



# Study of WH production through vector boson scattering and extraction of the relative sign of the W and Z couplings to the Higgs boson in proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$

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## Abstract

A search for the production of a W boson and a Higgs boson through vector boson scattering (VBS) is presented, using CMS data from proton-proton collisions at  $\sqrt{s} = 13 \text{ TeV}$  collected from 2016 to 2018. The integrated luminosity of the data sample is  $138 \text{ fb}^{-1}$ . Selected events must be consistent with the presence of two jets originating from VBS, the leptonic decay of the W boson to an electron or muon, and a Higgs boson decaying into a pair of b quarks, reconstructed as either a single merged jet or two resolved jets. A measurement of the process as predicted by the standard model (SM) is performed alongside a study of beyond-the-SM (BSM) scenarios. The SM analysis sets an observed (expected) 95% confidence level upper limit of 14.3 (9.0) on the ratio of the measured VBS WH cross section to that expected by the SM. The BSM analysis, conducted within the so-called  $\kappa$  framework, excludes all scenarios with  $\lambda_{WZ} < 0$  that are consistent with current measurements, where  $\lambda_{WZ} = \kappa_W/\kappa_Z$  and  $\kappa_W$  and  $\kappa_Z$  are the HWW and HZZ coupling modifiers, respectively. The significance of the exclusion is beyond 5 standard deviations, and it is consistent with the SM expectation of  $\lambda_{WZ} = 1$ .

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# 1 Introduction

Precise measurements of the Higgs boson couplings to the  $W$  and  $Z$  bosons serve as critical tests of electroweak symmetry breaking in the standard model (SM) [1–6]. Within the  $\kappa$  framework [7], where the  $HWW$  and  $HZZ$  coupling modifiers are denoted as  $\kappa_W$  and  $\kappa_Z$ , respectively, direct measurements of Higgs boson production and decay have tightly constrained the absolute values of  $\kappa_W$  and  $\kappa_Z$  [8, 9]. However, the sign of  $\lambda_{WZ} = \kappa_W/\kappa_Z$  has not been probed directly.

A process sensitive to the interference between the  $HWW$  and  $HZZ$  vertices is needed to extract the sign of  $\lambda_{WZ}$ . A natural choice is the production of a  $W$  boson and a Higgs boson ( $WH$ ) via vector boson scattering (VBS) [10], which proceeds primarily through the leading-order (LO) Feynman diagrams shown in Fig. 1. This is a rare SM process, but the cross section grows quadratically with  $\kappa_W$  or  $\kappa_Z$  and the kinematic distributions are different for the SM ( $\lambda_{WZ} = 1$ ), and  $\lambda_{WZ} < 0$ , where the  $W$  and Higgs bosons both receive a significant Lorentz boost. This is shown in Fig. 2, where the scalar sum of the transverse momentum ( $p_T$ ) of the Higgs and  $W$  bosons is displayed for  $\kappa_Z = 1$  and various values of  $\kappa_W$ .

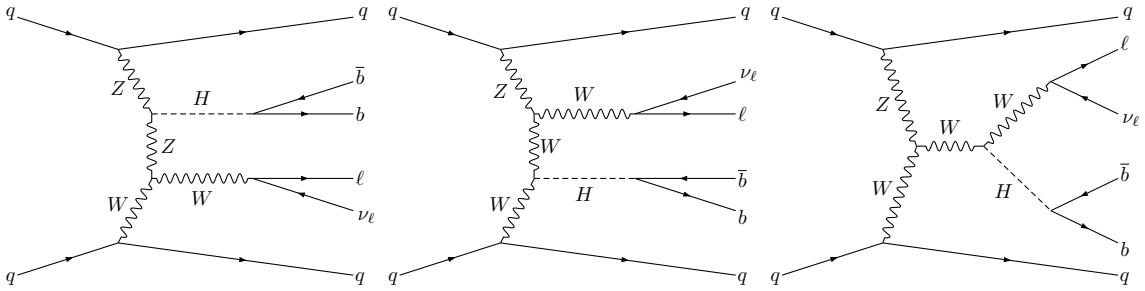


Figure 1: Tree-level Feynman diagrams for the production of  $WH \rightarrow \ell\nu\bar{b}b$  via VBS, where  $\ell$  is an electron or muon.

