$  GeV, to be consistent with the reconstructed mass of a t quark.

A simulation-to-data scale factor for the t tagging requirement is extracted by fitting the SD mass distribution in a highly enriched sample of SM  $t\bar{t}$  events in data and simulation. This scale factor is applied to correct differences between the top tagging efficiencies for simulated events and data. The scale factor is  $p_T$  dependent with a typical value of  $\approx 0.95$  and does not vary significantly between different running periods.

## 4.2 Tagging Higgs jets

In the case of a highly boosted Higgs boson in the  $b\bar{b}$  decay mode, the decay products tend to merge into a single jet with a mass that is consistent with that of a Higgs boson and contains two b hadron decays. The SD algorithm is used to extract the variable  $m_{\text{SD}}(\text{H})$  as a measure of the jet mass, but in this case, the jet is scaled using a  $p_T$ - and  $\eta$ -dependent correction suitable for two-prong resonances below the t quark mass [53].

To be selected, the jet should fulfill the condition  $105 < m_{\text{SD}}(\text{H}) < 140$  GeV, to be consistent with the reconstructed Higgs boson mass. Scale factors are used for the jet mass scale and resolution (JMS and JMR), which are derived from a fit to the SD mass distribution of the W boson in a sample enriched in lepton+jets  $t\bar{t}$  events using the technique outlined in ref. [54].

To identify the two b hadrons clustered into the merged Higgs jet, a dedicated double-b tagging algorithm (Dbtag) is used at an operating point that has an efficiency of  $\approx 60\%$  and a mistag probability of  $\approx 7\%$  for u, d, s quarks and gluon jets. This algorithm aims to identify two b quarks from the Higgs decay by using variables correlated with b hadron lifetime and mass combined using a boosted decision tree. Data enriched in QCD-produced  $b\bar{b}$  and  $t\bar{t}$  events are used to establish scale factors for Dbtag for signal (which is  $\approx 0.9$ ) and mistagged t quarks, respectively [55].

Figure 2 shows the simulated distributions of discriminants that are used for t and Higgs jet tagging in  $t\bar{t}$ , QCD, and signal for the tHb analysis.

## 4.3 Tagging Z jets

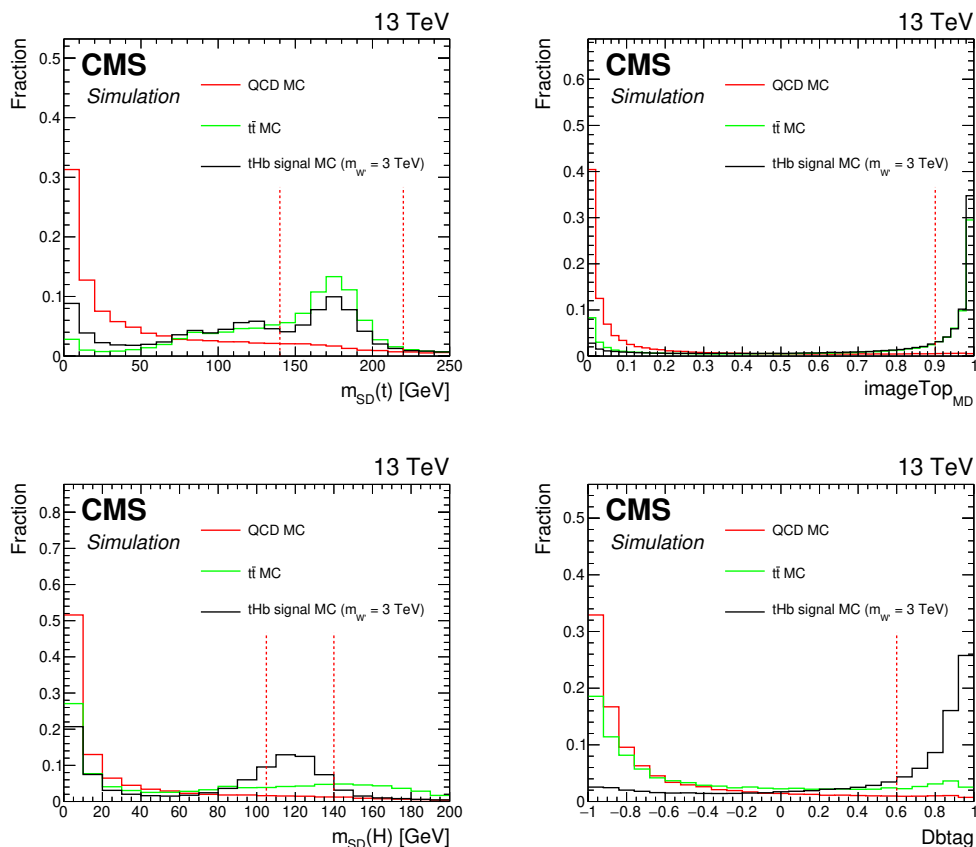
In contrast to the Higgs boson, the Z boson has significant decay branching fractions to all five kinematically accessible quark flavors, so we require a jet energy deposition pattern that is consistent with coming from two hard partons, along with a jet mass that is consistent with a Z boson.

The  $N$ -subjettiness [56] algorithm defines the  $\tau_N$  variable, which quantifies the consistency of the jet energy pattern with the expectation from  $N$  or fewer hard partons. The  $N$ -subjettiness is defined as

$$\tau_N = \frac{1}{d} \sum_i p_{T_i} \min\{\Delta R_{1,i}, \Delta R_{2,i}, \dots, \Delta R_{N,i}\}, \quad (4.1)$$

where the sum is over jet constituents. The  $\tau_N$  discriminant is bound between zero and one, with low values being more consistent with  $N$  or fewer partons. For a Z boson hadronic decay, the ratio of  $\tau_2$  to  $\tau_1$  ( $\tau_{21}$ ) is used at an operating point of  $\approx 85\%$  efficiency





**Figure 2.** Simulated distributions of the discriminating variables for  $t\bar{t}$ , QCD, and tHb signal simulated events normalized to unity for the tHb analysis. Discriminant thresholds are shown as vertical dashed lines.

and a mistag probability of  $\approx 20\%$  in QCD multijet events. Scale factors used for the  $N$ -subjettiness selection are derived simultaneously with those for the JMS and JMR as discussed in section 4.2, and have a value of  $\approx 0.98$ .

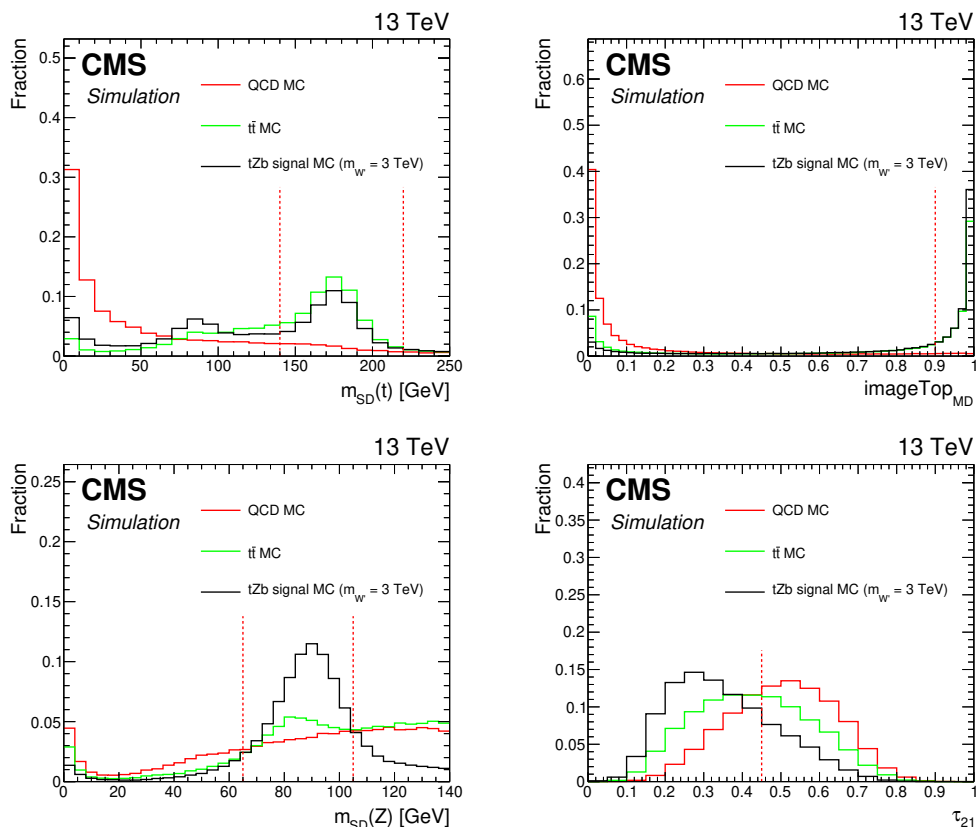
The  $m_{SD}(Z)$  is required to be within the range  $65 < m_{SD}(Z) < 105$  GeV, to be consistent with the mass of a  $Z$  boson.

Figure 3 shows the distributions of discriminants that are used for  $t$  and  $Z$  jet tagging in  $t\bar{t}$ , QCD, and signal simulation for the  $tZb$  analysis.

#### 4.4 Tagging b jets

The  $b$  quark from the VLQ or  $W'$  boson decay is reconstructed as an AK4 jet that is required to pass the DEEPJET  $b$  tagging algorithm [57, 58] at an operating point defined by a 1% light-quark and gluon misidentification probability, approximately 10%  $c$  quark misidentification probability, and approximately 80%  $b$  quark efficiency. A simulation-to-data scale factor for the  $b$  tagging requirement is used to improve the agreement between data and simulation and has a value of  $\approx 0.95$ .





**Figure 3.** Simulated distributions of the discriminating variables for  $t\bar{t}$ , QCD, and  $tZb$  signal simulated events normalized to unity for the  $tZb$  analysis. Discriminant thresholds are shown as vertical dashed lines.

### 4.5 Event selection

We categorize events into selection regions that are either used to search for the  $W'$  boson signal, predict the background in the signal region, or validate this background estimate. Event selection details are presented in table 1. The signal region is required to contain a tight  $t$  jet, a Higgs or  $Z$  jet, and a  $b$  jet. Regions used for background estimation and validation require combinations of loosened tagger criteria.

The sensitivity of the selections has been studied both in the context of the expected cross section upper limit and of the  $W'$  boson discovery potential. After identifying the  $t$ , Higgs or  $Z$ , and  $b$  jets, the  $W'$  boson candidate mass is taken as the invariant mass of the three jets. Table 2 shows the signal efficiency for all samples considered.

## 5 Background estimation

The primary background is from QCD multijet production and is estimated from data. For this estimate, we use control regions that are selected with identical kinematic criteria to the signal region, but with a reduced acceptance for signal events. Table 1 and figure 4 define various selection regions. A transfer function  $TF(p_T, \eta)$  is extracted from data by

Label	Tag	Discriminant	Mass
Tight	H	$0.6 < \text{Dbtag}$	$105 < m_{\text{SD}}(\text{H}) < 140 \text{ GeV}$
	Z	$\tau_{21} < 0.45$	$65 < m_{\text{SD}}(\text{Z}) < 105 \text{ GeV}$
	t	$0.9 < \text{imageTop}_{\text{MD}}$	$140 < m_{\text{SD}}(\text{t}) < 220 \text{ GeV}$
Medium	H	$0 < \text{Dbtag} < 0.6$	$105 < m_{\text{SD}}(\text{H}) < 140 \text{ GeV}$
	Z	$0.45 < \tau_{21} < 0.6$	$65 < m_{\text{SD}}(\text{Z}) < 105 \text{ GeV}$
	t	$0.3 < \text{imageTop}_{\text{MD}} < 0.9$	$140 < m_{\text{SD}}(\text{t}) < 220 \text{ GeV}$
Inverted	H	$-1 < \text{Dbtag} < 0$	$5 < m_{\text{SD}}(\text{H}) < 30 \text{ GeV}$
	Z	$0.6 < \tau_{21} < 1$	$5 < m_{\text{SD}}(\text{Z}) < 30 \text{ GeV}$
	t	$0 < \text{imageTop}_{\text{MD}} < 0.3$	$30 < m_{\text{SD}}(\text{t}) < 65 \text{ GeV}$

**Table 1.** Selection regions used for signal identification and background estimation. The AK8 jet discriminant and mass selections are explicitly defined here for the t, Higgs, and Z jet tags.

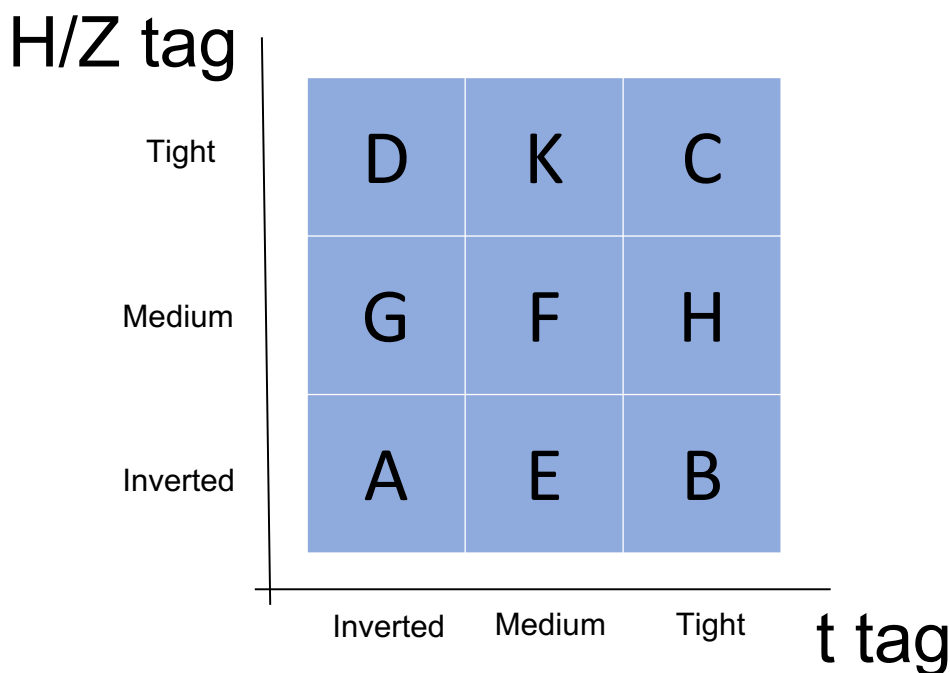
$m_{W'}(\text{GeV})$	tHb low	tHb medium	tHb high	tZb low	tZb medium	tZb high
1500	0.29	0.34	0.28	0.43	0.51	0.39
2000	1.2	1.4	0.78	1.7	1.9	1.1
2500	2.0	1.9	1.3	2.8	2.7	1.8
3000	2.3	2.2	1.8	2.7	3.0	2.5
3500	2.3	2.2	1.8	3.2	3.0	2.5
4000	2.2	2.0	1.8	3.1	2.9	2.6
4500	2.0	1.9	1.7	2.8	2.7	2.5
5000	1.8	1.7	1.5	2.6	2.5	2.4

**Table 2.** The signal efficiency (in percent) for the three VLQ mass ranges considered. The efficiency is given for the tHb and tZb final states, separated into the low, medium, and high VLQ mass categories.

inverting the Higgs or Z jet candidate selection. After this inversion,  $\text{TF}(p_T, \eta)$  is defined as the ratio of the jet  $p_T$  spectrum of the t candidate in the case that it passes (region B) to the case that it fails (region A) the t tagging algorithm. The  $\text{TF}(p_T, \eta)$  is extracted in two  $\eta$  ranges (central,  $|\eta| < 1.2$ , and forward,  $|\eta| > 1.2$ , regions).

The  $\text{TF}(p_T, \eta)$  distribution is used to predict the background in the signal region. This is accomplished by defining the control region D, which has identical Higgs or Z and b jet candidate selections to the signal region, but with an inverted t jet selection. Events that pass the region D selection use  $\text{TF}(p_T, \eta)$  as an event weight in a given t-candidate jet ( $p_T, \eta$ ) bin. These weighted events are then used to provide the QCD background estimate in the signal region. The primary assumption for this background estimate method is that the t jet substructure selection can be inverted without significantly biasing the Higgs or Z jet substructure selection.

In the  $\text{TF}(p_T, \eta)$  extraction procedure, the  $t\bar{t}$  production component derived from simulation is subtracted from data to ensure that  $\text{TF}(p_T, \eta)$  refers only to the QCD component.



**Figure 4.** Diagram showing the regions used for background estimation. The signal region is C, the regions A and B are used to determine  $TF(p_T, \eta)$ , and F, K, and H are validation regions. The  $x$  axis indicates the  $t$  tag category, and the  $y$  axis represents the Higgs or Z boson tag category. The inverted, medium, and tight tag category definitions are given in table 1.

Additionally, the  $t\bar{t}$  contamination of the QCD background estimate in the signal region must be subtracted. This is performed by applying the QCD background estimation procedure to simulated  $t\bar{t}$  events using the same  $TF(p_T, \eta)$  as is used when extracting the QCD estimate from data. The following relations are used to extract the QCD component of the signal region:

$$\begin{aligned}
 TF(p_T, \eta) &\equiv (B_{\text{data}} - B_{t\bar{t}})/(A_{\text{data}} - A_{t\bar{t}}), \\
 C_{\text{QCD}} &\simeq (D_{\text{data}} - D_{t\bar{t}}) TF(p_T, \eta).
 \end{aligned}
 \tag{5.1}$$

Here, the subscripts “data” and “ $t\bar{t}$ ” indicate that the distributions are obtained from data and  $t\bar{t}$  events, respectively.

To test the validity of the background estimate in data, a series of “validation” regions are defined (F, K, and H, as defined in figure 4). The transfer function used for predicting the background in the K and F regions ( $TF_v(p_T, \eta)$ ) is estimated from the ratio of regions E to A, whereas the transfer function for the H region is the same as for the signal region. The following relations are used to extract the QCD background component of the validation regions:

$$\begin{aligned}
 TF_v(p_T, \eta) &\equiv (E_{\text{data}} - E_{t\bar{t}})/(A_{\text{data}} - A_{t\bar{t}}), \\
 H_{\text{QCD}} &\simeq (G_{\text{data}} - G_{t\bar{t}}) TF(p_T, \eta),
 \end{aligned}$$

$$\begin{aligned}
 K_{\text{QCD}} &\simeq (D_{\text{data}} - D_{\text{t}\bar{\text{t}}}) \text{TF}_v(p_{\text{T}}, \eta), \\
 F_{\text{QCD}} &\simeq (G_{\text{data}} - G_{\text{t}\bar{\text{t}}}) \text{TF}_v(p_{\text{T}}, \eta).
 \end{aligned}
 \tag{5.2}$$

The background validation tests in the F, K, and H regions are shown in figure 5. These validation regions confirm the background estimate agreement with  $\chi^2/\text{ndf}$  values of 1.7, 1.0, and 1.3, respectively for the combined fit which considers systematic uncertainties (as discussed in section 6), where ndf is the number of degrees of freedom. The  $\text{t}\bar{\text{t}}$  background component in these validation regions is subtracted using the same procedure that is used when performing the signal region background estimate. The agreement demonstrates that the t jet selection can be inverted without biasing the Higgs jet selection. Figure 5 also shows for comparison the distributions expected from a potential signal for several  $W'$  mass values, assuming the medium VLQ mass hypothesis. The corresponding distributions for the low and high VLQ mass values have shapes that are similar to these, differing mainly in the normalization.

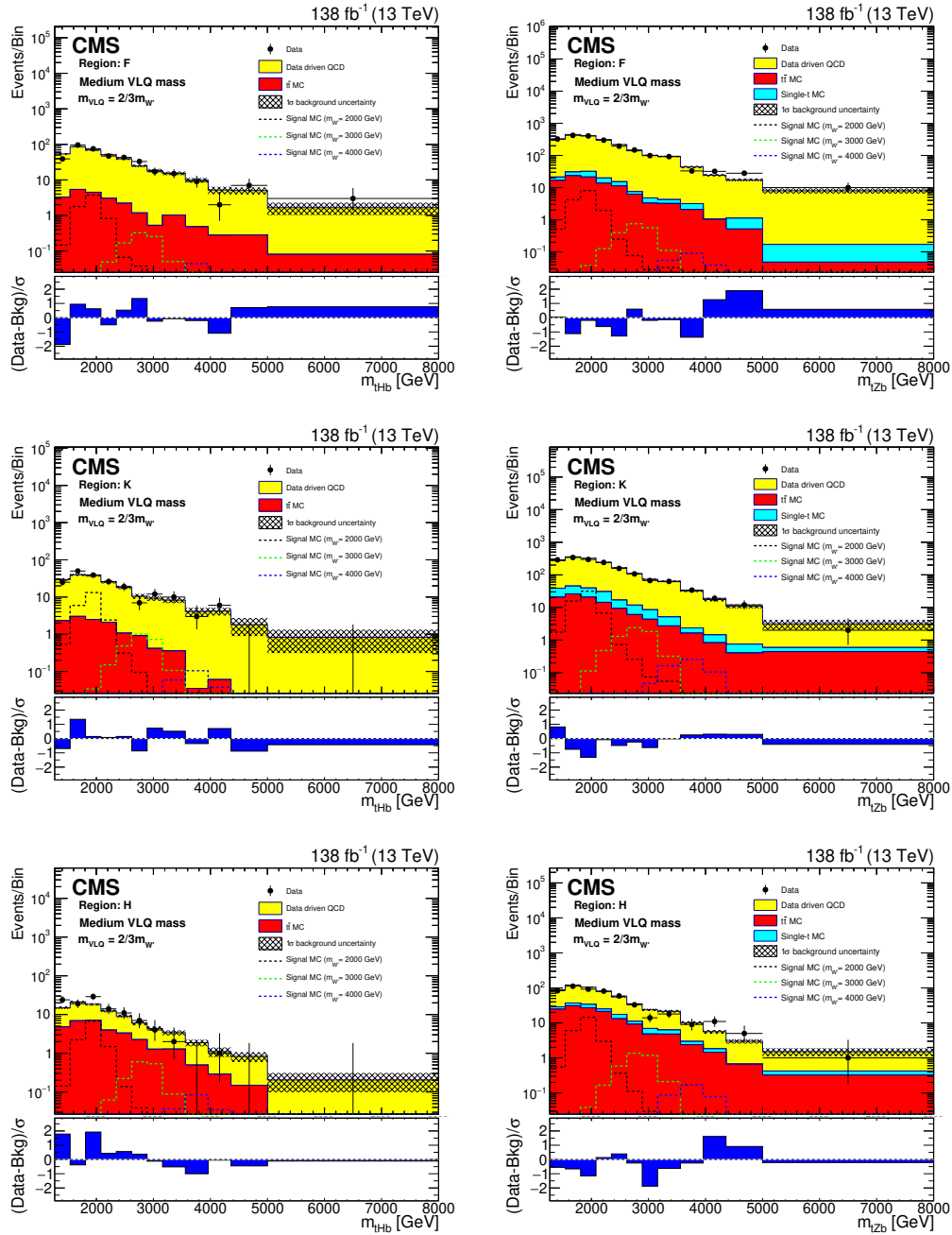
The  $\text{t}\bar{\text{t}}$  background component is estimated using simulated events with an additional event weight that corrects the generator t jet  $p_{\text{T}}$  distribution [59]. This correction reduces the disagreement between simulation and data due to a known generator-level mismodeling effect and is validated using a  $\text{t}\bar{\text{t}}$  control region. The final state for this control region contains two boosted AK8 t jets, so the selections on the AK4 b jet are loosened, and both of the AK8 jets are required to pass the same  $\text{imageTop}_{\text{MD}}$  selection as the signal region. After this selection, the composition is a nearly pure (approximately 99%) sample of hadronic  $\text{t}\bar{\text{t}}$  events, demonstrating the discrimination power of the  $\text{imageTop}_{\text{MD}}$  tagger. The QCD background estimate in this control region is performed in an analogous way to the signal region, and is estimated by weighting events with one inverted and one tight t tag by  $\text{TF}(p_{\text{T}}, \eta)$ . This control region is used to extract an additional correction, which is taken as a simple ratio of QCD-subtracted data to the  $\text{t}\bar{\text{t}}$  simulation estimate. The uncertainty in this procedure is taken as the uncorrelated combination of the statistical uncertainty in the ratio, 100% of the QCD estimate, and the t tag scale factor uncertainty. This correction is applied to all simulated  $\text{t}\bar{\text{t}}$  distributions.

## 6 Systematic uncertainties

A wide range of systematic uncertainties are considered, and organized into those that impact only the event yields, which are assumed to follow log-normal distributions [60], and those that affect the shape of the three-jet invariant mass distribution as well, which are assumed to follow Gaussian distributions. All of the systematic uncertainties are summarized in table 3.

### 6.1 Normalization uncertainties

The uncertainty in the integrated luminosity is taken as 1.2% for 2016, 2.3% for 2017, and 2.5% for 2018 data [23–25].



**Figure 5.** Background closure test for the reconstructed  $W'$  boson invariant mass in region F (upper), K (middle), and H (lower) for the purpose of validation in the  $tHb$  (left) and  $tZb$  (right) analyses. The data are shown as points with error bars and the estimated backgrounds as solid histograms after a background-only fit, with a hatched band indicating the uncertainty. Expected signals for several  $W'$  boson mass hypotheses are shown. The lower panel of each plot shows the difference between the number of events observed in the data and the predicted background, divided by the total uncertainty in the background and the statistical uncertainty in the data added in quadrature.

Source	Variation	Process
Integrated luminosity	$\pm 1.2\text{--}2.5\%$	signal, $t\bar{t}$ , single t
$t\bar{t}$ normalization	$\pm 11\text{--}15\%$	$t\bar{t}$
JES	$\pm 1\sigma(p_T, \eta)$	signal, $t\bar{t}$ , single t
JER	$\pm 1\sigma(p_T, \eta)$	signal, $t\bar{t}$ , single t
JMS	$\pm 1\sigma(m_{SD})$	signal, $t\bar{t}$ , single t
JMR	$\pm 1\sigma(m_{SD})$	signal, $t\bar{t}$ , single t
Z jet tagging	$\pm 1\sigma(p_T)$	signal
b tagging	$\pm 1\sigma(p_T)$	signal, $t\bar{t}$ , single t
b mistagging	$\pm 1\sigma(p_T)$	signal, $t\bar{t}$ , single t
Dbtag tagging	$\pm 1\sigma(p_T)$	signal
Dbtag mistagging	$\pm 1\sigma(p_T)$	signal, $t\bar{t}$ , single t
t jet tagging	$\pm 1\sigma(p_T)$	signal, $t\bar{t}$ , single t
Trigger	$\pm 1\sigma(H_T)$	signal, $t\bar{t}$ , single t
Pileup	$\pm 1\sigma$	signal, $t\bar{t}$ , single t
PDF, $\alpha_s$	$\pm 1\sigma$	signal, single t
$\mu_R$ and $\mu_F$	$\pm 1\sigma$	signal, single t
ISR/FSR	$\pm 1\sigma$	single t
TF( $p_T, \eta$ )	$\pm 1\sigma(p_T, \eta)$	QCD
$t\bar{t}$ contamination	$\pm 1\sigma(p_T, \eta)$	QCD

**Table 3.** Sources of systematic uncertainty that affect the final distributions. Sources that affect the normalization only are represented by a range of values for the systematic variation. Sources listing the systematic variation as  $\pm 1\sigma(x)$  affect the shape of the three-jet invariant mass distribution as well, which is dependent on  $x$ .