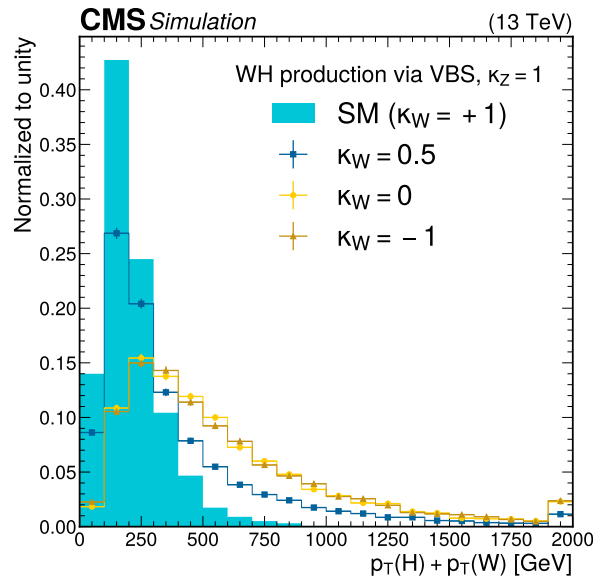


Figure 2: Distributions of the scalar sum of the Higgs boson and  $W$  boson  $p_T$ , as generated by MADGRAPH, for simulated signal events with  $\kappa_Z = 1$  and the following  $\kappa_W$  values:  $\kappa_W = 1$  (SM) in light blue (filled),  $\kappa_W = 0.5$  in dark blue,  $\kappa_W = 0$  in yellow, and  $\kappa_W = -1$  in gold. The highest bin also contains the overflows.

In this Letter, we present a study of the production of  $WH$  through VBS using the leptonic de-

cay of the  $W$  boson to an electron or a muon and the decay of the Higgs boson to  $b\bar{b}$ . The study focuses both on the SM scenario, where  $\kappa_W = \kappa_Z = 1$ , and on beyond-the-SM (BSM) scenarios, where  $\lambda_{WZ} < 0$ . The BSM analysis targets events where the Higgs boson decay to  $b$  quarks is reconstructed as a single merged jet because of the Lorentz boost it receives, whereas the SM analysis targets events where the  $b$  quarks from the Higgs boson are reconstructed as two resolved jets. The two scenarios are analyzed separately and use different methods. The study is based on data from proton-proton collisions at a center-of-mass energy of 13 TeV. The data were collected with the CMS detector [11] at the CERN LHC from 2016 to 2018, corresponding to an integrated luminosity of  $138 \text{ fb}^{-1}$ . Tabulated results are provided in the HEPData record for this work [12].

## 2 The CMS detector and object reconstruction

The CMS apparatus [11, 13] is a multipurpose, nearly hermetic detector, designed to trigger on [14, 15] and identify electrons, muons, photons, and (charged and neutral) hadrons [16–18]. A global “particle-flow” (PF) algorithm [19] aims to reconstruct all individual particles in an event (PF candidates), combining information provided by the all-silicon inner tracker and by the crystal electromagnetic and brass-scintillator hadron calorimeters (ECAL and HCAL, respectively), operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. The PF candidates are used to build  $\tau$  leptons, jets, and missing transverse momentum [20–22]. Forward calorimeters, made of steel and quartz-fibers, extend the pseudorapidity coverage provided by the barrel and endcap detectors. More detailed descriptions of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Refs. [11, 13].

Events of interest are collected using single-lepton triggers, where the charged lepton is required to be isolated from other significant detector activity and have  $p_T$  exceeding a threshold that depends on the data-taking period (year). The single-muon trigger requires  $p_T > 24$  (27) GeV in 2016 and 2018 (2017), whereas the single-electron trigger requires  $p_T > 27$  (32) GeV in 2016 (2017–18).

Muon candidates are reconstructed within the pseudorapidity range  $|\eta| < 2.4$  by combining the information from the silicon tracker and the muon chambers [17]. The muon candidates are also required to satisfy a set of quality criteria based on the number of hits measured in the silicon tracker and the muon system, the properties of the muon track, and the impact parameters of the track with respect to the primary vertex (PV) of the event, which is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone, as described in Section 9.4.1 of Ref. [23].

Electron candidates within  $|\eta| < 2.5$  are reconstructed by associating fitted tracks in the silicon tracker with electromagnetic energy clusters in the ECAL [24]. Electron candidates are required to satisfy identification criteria based on the shower shape of the energy deposit, the matching of the electron track to the ECAL energy cluster, the relative amount of energy deposited in the HCAL detector, and the consistency of the electron track with the PV. Electron candidates in the transition region between the ECAL barrel and endcaps,  $1.44 < |\eta| < 1.57$ , are discarded because of suboptimal detector performance. Electron candidates identified as originating from photon conversions in the detector are also rejected.

Muons and electrons are required to be isolated from hadronic activity in the event. The isolation value is defined by summing the  $p_T$  of all PF candidates originating from the PV in a cone of radius  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$  (0.3) around the muon (electron) track, where  $\phi$  is

the azimuthal angle in radians. The sum is corrected for the contribution of neutral particles from additional interactions in the same or nearby bunch crossings (pileup) [17, 24]. The relative isolation, defined as the isolation sum divided by the  $p_T$  of the lepton, is used in selecting well-isolated electrons and muons.

Both the SM and BSM analyses use the “tight” identification criteria described in Refs. [16, 17] to further identify electrons and muons, respectively. The electron identification criteria use a boosted decision tree (BDT) trained to identify electrons based on their kinematic values and isolation, whereas muons are required to pass a set of selections, including the requirement that their relative isolation be less than 0.15. In addition, a less stringent set of identification and isolation criteria, referred to as the “veto” criteria, are used to identify and reject additional leptons.