The uncertainty in the  $t\bar{t}$  normalization measurement (as discussed in section 5) used to correct the estimate in the signal region accounts for the full uncertainty in the  $t\bar{t}$  yield. It is calculated separately for data collected in 2016, 2017, and 2018, and ranges from 11 to 15%. This is considered a measurement of  $t\bar{t}$  uncertainties that have a large normalization effect, including top  $p_T$  reweighting, PDF, and renormalization and factorization ( $\mu_R$  and  $\mu_F$ ) scale uncertainties. Uncertainties that have a pronounced shape effect on the invariant mass distribution are included separately when setting limits (as shown in table 3).

## 6.2 Shape uncertainties

The uncertainty in the JES is taken into account by varying the JES within its uncertainty and observing the effect on the invariant mass distribution. The JES variation impacts the invariant mass distribution shape through a horizontal shift but also causes a normalization difference when the jet falls above or below a kinematic threshold. This uncertainty is propagated to the t jet  $m_{SD}(t)$  estimate. The uncertainty in the JER is also taken into account by the uncertainty in the JER correction used for simulated events. This uncertainty is applied to all simulated events and has only a small impact on the final limit.

The uncertainty in the JMS and JMR is measured in a highly enriched sample of  $t\bar{t}$  events containing one final-state lepton. In this sample, a fit is performed to the W boson PUPPI  $m_{\text{SD}}$  distribution, from which the mean and width are extracted. The JMS uncertainty is estimated from the uncertainty in the shift of the W mass peak, and the uncertainty in the JMR is estimated from the uncertainty in the width. These uncertainties are applied to the Higgs or Z boson  $m_{\text{SD}}$  estimates for all simulated events and have an  $\approx 4\%$  effect on the signal estimate.

The uncertainty in the  $\tau_{21}$  selection associated with Z jet tagging includes a constant uncertainty and a  $p_{\text{T}}$ -dependent uncertainty based on an extrapolation to momenta beyond the kinematic region of the scale factor measurement. This uncertainty is applied to all simulated events and has an  $\approx 15\%$  effect.

The uncertainty used for the b tagging requirement on the AK4 jet is evaluated by varying the b tagging and b mistagging scale factors within their uncertainties [55]. These uncertainty sources are considered uncorrelated and are applied to all simulated events and result in an  $\approx 5\%$  effect on the signal estimate.

The uncertainty in the Dbtag method used for the Higgs jet tagging [55] selection is evaluated by varying the Dbtag scale factor by the uncertainty. The scale factor is parameterized using three regions in  $p_{\text{T}}$ . Also evaluated is the scale factor for a Higgs boson that is mistagged as a t quark (as discussed in section 4). The uncertainties in both the Higgs jet tagging efficiency and the mistag probability are applied to all simulated events and are treated as uncorrelated during limit setting. The Higgs boson Dbtag uncertainty has an  $\approx 10\%$  effect on the signal estimate.

The uncertainty in the imageTop<sub>MD</sub> selection used for t tagging is  $p_{\text{T}}$  dependent and evaluated by varying the imageTop<sub>MD</sub> scale factor within the uncertainty. This has an  $\approx 6\%$  effect on the signal estimate.

The kinematic requirements ensure that the trigger is close to being fully efficient, and all simulated events are corrected using the method outlined in section 4. The uncertainty in this correction is taken to be half of the trigger inefficiency. This uncertainty is small and is applied to all simulated events.

As mentioned in section 3, the simulated pileup distribution is reweighted to match data using an effective total inelastic cross section. The uncertainty in this procedure is evaluated by varying the total inelastic cross section by  $\pm 4.6\%$  [61]. The resultant uncertainty is applied to all simulated events and has only a small impact on the final limit.

The PDF uncertainty is evaluated using the NNPDF3.1 [43, 44] set for the signal, and the PDF4LHC15 combined set [62, 63] for single t quark events. The uncertainty is calculated using the symmetric Hessian approach.

The uncertainty in the  $\mu_{\text{R}}$  and  $\mu_{\text{F}}$  scales are evaluated by varying the  $\mu_{\text{R}}$  or  $\mu_{\text{F}}$  scales up and down by a factor of two. Both independent and simultaneous variations of  $\mu_{\text{R}}$  and  $\mu_{\text{F}}$  are considered, resulting in six weights after excluding the two most extreme variations. The envelope of these weights is used as the uncertainty. The  $\mu_{\text{R}}$ ,  $\mu_{\text{F}}$ , and PDF uncertainties are taken as the signal cross section theoretical uncertainty. For the single t quark prediction, these uncertainties are considered when setting limits in addition to the parton shower variation in the initial- and final-state radiation (ISR and FSR). Together, the effect of



these theoretical uncertainties amount to  $\approx 65\%$ , and dominate the total uncertainty in the single top quark estimate.

The primary uncertainty in the shape of the QCD background estimate is taken from the statistical uncertainty in the  $\text{TF}(p_T, \eta)$ . This is propagated to the invariant mass spectrum by evaluating the  $\text{TF}(p_T, \eta)$  weight at  $\pm 1\sigma$  in a given  $(p_T, \eta)$  bin. The uncertainty from each  $\text{TF}(p_T, \eta)$  bin is added in quadrature to form the full uncertainty, and the effect on the QCD background estimate is  $\approx 20\%$ . The effect of the uncertainty in the  $t\bar{t}$  subtraction procedure is evaluated by varying the amount subtracted within the range of the  $t\bar{t}$  normalization uncertainty. The effect on the QCD background estimate is  $\approx 6\%$ .

The statistical uncertainty of the simulation is taken into account during limit setting by using the ‘‘Barlow-Beeston lite’’ method [64].

## 7 Results

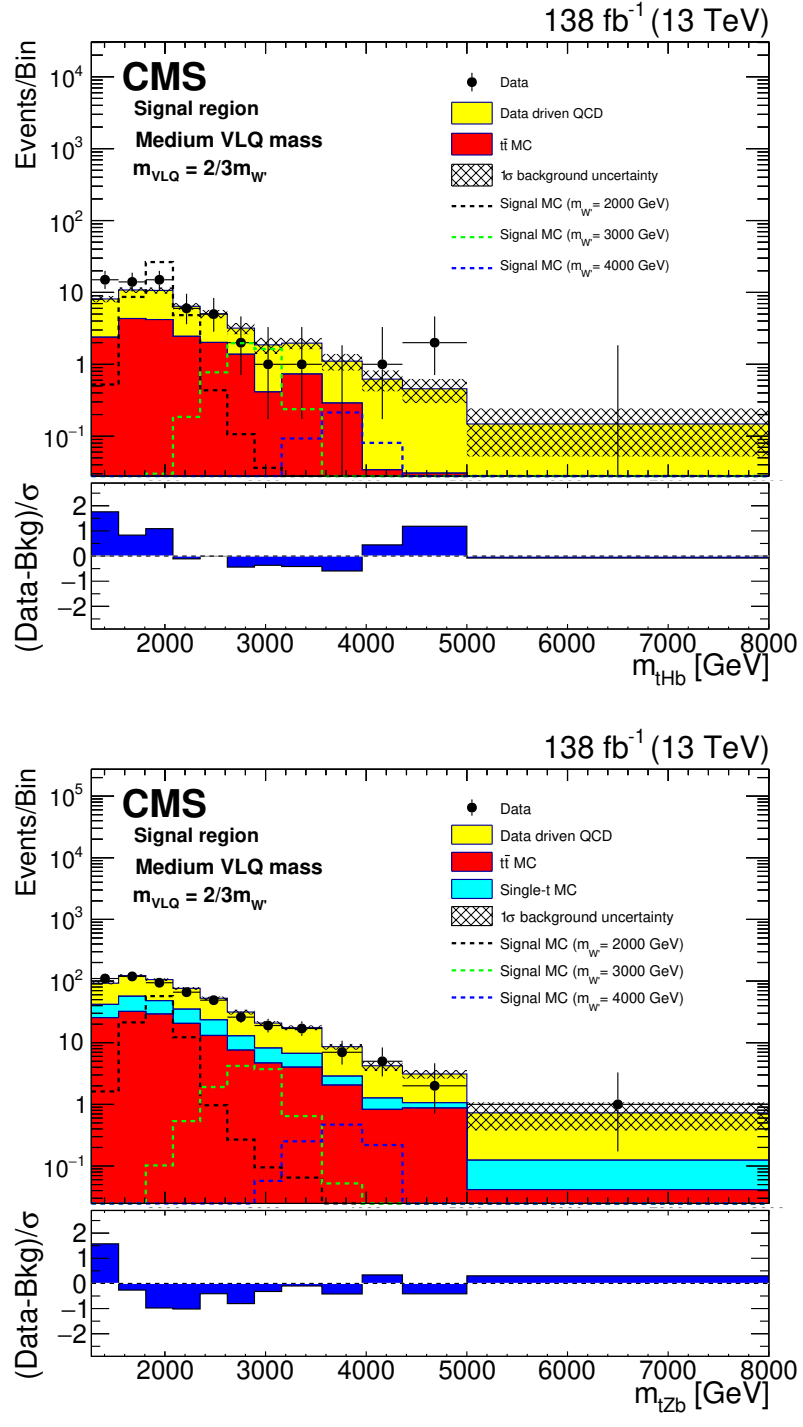
The final distributions of reconstructed  $m_{W'}$  for the signal region are shown in figure 6. The distributions expected from a potential signal for several  $W'$  mass values, assuming the medium VLQ mass hypothesis, are shown for comparison. Since no deviation from the SM expectation is observed, we place limits on the  $W'$  boson production cross section.

The 95% confidence level (CL) upper limits are obtained using the  $\text{CL}_s$  approach [65, 66] in the asymptotic approximation [67] on the product of the  $W'$  boson production cross section for the  $s_L = 0.5$  and  $\cot(\theta_2) = 3$  hypothesis [13], and for the benchmark branching fraction. A binned maximum likelihood fit to the data is used to calculate upper limits, in a process where all systematic uncertainties are included as nuisance parameters. For the signal template, the sum of the invariant mass distributions from the  $tB$  and  $bT$  decay channels are used. Upper limits on the product of cross section and branching fraction are shown in figure 7. A  $W'$  boson with a mass below 3.1 TeV is excluded at 95% CL for the medium VLQ mass case. The low and high VLQ mass benchmarks have a lower  $W' \rightarrow \text{VLQ}$  branching fraction, and the sensitivity is not sufficient to set mass exclusion limits.

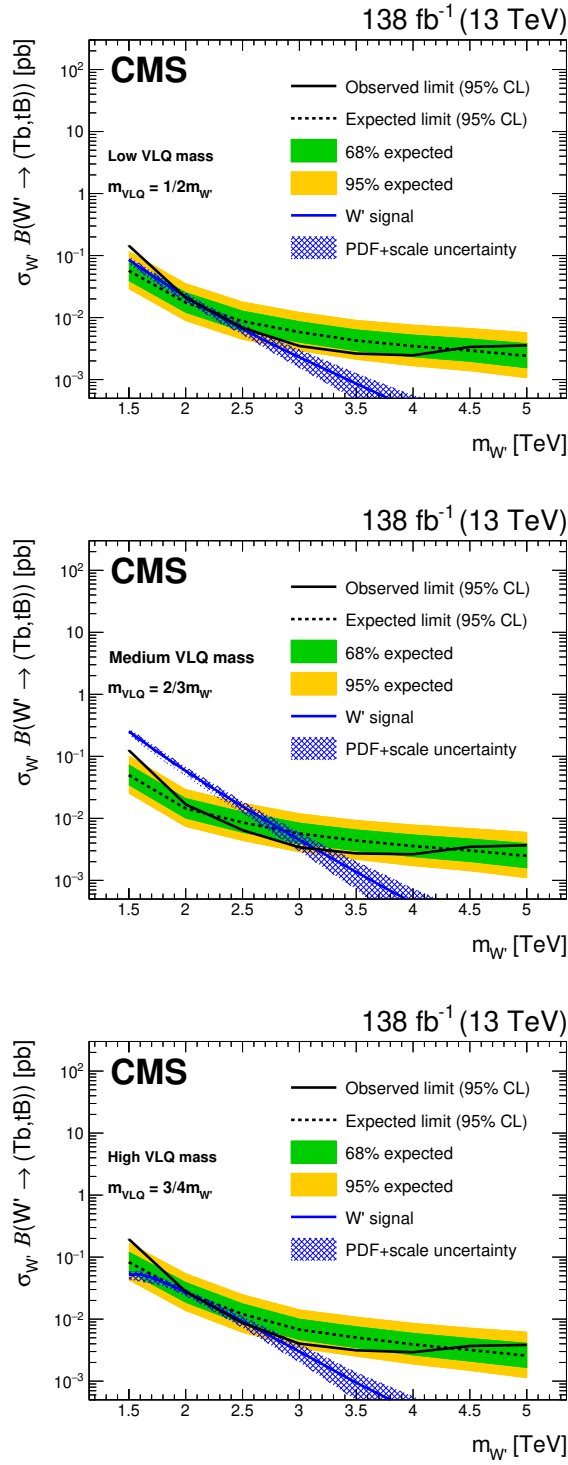
Variations of the primary assumptions of this benchmark are shown in figure 8 for the purpose of generalizing the results. Specifically, the fraction of  $bT$  and  $tB$  from the  $W'$  decay is varied between 0 and 1, and the VLQ branching fractions to  $qH$  and  $qZ$  are varied within the same bounds. Therefore, for both generalized coupling figures, the mass exclusion of the benchmark model corresponds to the point with coordinates  $[0.5, 0.5]$ , indicated with an asterisk.

## 8 Summary

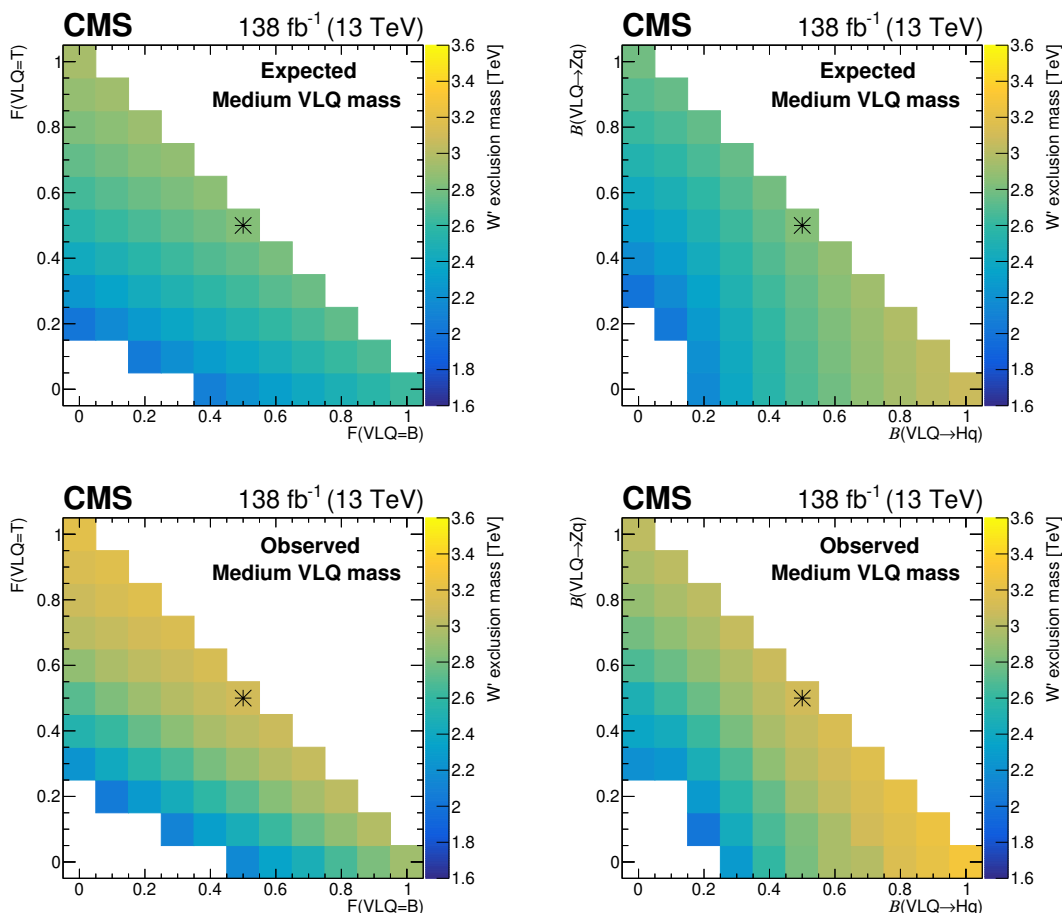
A search has been presented for a heavy  $W'$  boson decaying to a B or T vector-like quark and a t or b quark, respectively. The data correspond to an integrated luminosity of  $138 \text{ fb}^{-1}$  collected between 2016 and 2018 with the CMS detector at the LHC in proton-proton collisions at  $\sqrt{s} = 13 \text{ TeV}$ . The signature considered for both decay modes is a t quark and a Higgs or Z boson, each decaying hadronically, and a b quark jet. Boosted heavy-resonance identification techniques are used to select the events containing three



**Figure 6.** Reconstructed  $m_{W'}$  distributions ( $m_{tHb}$  (upper), and  $m_{tZb}$  (lower)) in the signal region with estimated backgrounds and signal for several  $W'$  boson mass hypotheses, after a background-only fit. The combined statistical and systematic uncertainty in the total estimated background is indicated by the hatched region. The lower panels show the difference between the number of events observed in the data and the predicted background, divided by the total uncertainty in the background and the statistical uncertainty in the data added in quadrature.



**Figure 7.** The  $W'$  boson 95% CL limits on the product of cross section and branching fraction. The expected (dashed) and observed (solid) limits, as well as the  $W'$  boson theoretical cross section, with its PDF and scale normalization uncertainties, are shown. The green (inner) and yellow (outer) bands indicate the 68% and 95% confidence intervals of the expected limit. The limits are given for the low (upper), medium (center), and high (lower) VLQ mass ranges.



**Figure 8.** Expected (upper) and observed (lower) 95% CL limits for generalized hypotheses varying the fraction of  $tB$  ( $F(\text{VLQ}=B)$ ) and  $bT$  ( $F(\text{VLQ}=T)$ ) from the  $W'$  decay (left), and the VLQ branching fraction to  $qH$  and  $qZ$  (right). The asterisk marker signifies the branching fractions for the benchmark model.

energetic jets and to suppress standard model backgrounds. No significant deviation from the standard model background prediction is observed. Upper limits are placed on the product of the  $W'$  boson cross section and the final state branching fraction as a function of the  $m_{W'}$ . A  $W'$  boson with a mass below 3.1 TeV is excluded at 95% confidence level, given the benchmark model assumption of democratic branching fractions. In addition, limits are set based on generalizations of these assumptions. These are the most sensitive limits to date for this final state.

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## The CMS collaboration

### Yerevan Physics Institute, Yerevan, Armenia

A. Tumasyan

### Institut für Hochenergiephysik, Vienna, Austria

W. Adam , J.W. Andrejkovic, T. Bergauer , S. Chatterjee , M. Dragicevic , A. Escalante Del Valle , R. Frühwirth<sup>1</sup>, M. Jeitler<sup>1</sup> , N. Krammer, L. Lechner , D. Liko, I. Mikulec, P. Paulitsch, F.M. Pitters, J. Schieck<sup>1</sup> , R. Schöfbeck , D. Schwarz, S. Templ , W. Waltenberger , C.-E. Wulz<sup>1</sup> 











### Institute for Nuclear Problems, Minsk, Belarus

V. Chekhovsky, A. Litomin, V. Makarenko 












### Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish<sup>2</sup>, E.A. De Wolf, T. Janssen , T. Kello<sup>3</sup>, A. Lelek , H. Rejeb Sfar, P. Van Mechelen , S. Van Putte, N. Van Remortel 






### Vrije Universiteit Brussel, Brussel, Belgium

F. Blekman , E.S. Bols , J. D'Hondt , M. Delcourt, H. El Faham , S. Lowette , S. Moortgat , A. Morton , D. Müller , A.R. Sahasransu , S. Tavernier , W. Van Doninck, P. Van Mulders













### Université Libre de Bruxelles, Bruxelles, Belgium

D. Beghin, B. Bilin , B. Clerbaux , G. De Lentdecker, L. Favart , A. Grebenyuk, A.K. Kalsi , K. Lee, M. Mahdavihorrani, I. Makarenko , L. Moureaux , L. Pétrel, A. Popov , N. Postiau, E. Starling , L. Thomas , M. Vanden Bemden, C. Vander Velde , P. Vanlaer , L. Wezenbeek

### Ghent University, Ghent, Belgium

T. Cornelis , D. Dobur, J. Knolle , L. Lambrecht, G. Mestdach, M. Niedziela , C. Roskas, A. Samalan, K. Skovpen , M. Tytgat , B. Vermassen, M. Vit















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

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






### Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G.A. Alves , C. Hensel, A. Moraes 


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

W.L. Aldá Júnior , M. Alves Gallo Pereira , M. Barroso Ferreira Filho, H. Brando Malbouisson, W. Carvalho , J. Chinellato<sup>4</sup>, E.M. Da Costa , G.G. Da Silveira<sup>5</sup> , D. De Jesus Damiao , S. Fonseca De Souza , D. Matos Figueiredo, C. Mora Herrera , K. Mota Amarilo, L. Mundim , H. Nogima, P. Rebello Teles , A. Santoro, S.M. Silva Do Amaral , A. Sznajder , M. Thiel, F. Torres Da Silva De Araujo , A. Vilela Pereira 

**Universidade Estadual Paulista (a), Universidade Federal do ABC (b), São Paulo, Brazil**

C.A. Bernardes<sup>5</sup> , L. Calligaris , T.R. Fernandez Perez Tomei , E.M. Gregores , D.S. Lemos , P.G. Mercadante , S.F. Novaes , Sandra S. Padula 


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

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





**University of Sofia, Sofia, Bulgaria**

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














**Beihang University, Beijing, China**

T. Cheng , T. Javaid<sup>6</sup>, M. Mittal, L. Yuan





**Department of Physics, Tsinghua University, Beijing, China**

M. Ahmad , G. Bauer, C. Dozen<sup>7</sup> , Z. Hu , J. Martins<sup>8</sup> , Y. Wang, K. Yi<sup>9,10</sup>


**Institute of High Energy Physics, Beijing, China**

E. Chapon , G.M. Chen<sup>6</sup> , H.S. Chen<sup>6</sup> , M. Chen , F. Iemmi, A. Kapoor , D. Leggat, H. Liao, Z.-A. Liu<sup>6</sup> , V. Milosevic , F. Monti , R. Sharma , J. Tao , J. Thomas-Wilsker, J. Wang , H. Zhang , J. Zhao 

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

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

**Sun Yat-Sen University, Guangzhou, China**

M. Lu, Z. You 

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

X. Gao<sup>3</sup>, H. Okawa 



**Zhejiang University, Hangzhou, China, Zhejiang, China**

Z. Lin , M. Xiao 

**Universidad de Los Andes, Bogota, Colombia**












C. Avila , A. Cabrera , C. Florez , J. Fraga

**Universidad de Antioquia, Medellin, Colombia**


























J. Mejia Guisao, F. Ramirez, J.D. Ruiz Alvarez , C.A. Salazar González 

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














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

**University of Split, Faculty of Science, Split, Croatia**Z. Antunovic, M. Kovac, T. Sculac **Institute Rudjer Boskovic, Zagreb, Croatia**V. Brigljevic , D. Ferencek , D. Majumder , M. Roguljic, A. Starodumov<sup>11</sup> , T. Susa **University of Cyprus, Nicosia, Cyprus**A. Attikis , K. Christoforou, E. Erodotou, A. Ioannou, G. Kole , M. Kolosova, S. Konstantinou, J. Mousa , C. Nicolaou, F. Ptochos , P.A. Razis, H. Rykaczewski, H. Saka **Charles University, Prague, Czech Republic**M. Finger<sup>12</sup>, M. Finger Jr.<sup>12</sup> , A. Kveton**Escuela Politecnica Nacional, Quito, Ecuador**






E. Ayala

**Universidad San Francisco de Quito, Quito, Ecuador**E. Carrera Jarrin **Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt**H. Abdalla<sup>13</sup> , S. Khalil<sup>14</sup> **Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt**A. Lotfy , M.A. Mahmoud **National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**S. Bhowmik , R.K. Dewanjee , K. Ehataht, M. Kadastik, S. Nandan, C. Nielsen, J. Pata, M. Raidal , L. Tani, C. Veelken**Department of Physics, University of Helsinki, Helsinki, Finland**P. Eerola , L. Forthomme , H. Kirschenmann , K. Osterberg , M. Voutilainen **Helsinki Institute of Physics, Helsinki, Finland**S. Bharthuar, E. Brücken , F. Garcia , J. Havukainen , M.S. Kim , R. Kinnunen, T. Lampén, K. Lassila-Perini , S. Lehti , T. Lindén, M. Lotti, L. Martikainen, M. Myllymäki, J. Ott , H. Siikonen, E. Tuominen , J. Tuominiemi**Lappeenranta University of Technology, Lappeenranta, Finland**P. Luukka , H. Petrow, T. Tuuva**IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France**C. Amendola , M. Besancon, F. Couderc , M. Dejardin, D. Denegri, J.L. Faure, F. Ferri , S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault , P. Jarry, B. Lenzi , E. Locci, J. Malcles, J. Rander, A. Rosowsky , M.Ö. Sahin , A. Savoy-Navarro<sup>15</sup>, M. Titov , G.B. Yu 













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

S. Ahuja , F. Beaudette , M. Bonanomi , A. Buchot Perraguin, P. Busson, A. Cappati, C. Charlot, O. Davignon, B. Diab, G. Falmagne , S. Ghosh, R. Granier de Cassagnac , A. Hakimi, I. Kucher , J. Motta, M. Nguyen , C. Ochando , P. Paganini , J. Rembser, R. Salerno , J.B. Sauvan , Y. Sirois , A. Tarabini, A. Zabi, A. Zghiche 

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

J.-L. Agram<sup>16</sup> , J. Andrea, D. Apparu, D. Bloch , G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard , D. Darej, J.-C. Fontaine<sup>16</sup>, U. Goerlach, C. Grimault, A.-C. Le Bihan, E. Nibigira , P. Van Hove 



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

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













**Georgian Technical University, Tbilisi, Georgia**

I. Lomidze, T. Toriashvili<sup>17</sup>, Z. Tsamalaidze<sup>12</sup>







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

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
























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

A. Dodonova, D. Eliseev, M. Erdmann , P. Fackeldey , B. Fischer, S. Ghosh , T. Hebbeker , K. Hoepfner, F. Ivone, L. Mastrolorenzo, M. Merschmeyer , A. Meyer , G. Mocellin, S. Mondal, S. Mukherjee , D. Noll , A. Novak, T. Pook , A. Pozdnyakov , Y. Rath, H. Reithler, J. Roemer, A. Schmidt , S.C. Schuler, A. Sharma , L. Vigilante, S. Wiedenbeck, S. Zaleski









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

C. Dziwok, G. Flügge, W. Haj Ahmad<sup>18</sup> , O. Hlushchenko, T. Kress, A. Nowack , C. Pistone, O. Pooth, D. Roy , H. Sert , A. Stahl<sup>19</sup> , T. Ziemons , A. Zotz




















**Deutsches Elektronen-Synchrotron, Hamburg, Germany**

H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, S. Baxter, M. Bayatmakou, O. Behnke, A. Bermúdez Martínez, S. Bhattacharya, A.A. Bin Anuar , K. Borras<sup>20</sup>, D. Brunner, A. Campbell , A. Cardini , C. Cheng, F. Colombina, S. Consuegra Rodríguez , G. Correia Silva, V. Danilov, M. De Silva, L. Didukh, G. Eckerlin, D. Eckstein, L.I. Estevez Banos , O. Filatov , E. Gallo<sup>21</sup>, A. Geiser, A. Giraldi, A. Grohsjean , M. Guthoff, A. Jafari<sup>22</sup> , N.Z. Jomhari , H. Jung , A. Kasem<sup>20</sup> , M. Kase- mann , H. Kaveh , C. Kleinwort , D. Krücker , W. Lange, J. Lidrych , K. Lipka, W. Lohmann<sup>23</sup>, R. Mankel, I.-A. Melzer-Pellmann , M. Mendizabal Morentin, J. Metwally, A.B. Meyer , M. Meyer , J. Mnich , A. Mussgiller, Y. Otariid, D. Pérez Adán , D. Pitzl, A. Raspereza, B. Ribeiro Lopes, J. Rübenach, A. Saggio , A. Saibel 
















M. Savitskyi , M. Scham<sup>24</sup>, V. Scheurer, P. Schütze, C. Schwanenberger<sup>21</sup> , A. Singh, R.E. Sosa Ricardo , D. Stafford, N. Tonon , M. Van De Klundert , R. Walsh , D. Walter, Y. Wen , K. Wichmann, L. Wiens, C. Wissing, S. Wuchterl 

**University of Hamburg, Hamburg, Germany**

R. Aggleton, S. Albrecht , S. Bein , L. Benato , P. Connor , K. De Leo , M. Eich, F. Feindt, A. Fröhlich, C. Garbers , E. Garutti , P. Gunnellini, M. Hajheidari, J. Haller , A. Hinzmann , G. Kasieczka, R. Klanner , R. Kogler , T. Kramer, V. Kutzner, J. Lange , T. Lange , A. Lobanov , A. Malara , A. Nigamova, K.J. Pena Rodriguez, O. Rieger, P. Schleper, M. Schröder , J. Schwandt , J. Sonn-eveld , H. Stadie, G. Steinbrück, A. Tews, I. Zoi 





**Karlsruher Institut fuer Technologie, Karlsruhe, Germany**

J. Bechtel , S. Brommer, E. Butz , R. Caspart , T. Chwalek, W. De Boer<sup>†</sup>, A. Dier-lamm, A. Droll, K. El Morabit, N. Faltermann , M. Giffels, J.o. Gosewisch, A. Gottmann, F. Hartmann<sup>19</sup> , C. Heidecker, U. Husemann , P. Keicher, R. Koppenhöfer, S. Maier, M. Metzler, S. Mitra , Th. Müller, M. Neukum, A. Nürnberg, G. Quast , K. Rab-berth , J. Rauser, D. Savoie , M. Schnepf, D. Seith, I. Shvetsov, H.J. Simonis, R. Ulrich , J. Van Der Linden, R.F. Von Cube, M. Wassmer, M. Weber , S. Wieland, R. Wolf , S. Wozniewski, S. Wunsch

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

G. Anagnostou, G. Daskalakis, T. Gerasis , A. Kyriakis, D. Loukas, A. Stakia 

**National and Kapodistrian University of Athens, Athens, Greece**

M. Diamantopoulou, D. Karasavvas, G. Karathanasis, P. Kontaxakis , C.K. Koraka, A. Manousakis-Katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou , K. Theofi-latos , E. Tziaferi , K. Vellidis, E. Vourliotis






**National Technical University of Athens, Athens, Greece**

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






**University of Ioánnina, Ioánnina, Greece**

K. Adamidis, I. Bestintzanos, I. Evangelou , C. Foudas, P. Giannelios, P. Katsoulis, P. Kokkas, N. Manthos, I. Papadopoulos , J. Strologas 

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

M. Csanad , K. Farkas, M.M.A. Gadallah<sup>25</sup> , S. Lökös<sup>26</sup> , P. Major, K. Mandal , A. Mehta , G. Pasztor , A.J. Rádl, O. Surányi, G.I. Veres 













































**Wigner Research Centre for Physics, Budapest, Hungary**

M. Bartók<sup>27</sup> , G. Bencze, C. Hajdu , D. Horvath<sup>28</sup> , F. Sikler , V. Veszpremi , G. Vesztergombi<sup>†</sup>

**Institute of Nuclear Research ATOMKI, Debrecen, Hungary**

S. Czellar, J. Karancsi<sup>27</sup> , J. Molnar, Z. Szillasi, D. Teyssier



**Institute of Physics, University of Debrecen, Debrecen, Hungary**P. Raics, Z.L. Trocsanyi<sup>29</sup> , B. Ujvari**Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary**T. Csorgo<sup>30</sup> , F. Nemes<sup>30</sup>, T. Novak**Indian Institute of Science (IISc), Bangalore, India**J.R. Komaragiri , D. Kumar, L. Panwar , P.C. Tiwari **National Institute of Science Education and Research, HBNI, Bhubaneswar, India**S. Bahinipati<sup>31</sup> , C. Kar , P. Mal, T. Mishra , V.K. Muraleedharan Nair Bindhu<sup>32</sup>, A. Nayak<sup>32</sup> , P. Saha, N. Sur , S.K. Swain, D. Vats<sup>32</sup>**Panjab University, Chandigarh, India**S. Bansal , S.B. Beri, V. Bhatnagar , G. Chaudhary , S. Chauhan , N. Dhingra<sup>33</sup> , R. Gupta, A. Kaur, M. Kaur , S. Kaur, P. Kumari , M. Meena, K. Sandeep , J.B. Singh , A.K. Viridi **University of Delhi, Delhi, India**A. Ahmed, A. Bhardwaj , B.C. Choudhary , M. Gola, S. Keshri , A. Kumar , M. Naimuddin , P. Priyanka , K. Ranjan, A. Shah **Saha Institute of Nuclear Physics, HBNI, Kolkata, India**M. Bharti<sup>34</sup>, R. Bhattacharya, S. Bhattacharya , D. Bhowmik, S. Dutta, S. Dutta, B. Gomber<sup>35</sup> , M. Maity<sup>36</sup>, P. Palit , P.K. Rout , G. Saha, B. Sahu , S. Sarkar, M. Sharan, B. Singh<sup>34</sup>, S. Thakur<sup>34</sup>**Indian Institute of Technology Madras, Madras, India**P.K. Behera , S.C. Behera, P. Kalbhor , A. Muhammad, R. Pradhan, P.R. Pujahari, A. Sharma , A.K. Sikdar**Bhabha Atomic Research Centre, Mumbai, India**D. Dutta , V. Jha, V. Kumar , D.K. Mishra, K. Naskar<sup>37</sup>, P.K. Netrakanti, L.M. Pant, P. Shukla **Tata Institute of Fundamental Research-A, Mumbai, India**T. Aziz, S. Dugad, M. Kumar, G.B. Mohanty , U. Sarkar **Tata Institute of Fundamental Research-B, Mumbai, India**S. Banerjee , R. Chudasama, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee **Indian Institute of Science Education and Research (IISER), Pune, India**K. Alpana, S. Dube , B. Kansal, A. Laha, S. Pandey , A. Rane , A. Rastogi , S. Sharma **Isfahan University of Technology, Isfahan, Iran**H. Bakhshiansohi<sup>38</sup> , E. Khazaie, M. Zeinali<sup>39</sup>




























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

S. Chenarani<sup>40</sup>, S.M. Etesami , M. Khakzad , M. Mohammadi Najafabadi 


**University College Dublin, Dublin, Ireland**

M. Grunewald 






**INFN Sezione di Bari<sup>a</sup>, Bari, Italy, Università di Bari<sup>b</sup>, Bari, Italy, Politecnico di Bari<sup>c</sup>, Bari, Italy**

M. Abbrescia<sup>a,b</sup> , R. Aly<sup>a,b,41</sup> , C. Aruta<sup>a,b</sup>, A. Colaleo<sup>a</sup> , D. Creanza<sup>a,c</sup> , N. De Filippis<sup>a,c</sup> , M. De Palma<sup>a,b</sup> , A. Di Florio<sup>a,b</sup>, A. Di Pilato<sup>a,b</sup> , W. Elmetenawee<sup>a,b</sup> , L. Fiore<sup>a</sup> , A. Gelmi<sup>a,b</sup> , M. Gul<sup>a</sup> , G. Iaselli<sup>a,c</sup> , M. Ince<sup>a,b</sup> , S. Lezki<sup>a,b</sup> , G. Maggi<sup>a,c</sup> , M. Maggi<sup>a</sup> , I. Margjeka<sup>a,b</sup>, V. Mastrapasqua<sup>a,b</sup> , J.A. Merlin<sup>a</sup>, S. My<sup>a,b</sup> , S. Nuzzo<sup>a,b</sup> , A. Pellecchia<sup>a,b</sup>, A. Pompili<sup>a,b</sup> , G. Pugliese<sup>a,c</sup> , D. Ramos, A. Ranieri<sup>a</sup> , G. Selvaggi<sup>a,b</sup> , L. Silvestris<sup>a</sup> , F.M. Simone<sup>a,b</sup> , R. Venditti<sup>a</sup> , P. Verwilligen<sup>a</sup> 













**INFN Sezione di Bologna<sup>a</sup>, Bologna, Italy, Università di Bologna<sup>b</sup>, Bologna, Italy**

G. Abbiendi<sup>a</sup> , C. Battilana<sup>a,b</sup> , D. Bonacorsi<sup>a,b</sup> , L. Borgonovi<sup>a</sup>, L. Brigliadori<sup>a</sup>, R. Campanini<sup>a,b</sup> , P. Capiluppi<sup>a,b</sup> , A. Castro<sup>a,b</sup> , F.R. Cavallo<sup>a</sup> , M. Cuffiani<sup>a,b</sup> , G.M. Dallavalle<sup>a</sup> , T. Diotallevi<sup>a,b</sup> , F. Fabbri<sup>a</sup> , A. Fanfani<sup>a,b</sup> , P. Giacomelli<sup>a</sup> , L. Giommi<sup>a,b</sup> , C. Grandi<sup>a</sup> , L. Guiducci<sup>a,b</sup>, S. Lo Meo<sup>a,42</sup>, L. Lunerti<sup>a,b</sup>, S. Marcellini<sup>a</sup> , G. Masetti<sup>a</sup> , F.L. Navarria<sup>a,b</sup> , A. Perrotta<sup>a</sup> , F. Primavera<sup>a,b</sup> , A.M. Rossi<sup>a,b</sup> , T. Rovelli<sup>a,b</sup> , G.P. Siroli<sup>a,b</sup> 

**INFN Sezione di Catania<sup>a</sup>, Catania, Italy, Università di Catania<sup>b</sup>, Catania, Italy**

S. Albergo<sup>a,b,43</sup> , S. Costa<sup>a,b,43</sup> , A. Di Mattia<sup>a</sup> , R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b,43</sup> , C. Tuve<sup>a,b</sup> 

**INFN Sezione di Firenze<sup>a</sup>, Firenze, Italy, Università di Firenze<sup>b</sup>, Firenze, Italy**

G. Barbagli<sup>a</sup> , A. Cassese<sup>a</sup> , R. Ceccarelli<sup>a,b</sup>, V. Ciulli<sup>a,b</sup> , C. Civinini<sup>a</sup> , R. D'Alessandro<sup>a,b</sup> , E. Focardi<sup>a,b</sup> , G. Latino<sup>a,b</sup> , P. Lenzi<sup>a,b</sup> , M. Lizzo<sup>a,b</sup>, M. Meschini<sup>a</sup> , S. Paoletti<sup>a</sup> , R. Seidita<sup>a,b</sup>, G. Sguazzoni<sup>a</sup> , L. Viliani<sup>a</sup> 




















**INFN Laboratori Nazionali di Frascati, Frascati, Italy**

L. Benussi , S. Bianco , D. Piccolo 











**INFN Sezione di Genova<sup>a</sup>, Genova, Italy, Università di Genova<sup>b</sup>, Genova, Italy**

M. Bozzo<sup>a,b</sup> , F. Ferro<sup>a</sup> , R. Mulargia<sup>a,b</sup>, E. Robutti<sup>a</sup> , S. Tosi<sup>a,b</sup> 


























**INFN Sezione di Milano-Bicocca<sup>a</sup>, Milano, Italy, Università di Milano-Bicocca<sup>b</sup>, Milano, Italy**

A. Benaglia<sup>a</sup> , G. Boldrini , F. Brivio<sup>a,b</sup>, F. Cetorelli<sup>a,b</sup>, F. De Guio<sup>a,b</sup> , M.E. Dinardo<sup>a,b</sup> , P. Dini<sup>a</sup> , S. Gennai<sup>a</sup> , A. Ghezzi<sup>a,b</sup> , P. Govoni<sup>a,b</sup> , L. Guzzi<sup>a,b</sup> , M. Malberti<sup>a</sup>, S. Malvezzi<sup>a</sup> , A. Massironi<sup>a</sup> , D. Menasce<sup>a</sup> , L. Moroni<sup>a</sup> , M. Paganoni<sup>a,b</sup> , D. Pedrini<sup>a</sup> , B.S. Pinolini, S. Ragazzi<sup>a,b</sup> , N. Redaelli<sup>a</sup> , T. Tabarelli de Fatis<sup>a,b</sup> , D. Valsecchi<sup>a,b,19</sup>, D. Zuolo<sup>a,b</sup> 








**INFN Sezione di Napoli<sup>a</sup>, Napoli, Italy, Università di Napoli 'Federico II'<sup>b</sup>, Napoli, Italy, Università della Basilicata<sup>c</sup>, Potenza, Italy, Università G. Marconi<sup>d</sup>, Roma, Italy**

S. Buontempo<sup>a</sup> , F. Carnevali<sup>a,b</sup>, N. Cavallo<sup>a,c</sup> , A. De Iorio<sup>a,b</sup> , F. Fabozzi<sup>a,c</sup> , A.O.M. Iorio<sup>a,b</sup> , L. Lista<sup>a,b</sup> , S. Meola<sup>a,d,19</sup> , P. Paolucci<sup>a,19</sup> , B. Rossi<sup>a</sup> , C. Sciacca<sup>a,b</sup> 












**INFN Sezione di Padova<sup>a</sup>, Padova, Italy, Università di Padova<sup>b</sup>, Padova, Italy, Università di Trento<sup>c</sup>, Trento, Italy**

P. Azzi<sup>a</sup> , N. Bacchetta<sup>a</sup> , D. Bisello<sup>a,b</sup> , P. Bortignon<sup>a</sup> , A. Bragagnolo<sup>a,b</sup> , R. Carlin<sup>a,b</sup> , P. Checchia<sup>a</sup> , T. Dorigo<sup>a</sup> , U. Dosselli<sup>a</sup> , F. Gasparini<sup>a,b</sup> , U. Gasparini<sup>a,b</sup> , G. Grosso, S.Y. Hoh<sup>a,b</sup> , L. Layer<sup>a,44</sup>, E. Lusiani , M. Margoni<sup>a,b</sup> , A.T. Meneguzzo<sup>a,b</sup> , J. Pazzini<sup>a,b</sup> , M. Presilla<sup>a,b</sup> , P. Ronchese<sup>a,b</sup> , R. Rossin<sup>a,b</sup>, F. Simonetto<sup>a,b</sup> , G. Strong<sup>a</sup> , M. Tosi<sup>a,b</sup> , H. Yarar<sup>a,b</sup>, M. Zanetti<sup>a,b</sup> , P. Zotto<sup>a,b</sup> , A. Zucchetta<sup>a,b</sup> , G. Zumerle<sup>a,b</sup> 




























**INFN Sezione di Pavia<sup>a</sup>, Pavia, Italy, Università di Pavia<sup>b</sup>, Pavia, Italy**

C. Aimè<sup>a,b</sup>, A. Braghieri<sup>a</sup> , S. Calzaferri<sup>a,b</sup>, D. Fiorina<sup>a,b</sup> , P. Montagna<sup>a,b</sup>, S.P. Ratti<sup>a,b</sup>, V. Re<sup>a</sup> , C. Riccardi<sup>a,b</sup> , P. Salvini<sup>a</sup> , I. Vai<sup>a</sup> , P. Vitulo<sup>a,b</sup> 














**INFN Sezione di Perugia<sup>a</sup>, Perugia, Italy, Università di Perugia<sup>b</sup>, Perugia, Italy**

P. Asenov<sup>a,45</sup> , G.M. Bilei<sup>a</sup> , D. Ciangottini<sup>a,b</sup> , L. Fanò<sup>a,b</sup> , P. Lariccia<sup>a,b</sup>, M. Magherini<sup>b</sup>, G. Mantovani<sup>a,b</sup>, V. Mariani<sup>a,b</sup>, M. Menichelli<sup>a</sup> , F. Moscatelli<sup>a,45</sup> , A. Piccinelli<sup>a,b</sup> , A. Rossi<sup>a,b</sup> , A. Santocchia<sup>a,b</sup> , D. Spiga<sup>a</sup> , T. Tedeschi<sup>a,b</sup> 

**INFN Sezione di Pisa<sup>a</sup>, Pisa, Italy, Università di Pisa<sup>b</sup>, Pisa, Italy, Scuola Normale Superiore di Pisa<sup>c</sup>, Pisa, Italy, Università di Siena<sup>d</sup>, Siena, Italy**

























P. Azzurri<sup>a</sup> , G. Bagliesi<sup>a</sup> , V. Bertacchi<sup>a,c</sup> , L. Bianchini<sup>a</sup> , T. Boccali<sup>a</sup> , E. Bossini<sup>a,b</sup> , R. Castaldi<sup>a</sup> , M.A. Ciocci<sup>a,b</sup> , V. D'Amante<sup>a,d</sup> , R. Dell'Orso<sup>a</sup> , M.R. Di Domenico<sup>a,d</sup> , S. Donato<sup>a</sup> , A. Giassi<sup>a</sup> , F. Ligabue<sup>a,c</sup> , E. Manca<sup>a,c</sup> , G. Mandorli<sup>a,c</sup> , A. Messineo<sup>a,b</sup> , F. Palla<sup>a</sup> , S. Parolia<sup>a,b</sup>, G. Ramirez-Sanchez<sup>a,c</sup>, A. Rizzi<sup>a,b</sup> , G. Rolandi<sup>a,c</sup> , S. Roy Chowdhury<sup>a,c</sup>, A. Scribano<sup>a</sup>, N. Shafiei<sup>a,b</sup> , P. Spagnolo<sup>a</sup> , R. Tenchini<sup>a</sup> , G. Tonelli<sup>a,b</sup> , N. Turini<sup>a,d</sup> , A. Venturi<sup>a</sup> , P.G. Verdini<sup>a</sup> 

**INFN Sezione di Roma<sup>a</sup>, Rome, Italy, Sapienza Università di Roma<sup>b</sup>, Rome, Italy**








P. Barria<sup>a</sup> , M. Campana<sup>a,b</sup>, F. Cavallari<sup>a</sup> , D. Del Re<sup>a,b</sup> , E. Di Marco<sup>a</sup> , M. Diemoz<sup>a</sup> , E. Longo<sup>a,b</sup> , P. Meridiani<sup>a</sup> , G. Organtini<sup>a,b</sup> , F. Pandolfi<sup>a</sup>, R. Paramatti<sup>a,b</sup> , C. Quaranta<sup>a,b</sup>, S. Rahatlou<sup>a,b</sup> , C. Rovelli<sup>a</sup> , F. Santanastasio<sup>a,b</sup> , L. Soffi<sup>a</sup> , R. Tramontano<sup>a,b</sup>

**INFN Sezione di Torino<sup>a</sup>, Torino, Italy, Università di Torino<sup>b</sup>, Torino, Italy, Università del Piemonte Orientale<sup>c</sup>, Novara, Italy**









N. Amapane<sup>a,b</sup> , R. Arcidiacono<sup>a,c</sup> , S. Argiro<sup>a,b</sup> , M. Arneodo<sup>a,c</sup> , N. Bartosik<sup>a</sup> , R. Bellan<sup>a,b</sup> , A. Bellora<sup>a,b</sup> , J. Berenguer Antequera<sup>a,b</sup> , C. Biino<sup>a</sup> , N. Cartiglia<sup>a</sup> 

S. Cometti<sup>a</sup> , M. Costa<sup>a,b</sup> , R. Covarelli<sup>a,b</sup> , N. Demaria<sup>a</sup> , B. Kiani<sup>a,b</sup> ,  
 F. Legger<sup>a</sup> , C. Mariotti<sup>a</sup> , S. Maselli<sup>a</sup> , E. Migliore<sup>a,b</sup> , E. Monteil<sup>a,b</sup> ,  
 M. Monteno<sup>a</sup> , M.M. Obertino<sup>a,b</sup> , G. Ortona<sup>a</sup> , L. Pacher<sup>a,b</sup> , N. Pastrone<sup>a</sup> ,  
 M. Pelliccioni<sup>a</sup> , G.L. Pinna Angioni<sup>a,b</sup>, M. Ruspa<sup>a,c</sup> , K. Shchelina<sup>a</sup> , F. Siviero<sup>a,b</sup> ,  
 V. Sola<sup>a</sup> , A. Solano<sup>a,b</sup> , D. Soldi<sup>a,b</sup> , A. Staiano<sup>a</sup> , M. Tornago<sup>a,b</sup>, D. Trocino<sup>a</sup> ,  
 A. Vagnerini<sup>a,b</sup>



**INFN Sezione di Trieste<sup>a</sup>, Trieste, Italy, Università di Trieste<sup>b</sup>, Trieste, Italy**

S. Belforte<sup>a</sup> , V. Candelise<sup>a,b</sup> , M. Casarsa<sup>a</sup> , F. Cossutti<sup>a</sup> , A. Da Rold<sup>a,b</sup> ,  
 G. Della Ricca<sup>a,b</sup> , G. Sorrentino<sup>a,b</sup>, F. Vazzoler<sup>a,b</sup> 




**Kyungpook National University, Daegu, Korea**

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

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

H. Kim , D.H. Moon 

**Hanyang University, Seoul, Korea**

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

**Korea University, Seoul, Korea**

S. Cho, S. Choi , Y. Go, B. Hong , K. Lee, K.S. Lee , J. Lim, J. Park, S.K. Park, J. Yoo

**Kyung Hee University, Department of Physics, Seoul, Republic of Korea, Seoul, Korea**

J. Goh , A. Gurtu



**Sejong University, Seoul, Korea**

H.S. Kim , Y. Kim

**Seoul National University, Seoul, Korea**

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**University of Seoul, Seoul, Korea**

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

**Yonsei University, Department of Physics, Seoul, Korea**




S. Ha, H.D. Yoo

**Sungkyunkwan University, Suwon, Korea**



M. Choi, Y. Jeong, H. Lee, Y. Lee, I. Yu 

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





T. Beyrouthy, Y. Maghrbi

**Riga Technical University, Riga, Latvia**T. Torims, V. Veckalns<sup>46</sup> **Vilnius University, Vilnius, Lithuania**M. Ambrozias, A. Carvalho Antunes De Oliveira , A. Juodagalvis , A. Rinkevicius ,  
G. Tamulaitis **National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia**N. Bin Norjoharuddeen , W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli**Universidad de Sonora (UNISON), Hermosillo, Mexico**J.F. Benitez , A. Castaneda Hernandez , M. León Coello, J.A. Murillo Quijada ,  
A. Sehrawat, L. Valencia Palomo **Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico**G. Ayala, H. Castilla-Valdez, E. De La Cruz-Burelo , I. Heredia-De La Cruz<sup>47</sup> ,  
R. Lopez-Fernandez, C.A. Mondragon Herrera, D.A. Perez Navarro, A. Sánchez Hernández **Universidad Iberoamericana, Mexico City, Mexico**S. Carrillo Moreno, C. Oropeza Barrera , F. Vazquez Valencia**Benemerita Universidad Autonoma de Puebla, Puebla, Mexico**

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

**University of Montenegro, Podgorica, Montenegro**J. Mijuskovic<sup>48</sup>, N. Raicevic**University of Auckland, Auckland, New Zealand**D. Krofcheck **University of Canterbury, Christchurch, New Zealand**P.H. Butler **National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan**A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, H.R. Hoorani, W.A. Khan, M.A. Shah,  
M. Shoaib , M. Waqas **AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland**



V. Avati, L. Grzanka, M. Malawski

**National Centre for Nuclear Research, Swierk, Poland**H. Bialkowska, M. Bluj , B. Boimska , M. Górski, M. Kazana, M. Szleper , P. Zalewski**Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland**K. Bunkowski, K. Doroba, A. Kalinowski , M. Konecki , J. Krolikowski ,  
M. Walczak 




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

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






**Joint Institute for Nuclear Research, Dubna, Russia**

S. Afanasiev, D. Budkouski, I. Golutvin, I. Gorbunov , V. Karjavine, V. Korenkov , A. Lanev, A. Malakhov, V. Matveev<sup>49,50</sup>, V. Palichik, V. Perelygin, M. Savina, D. Seitova, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, B.S. Yuldashev<sup>51</sup>, A. Zarubin, I. Zhizhin

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

G. Gavrillov , V. Golovtcov, Y. Ivanov, V. Kim<sup>52</sup> , E. Kuznetsova<sup>53</sup>, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov , V. Sulimov, L. Uvarov, S. Volkov, A. Vorobyev


**Institute for Nuclear Research, Moscow, Russia**

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

**Moscow Institute of Physics and Technology, Moscow, Russia**

T. Aushev

**National Research Center 'Kurchatov Institute', Moscow, Russia**

V. Epshteyn, V. Gavrillov, N. Lychkovskaya, A. Nikitenko<sup>54</sup>, V. Popov, A. Stepenov, M. Toms, E. Vlasov , A. Zhokin






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

M. Danilov<sup>55</sup> , A. Oskin, P. Parygin, S. Polikarpov<sup>55</sup> , D. Selivanova


**P.N. Lebedev Physical Institute, Moscow, Russia**

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






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

A. Belyaev, E. Boos , V. Bunichev, M. Dubinin<sup>56</sup> , L. Dudko , A. Gribushin, V. Klyukhin , I. Lokhtin , S. Obraztsov, M. Perfilov, S. Petrushanko, V. Savrin, P. Volkov

**Novosibirsk State University (NSU), Novosibirsk, Russia**

V. Blinov<sup>57</sup>, T. Dimova<sup>57</sup>, L. Kardapoltsev<sup>57</sup>, A. Kozyrev<sup>57</sup>, I. Ovtin<sup>57</sup>, Y. Skovpen<sup>57</sup> 

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

I. Azhgirey , I. Bayshev, D. Elumakhov, V. Kachanov, 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, V. Okhotnikov




















**Tomsk State University, Tomsk, Russia**

V. Borshch, V. Ivanchenko , E. Tcherniaev 

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

P. Adzic<sup>58</sup> , M. Dordevic , P. Milenovic , J. Milosevic 










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

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















**Universidad Autónoma de Madrid, Madrid, Spain**

J.F. de Trocóniz, R. Reyes-Almanza 

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

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

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

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










**University of Colombo, Colombo, Sri Lanka**

M.K. Jayananda, B. Kailasapathy<sup>59</sup>, D.U.J. Sonnadara, D.D.C. Wickramarathna










































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

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

**CERN, European Organization for Nuclear Research, Geneva, Switzerland**

T.K. Aarrestad , D. Abbaneo, J. Alimena , E. Auffray, G. Auzinger, J. Baechler, P. Baillon<sup>†</sup>, D. Barney , J. Bendavid, M. Bianco , A. Bocci , T. Camporesi, M. Capeans Garrido , G. Cerminara, S.S. Chhibra , M. Cipriani , L. Cristella 




















D. d'Enterria , A. Dabrowski , A. David , A. De Roeck , M.M. Defranchis , M. Deile , M. Dobson, M. Dünser , N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita<sup>60</sup>, D. Fasanella , A. Florent , G. Franzoni , W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos , M. Haranko , J. Hegeman , V. Innocente , T. James, P. Janot , J. Kieseler , M. Komm , N. Kratochwil, C. Lange , S. Laurila, P. Lecoq , K. Long , C. Lourenço , B. Maier, L. Malgeri , S. Mallios, M. Mannelli, A.C. Marini , F. Meijers, S. Mersi , E. Meschi , F. Moortgat , M. Mulders , S. Orfanelli, L. Orsini, F. Pantaleo , L. Pape, E. Perez, M. Peruzzi , A. Petrilli, G. Petrucciani , A. Pfeiffer , M. Pierini , D. Piparo, M. Pitt , H. Qu , T. Quast, D. Rabadý , A. Racz, G. Reales Gutiérrez, M. Rieger , M. Rovere, H. Sakulin, J. Salfeld-Nebgen , S. Scarfi, C. Schäfer, C. Schwick, M. Selvaggi , A. Sharma, P. Silva , W. Snoeys , P. Sphicas<sup>61</sup> , S. Summers , K. Tatar , V.R. Tavolaro , D. Treille, A. Tsirou, G.P. Van Onsem , J. Wanczyk<sup>62</sup>, K.A. Wozniak, W.D. Zeuner














#### Paul Scherrer Institut, Villigen, Switzerland

L. Caminada<sup>63</sup> , A. Ebrahimi , W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, M. Missiroli , T. Rohe

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

K. Androsov<sup>62</sup> , M. Backhaus , P. Berger, A. Calandri , N. Chernyavskaya , A. De Cosa, G. Dissertori , M. Dittmar, M. Donegà, C. Dorfer , F. Eble, K. Gedia, F. Glessgen, T.A. Gómez Espinosa , C. Grab , D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni , L. Marchese , C. Martin Perez, M.T. Meinhard, F. Nessi-Tedaldi, J. Niedziela , F. Pauss, V. Perovic, S. Pigazzini , M.G. Ratti , M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic , D. Ruini, D.A. Sanz Becerra , V. Stampf, J. Steggemann<sup>62</sup> , R. Wallny , D.H. Zhu






#### Universität Zürich, Zurich, Switzerland

C. Amsler<sup>64</sup> , P. Bäertschi, C. Botta , D. Brzhechko, M.F. Canelli , K. Cormier, A. De Wit , R. Del Burgo, J.K. Heikkilä , M. Huwiler, W. Jin, A. Jofrehei , B. Kilminster , S. Leontsinis , S.P. Liechti, A. Macchiolo , P. Meiring, V.M. Mikuni , U. Molinatti, I. Neutelings, A. Reimers, P. Robmann, S. Sanchez Cruz , K. Schweiger , Y. Takahashi 




#### National Central University, Chung-Li, Taiwan

C. Adloff<sup>65</sup>, C.M. Kuo, W. Lin, A. Roy , T. Sarkar<sup>36</sup> , S.S. Yu

#### National Taiwan University (NTU), Taipei, Taiwan











L. Ceard, Y. Chao, K.F. Chen , P.H. Chen , W.-S. Hou , Y.y. Li, R.-S. Lu, E. Paganis , A. Psallidas, A. Steen, H.y. Wu, E. Yazgan , P.r. Yu

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



B. Asavapibhop , C. Asawatangtrakuldee , N. Srimanobhas 







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

F. Boran , S. Damarseckin<sup>66</sup>, Z.S. Demiroglu , F. Dolek , I. Dumanoglu<sup>67</sup> , E. Eskut, Y. Guler<sup>68</sup> , E. Gurpinar Guler<sup>68</sup> , I. Hos<sup>69</sup>, C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu , G. Onengut, K. Ozdemir<sup>70</sup>, A. Polatoz, A.E. Simsek , B. Tali<sup>71</sup>, U.G. Tok , S. Turkcapar, I.S. Zorbakir , C. Zorbilmez

**Middle East Technical University, Physics Department, Ankara, Turkey**

B. Isildak<sup>72</sup>, G. Karapinar<sup>73</sup>, K. Ocalan<sup>74</sup> , M. Yalvac<sup>75</sup> 

**Bogazici University, Istanbul, Turkey**

B. Akgun, I.O. Atakisi , E. Gülmez , M. Kaya<sup>76</sup> , O. Kaya<sup>77</sup>, Ö. Özçelik, S. Tekten<sup>78</sup>, E.A. Yetkin<sup>79</sup> 

**Istanbul Technical University, Istanbul, Turkey**

A. Cakir , K. Cankocak<sup>67</sup> , Y. Komurcu, S. Sen<sup>80</sup> 

**Istanbul University, Istanbul, Turkey**

S. Cerci<sup>71</sup>, B. Kaynak, S. Ozkorucuklu, D. Sunar Cerci<sup>71</sup> 












**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**








































































D. Anthony, E. Bhal , S. Bologna, J.J. Brooke , A. Bundock , E. Clement , D. Cussans , H. Flacher , J. Goldstein , G.P. Heath, H.F. Heath , L. Kreczko , B. Krikler , S. Paramesvaran, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou<sup>81</sup> , K. Walkingshaw Pass, R. White

**Rutherford Appleton Laboratory, Didcot, United Kingdom**













K.W. Bell, A. Belyaev<sup>82</sup> , C. Brew , R.M. Brown, D.J.A. Cockerill, C. Cooke, K.V. Ellis, K. Harder, S. Harper, M.-L. Holmberg<sup>83</sup>, J. Linacre , K. Manolopoulos, D.M. Newbold , E. Olaiya, D. Petyt, T. Reis , T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, T. Williams 

**Imperial College, London, United Kingdom**







R. Bainbridge , P. Bloch , S. Bonomally, J. Borg , S. Breeze, O. Buchmuller, V. Cepaitis , G.S. Chahal<sup>84</sup> , D. Colling, P. Dauncey , G. Davies , M. Della Negra , S. Fayer, G. Fedi , G. Hall , M.H. Hassanshahi, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli , D.G. Monk, J. Nash<sup>85</sup> , M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott , C. Seez, A. Shtipliyski, A. Tapper , K. Uchida, T. Virdee<sup>19</sup> , M. Vojinovic , N. Wardle , S.N. Webb , D. Winterbottom

**Brunel University, Uxbridge, United Kingdom**K. Coldham, J.E. Cole , A. Khan, P. Kyberd , I.D. Reid , L. Teodorescu, S. Zahid **Baylor University, Waco, Texas, USA**S. Abdullin , A. Brinkerhoff , B. Caraway , J. Dittmann , K. Hatakeyama , A.R. Kanuganti, B. McMaster , N. Pastika, M. Saunders , S. Sawant, C. Sutantawibul, J. Wilson **Catholic University of America, Washington, DC, USA**R. Bartek , A. Dominguez , R. Uniyal , A.M. Vargas Hernandez**The University of Alabama, Tuscaloosa, Alabama, USA**A. Buccilli , S.I. Cooper , D. Di Croce , S.V. Gleyzer , C. Henderson , C.U. Perez , P. Rumerio<sup>86</sup> , C. West **Boston University, Boston, Massachusetts, USA**A. Akpinar , A. Albert , D. Arcaro , C. Cosby , Z. Demiragli , E. Fontanesi, D. Gastler, S. May , J. Rohlf , K. Salyer , D. Sperka, D. Spitzbart , I. Suarez , A. Tsatsos, S. Yuan, D. Zou**Brown University, Providence, Rhode Island, USA**G. Benelli , B. Burkle , X. Coubez<sup>20</sup> , D. Cutts , M. Hadley , U. Heintz , J.M. Hogan<sup>87</sup> , G. Landsberg , K.T. Lau , M. Lukasik, J. Luo , M. Narain, S. Sagir<sup>88</sup> , E. Usai , W.Y. Wong, X. Yan , D. Yu , W. Zhang**University of California, Davis, Davis, California, USA**J. Bonilla , C. Brainerd , R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok , J. Conway , P.T. Cox, R. Erbacher, G. Haza, F. Jensen , O. Kukral, R. Lander, M. Mulhearn , D. Pellett, B. Regnery , D. Taylor , Y. Yao , F. Zhang **University of California, Los Angeles, California, USA**M. Bachtis , R. Cousins , A. Datta , D. Hamilton, J. Hauser , M. Ignatenko, M.A. Iqbal, T. Lam, W.A. Nash, S. Regnard , D. Saltzberg , B. Stone, V. Valuev **University of California, Riverside, Riverside, California, USA**K. Burt, Y. Chen, R. Clare , J.W. Gary , M. Gordon, G. Hanson , G. Karapostoli , O.R. Long , N. Manganeli, M. Olmedo Negrete, W. Si , S. Wimpenny, Y. Zhang**University of California, San Diego, La Jolla, California, USA**J.G. Branson, P. Chang , S. Cittolin, S. Cooperstein , N. Deelen , D. Diaz , J. Duarte , R. Gerosa , L. Giannini , D. Gilbert , J. Guiang, R. Kansal , V. Krutelyov , R. Lee, J. Letts , M. Masciovecchio , M. Pieri , B.V. Sathia Narayanan , V. Sharma , M. Tadel, A. Vartak , F. Würthwein , Y. Xiang , A. Yagil **University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA**N. Amin, C. Campagnari , M. Citron , A. Dorsett, V. Dutta , J. Incandela , M. Kilpatrick , J. Kim , B. Marsh, H. Mei, M. Oshiro, M. Quinnan , J. Richman, U. Sarica , F. Setti, J. Sheplock, D. Stuart, S. Wang 







**California Institute of Technology, Pasadena, California, USA**

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














**Carnegie Mellon University, Pittsburgh, Pennsylvania, USA**

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












































**University of Colorado Boulder, Boulder, Colorado, USA**

J.P. Cumalat , W.T. Ford , A. Hassani, E. MacDonald, R. Patel, A. Perloff , C. Savard, K. Stenson , K.A. Ulmer , S.R. Wagner 














**Cornell University, Ithaca, New York, USA**

J. Alexander , S. Bright-Thonney , Y. Cheng , D.J. Cranshaw , S. Hogan, J. Monroy , J.R. Patterson , D. Quach , J. Reichert , M. Reid , A. Ryd, W. Sun , J. Thom , P. Wittich , R. Zou 







**Fermi National Accelerator Laboratory, Batavia, Illinois, USA**

M. Albrow , M. Alyari , G. Apollinari, A. Apresyan , A. Apyan , S. Banerjee, L.A.T. Bauerdick , D. Berry , J. Berryhill , P.C. Bhat, K. Burkett , J.N. Butler, A. Canepa, G.B. Cerati , H.W.K. Cheung , F. Chlebana, M. Cremonesi, K.F. Di Petrillo , V.D. Elvira , Y. Feng, J. Freeman, Z. Gecse, L. Gray, D. Green, S. Grünendahl , O. Gutsche , R.M. Harris , R. Heller, T.C. Herwig , J. Hirschauer , B. Jayatilaka , S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma , B. Klima , K.H.M. Kwok, S. Lammel , D. Lincoln , R. Lipton, T. Liu, C. Madrid, K. Maeshima, C. Mantilla , D. Mason, P. McBride , P. Merkel, S. Mrenna , S. Nahn , J. Ngadiuba , V. O'Dell, V. Papadimitriou, K. Pedro , C. Pena<sup>56</sup> , O. Prokofyev, F. Ravera , A. Reinsvold Hall , L. Ristori , E. Sexton-Kennedy , N. Smith , A. Soha , W.J. Spalding , L. Spiegel, S. Stoynev , J. Strait , L. Taylor , S. Tkaczyk, N.V. Tran , L. Uplegger , E.W. Vaandering , H.A. Weber 







**University of Florida, Gainesville, Florida, USA**

D. Acosta , P. Avery, D. Bourilkov , L. Cadamuro , V. Cherepanov, F. Errico , R.D. Field, D. Guerrero, B.M. Joshi , M. Kim, E. Koenig, J. Konigsberg , A. Korytov, K.H. Lo, K. Matchev , N. Menendez , G. Mitselmakher , A. Muthirakalayil Madhu, N. Rawal, D. Rosenzweig, S. Rosenzweig, K. Shi , J. Sturdy , J. Wang , E. Yigitbasi , X. Zuo















**Florida State University, Tallahassee, Florida, USA**

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








**Florida Institute of Technology, Melbourne, Florida, USA**

M.M. Baarmand , S. Butalla, T. Elkafrawy<sup>89</sup> , M. Hohlmann , R. Kumar Verma , D. Noonan , M. Rahmani, F. Yumiceva 









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

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

















**The University of Iowa, Iowa City, Iowa, USA**

M. Alhusseini , K. Dilsiz<sup>90</sup> , R.P. Gandrajula , O.K. Köseyan , J.-P. Merlo, A. Mestvirishvili<sup>91</sup>, J. Nachtman, H. Ogul<sup>92</sup> , Y. Onel , A. Penzo, C. Snyder, E. Tiras<sup>93</sup> 

**Johns Hopkins University, Baltimore, Maryland, USA**

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

**The University of Kansas, Lawrence, Kansas, USA**

A. Abreu, J. Anguiano, C. Baldenegro Barrera , P. Baringer , A. Bean , A. Bylinkin , Z. Flowers, T. Isidori, S. Khalil , J. King, G. Krintiras , A. Kropivnitskaya , M. Lazarovits, C. Lindsey, J. Marquez, N. Minafra , M. Murray , M. Nickel, C. Rogan , C. Royon, R. Salvatico , S. Sanders, E. Schmitz, C. Smith , J.D. Tapia Takaki , Q. Wang , Z. Warner, J. Williams , G. Wilson 









**Kansas State University, Manhattan, Kansas, USA**

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
















**Lawrence Livermore National Laboratory, Livermore, California, USA**

F. Rebassoo, D. Wright







**University of Maryland, College Park, Maryland, USA**

E. Adams, A. Baden, O. Baron, A. Belloni , S.C. Eno , N.J. Hadley , S. Jabeen , R.G. Kellogg, T. Koeth, A.C. Mignerey, S. Nabili, C. Palmer , M. Seidel , A. Skuja , L. Wang, K. Wong 






**Massachusetts Institute of Technology, Cambridge, Massachusetts, USA**

D. Abercrombie, G. Andreassi, R. Bi, S. Brandt, W. Busza , I.A. Cali, Y. Chen , M. D'Alfonso , J. Eysermans, C. Freer , G. Gomez Ceballos, M. Goncharov, P. Harris, M. Hu, M. Klute , D. Kovalskiy , J. Krupa, Y.-J. Lee , C. Mironov , C. Paus , D. Rankin , C. Roland , G. Roland, Z. Shi , G.S.F. Stephans , J. Wang, Z. Wang , B. Wyslouch 









**University of Minnesota, Minneapolis, Minnesota, USA**

R.M. Chatterjee, A. Evans , P. Hansen, J. Hiltbrand, Sh. Jain , M. Krohn, Y. Kubota, J. Mans , M. Revering, R. Rusack , R. Saradhy, N. Schroeder , N. Strobbe , M.A. Wadud










**University of Nebraska-Lincoln, Lincoln, Nebraska, USA**

K. Bloom , M. Bryson, S. Chauhan , D.R. Claes, C. Fangmeier, L. Finco , F. Golf , C. Joo, I. Kravchenko , M. Musich, I. Reed, J.E. Siado, G.R. Snow<sup>†</sup>, W. Tabb, F. Yan, A.G. Zecchinelli

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

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











**Northeastern University, Boston, Massachusetts, USA**

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






**Northwestern University, Evanston, Illinois, USA**

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















**University of Notre Dame, Notre Dame, Indiana, USA**

R. Band , R. Bucci, A. Das , N. Dev , R. Goldouzian , M. Hildreth, K. Hurtado Anampa , C. Jessop , K. Lannon , J. Lawrence, N. Loukas , D. Lutton, N. Marinelli, I. Mcalister, T. McCauley , C. Mcgrady, K. Mohrman, Y. Musienko<sup>49</sup>, R. Ruchti, P. Siddireddy, A. Townsend, M. Wayne, A. Wightman, M. Zarucki , L. Zygala

**The Ohio State University, Columbus, Ohio, USA**

B. Bylsma, B. Cardwell, L.S. Durkin , B. Francis , C. Hill , M. Nunez Ornelas , K. Wei, B.L. Winer, B.R. Yates 













**Princeton University, Princeton, New Jersey, USA**

F.M. Addesa , B. Bonham , P. Das , G. Dezoort, P. Elmer , A. Frankenthal , B. Greenberg , N. Haubrich, S. Higginbotham, A. Kalogeropoulos , G. Kopp, S. Kwan , D. Lange, M.T. Lucchini , D. Marlow , K. Mei , I. Ojalvo, J. Olsen , D. Stickland , C. Tully 

**University of Puerto Rico, Mayaguez, Puerto Rico, USA**

S. Malik , S. Norberg











**Purdue University, West Lafayette, Indiana, USA**

A.S. Bakshi, V.E. Barnes , R. Chawla , S. Das , L. Gutay, M. Jones , A.W. Jung , S. Karmarkar, M. Liu, G. Negro, N. Neumeister , G. Paspalaki, C.C. Peng, S. Piperov , A. Purohit, J.F. Schulte , M. Stojanovic<sup>15</sup>, J. Thieman , F. Wang , R. Xiao , W. Xie 

**Purdue University Northwest, Hammond, Indiana, USA**

J. Dolen , N. Parashar












**Rice University, Houston, Texas, USA**

A. Baty , M. Decaro, S. Dildick , K.M. Ecklund , S. Freed, P. Gardner, F.J.M. Geurts , A. Kumar , W. Li, B.P. Padley , R. Redjimi, W. Shi , A.G. Stahl Leiton , S. Yang , L. Zhang, Y. Zhang 

**University of Rochester, Rochester, New York, USA**

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








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

B. Chiarito, J.P. Chou , A. Gandrakota , Y. Gershtein , E. Halkiadakis , A. Hart, M. Heindl , O. Karacheban<sup>23</sup> , I. Laffotte, A. Lath , R. Montalvo, K. Nash, M. Os-  
herson, S. Salur , S. Schnetzer, S. Somalwar , R. Stone, S.A. Thayil , S. Thomas, H. Wang 




**University of Tennessee, Knoxville, Tennessee, USA**

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







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

O. Bouhali<sup>94</sup> , M. Dalchenko , A. Delgado , R. Eusebi, J. Gilmore, T. Huang, T. Kamon<sup>95</sup>, H. Kim , S. Luo , S. Malhotra, R. Mueller, D. Overton, D. Rathjens , A. Safonov 

**Texas Tech University, Lubbock, Texas, USA**

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

**Vanderbilt University, Nashville, Tennessee, USA**

E. Appelt , S. Greene, A. Gurrola , W. Johns, A. Melo, H. Ni, K. Padeken , F. Romeo , P. Sheldon , S. Tuo, J. Velkovska 












**University of Virginia, Charlottesville, Virginia, USA**

M.W. Arenton , B. Cox , G. Cummings , J. Hakala , R. Hirosky , M. Joyce , A. Ledovskoy , A. Li, C. Neu , B. Tannenwald , S. White , E. Wolfe 

**Wayne State University, Detroit, Michigan, USA**

N. Poudyal 

**University of Wisconsin - Madison, Madison, WI, Wisconsin, USA**

K. Black , T. Bose , C. Caillol, S. Dasu , I. De Bruyn , P. Everaerts , F. Fienga , C. Galloni, H. He, M. Herndon , A. Hervé, U. Hussain, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudanan Sreekala , A. Mallampalli, A. Mohammadi, D. Pinna, A. Savin, V. Shang, V. Sharma , W.H. Smith , D. Teague, S. Trembath-Reichert, W. Vetens 

†: Deceased

1: Also at TU Wien, Wien, Austria

2: Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt

- 3: Also at Université Libre de Bruxelles, Bruxelles, Belgium
- 4: Also at Universidade Estadual de Campinas, Campinas, Brazil
- 5: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
- 6: Also at University of Chinese Academy of Sciences, Beijing, China
- 7: Also at Department of Physics, Tsinghua University, Beijing, China
- 8: Also at UFMS, Nova Andradina, Brazil
- 9: Also at Nanjing Normal University Department of Physics, Nanjing, China
- 10: Now at The University of Iowa, Iowa City, Iowa, USA
- 11: Also at National Research Center ‘Kurchatov Institute’, Moscow, Russia
- 12: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 13: Also at Cairo University, Cairo, Egypt
- 14: Also at Zewail City of Science and Technology, Zewail, Egypt
- 15: Also at Purdue University, West Lafayette, Indiana, USA
- 16: Also at Université de Haute Alsace, Mulhouse, France
- 17: Also at Tbilisi State University, Tbilisi, Georgia
- 18: Also at Erzincan Binali Yildirim University, Erzincan, Turkey
- 19: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 20: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- 21: Also at University of Hamburg, Hamburg, Germany
- 22: Also at Isfahan University of Technology, Isfahan, Iran
- 23: Also at Brandenburg University of Technology, Cottbus, Germany
- 24: Also at Forschungszentrum Jülich, Juelich, Germany
- 25: Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
- 26: Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
- 27: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
- 28: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 29: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
- 30: Also at Wigner Research Centre for Physics, Budapest, Hungary
- 31: Also at IIT Bhubaneswar, Bhubaneswar, India
- 32: Also at Institute of Physics, Bhubaneswar, India
- 33: Also at G.H.G. Khalsa College, Punjab, India
- 34: Also at Shoolini University, Solan, India
- 35: Also at University of Hyderabad, Hyderabad, India
- 36: Also at University of Visva-Bharati, Santiniketan, India
- 37: Also at Indian Institute of Technology (IIT), Mumbai, India
- 38: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- 39: Also at Sharif University of Technology, Tehran, Iran
- 40: Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- 41: Now at INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy
- 42: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- 43: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- 44: Also at Università di Napoli ‘Federico II’, Napoli, Italy
- 45: Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- 46: Also at Riga Technical University, Riga, Latvia
- 47: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico



- 48: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- 49: Also at Institute for Nuclear Research, Moscow, Russia
- 50: Now at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
- 51: Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
- 52: Also at St. Petersburg Polytechnic University, St. Petersburg, Russia
- 53: Also at University of Florida, Gainesville, Florida, USA
- 54: Also at Imperial College, London, United Kingdom
- 55: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 56: Also at California Institute of Technology, Pasadena, California, USA
- 57: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
- 58: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 59: Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- 60: Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
- 61: Also at National and Kapodistrian University of Athens, Athens, Greece
- 62: Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- 63: Also at Universität Zürich, Zurich, Switzerland
- 64: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- 65: Also at Laboratoire d’Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
- 66: Also at Şirnak University, Sirnak, Turkey
- 67: Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey
- 68: Also at Konya Technical University, Konya, Turkey
- 69: Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
- 70: Also at Piri Reis University, Istanbul, Turkey
- 71: Also at Adiyaman University, Adiyaman, Turkey
- 72: Also at Ozyegin University, Istanbul, Turkey
- 73: Also at Izmir Institute of Technology, Izmir, Turkey
- 74: Also at Necmettin Erbakan University, Konya, Turkey
- 75: Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey
- 76: Also at Marmara University, Istanbul, Turkey
- 77: Also at Milli Savunma University, Istanbul, Turkey
- 78: Also at Kafkas University, Kars, Turkey
- 79: Also at Istanbul Bilgi University, Istanbul, Turkey
- 80: Also at Hacettepe University, Ankara, Turkey
- 81: Also at Vrije Universiteit Brussel, Brussel, Belgium
- 82: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 83: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 84: Also at IPPP Durham University, Durham, United Kingdom
- 85: Also at Monash University, Faculty of Science, Clayton, Australia
- 86: Also at Università di Torino, Torino, Italy
- 87: Also at Bethel University, St. Paul, Minneapolis, USA
- 88: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- 89: Also at Ain Shams University, Cairo, Egypt
- 90: Also at Bingol University, Bingol, Turkey



- 91: Also at Georgian Technical University, Tbilisi, Georgia
- 92: Also at Sinop University, Sinop, Turkey
- 93: Also at Erciyes University, Kayseri, Turkey
- 94: Also at Texas A&M University at Qatar, Doha, Qatar
- 95: Also at Kyungpook National University, Daegu, Korea