The missing transverse momentum vector  $\vec{p}_T^{\text{miss}}$  is computed as the negative vector  $\vec{p}_T$  sum of all PF candidates reconstructed in the event. Its magnitude is denoted as  $p_T^{\text{miss}}$  [22]. Jets are clustered using the anti- $k_T$  algorithm [25, 26] taking as input the PF candidates. The clustering algorithm is used with distance parameters of 0.4 and 0.8 to reconstruct so-called AK4 and AK8 jets, respectively. Genuine hadronic jets are identified by stringent criteria, while jets originating from pileup collisions are rejected via a multivariate discriminator [27].

The AK4 jets originating from b quark hadronization and decay (b jets) are identified using DEEPJET [28–30], a deep neural network whose inputs are the kinematic values of the jets and their constituents, including secondary vertices associated with the jets. A requirement is placed on the output of DEEPJET in order to classify jets as “b-tagged.” For the chosen working point, the efficiency to select b jets ranges from 71 to 81%, depending on the  $p_T$  and  $\eta$  of the jet, and the rate for incorrectly tagging jets originating from the hadronization of gluons or light quarks is approximately 1%. Pairs of b-tagged AK4 jets are used to identify Higgs boson candidates in the SM analysis.

The AK8 jets are used to reconstruct the Higgs boson candidates in the BSM analysis. The mass-decorrelated  $X \rightarrow b\bar{b}$  PARTICLENET tagger [31], a graph neural network that uses the components of an AK8 jet to identify its source, is used to identify  $H \rightarrow b\bar{b}$  candidates. The soft-drop grooming algorithm [32] with angular exponent  $\beta = 0$  and soft radiation fraction  $z = 0.1$ , also known as the modified mass-drop algorithm [33], is applied to the AK8 jets to remove soft and wide-angle radiation when estimating the Higgs boson candidate mass. This estimate of the mass is referred to as the soft-drop mass, or  $m_{\text{SD}}$ , whereas the ungroomed jet mass is denoted as  $m$ .

### 3 Simulated event samples

We model VBS WH events at LO using the MADGRAPH5\_aMC@NLO (v2.6.5) [34] Monte Carlo (MC) event generator, interfaced with the PYTHIA (v8.240) [35] program, which is responsible for the modeling of the boson decays. The SM cross section of the generated events is approximately 13 fb after the W boson decays leptonically and the Higgs boson decays to  $b\bar{b}$ . In order to study different  $\lambda_{WZ}$  scenarios, in addition to the SM value of  $\kappa_W = \kappa_Z = 1$ , we also generate events with  $\kappa_W = -1$  and  $\kappa_Z = +1$  to test the hypothesis  $\lambda_{WZ} = -1$ . These BSM events are generated using a different version (v2.6.1) of MADGRAPH5\_aMC@NLO. With these same settings, a third VBS WH sample is generated with a reweighting scheme for 625 different values of  $\kappa_W$  and  $\kappa_Z$  in the range  $[-2, 2]$ , allowing for a two-dimensional scan of the parameter space.

The main sources of background for both the SM and BSM analyses are  $t\bar{t}$  and  $W + \text{jets}$  pro-

duction, because of the presence of at least one  $W$  boson and a high jet multiplicity. The  $t\bar{t}$  background [36] is generated at next-to-leading-order (NLO) accuracy in perturbative quantum chromodynamics (QCD) with the POWHEG (v2.0) program [37–39]. The  $W + \text{jets}$  background is generated with MADGRAPH5\_aMC@NLO (v2.6.5) at LO accuracy for up to 4 additional partons merged using the MLM matching scheme [40].

The largest subleading backgrounds for both the SM and BSM analyses are diboson and single top quark production. Diboson events are generated with MADGRAPH5\_aMC@NLO at NLO with up to one additional parton, using the FxFx merging scheme [41], or with POWHEG at NLO accuracy. The  $tW$  and  $t$ -channel single top quark processes are generated to NLO accuracy with POWHEG, whereas  $s$ -channel single top quark production is modeled with MADGRAPH5\_aMC@NLO (v2.6.5) at NLO accuracy [42–44].

In the SM analysis, we also consider backgrounds from VBS production of a  $W$  boson, quark-initiated WH, and  $Z + \text{jets}$  production. The  $Z + \text{jets}$  events are generated with the same settings used to generate  $W + \text{jets}$  events. The VBS  $W$  background events are also generated with these settings, without any additional jets. Finally, quark-initiated WH production is generated at NLO QCD accuracy using the POWHEG event generator extended with the MinLO procedure [45].

The generated matrix-element-level background events are interfaced with PYTHIA v8.240 or later versions to model parton showers and hadronization, as well as the underlying event. In the case of VBS WH production, we also use PYTHIA, but with a dipole recoil scheme chosen to correctly emulate the color structure [46]. The generation of all samples is based on the CP5 tune [47] for PYTHIA and the NNPDF v3.1 next-to-next-to-leading-order (NNLO) parton distribution functions (PDFs) [48, 49]. Simulated pileup interactions are added to the hard-scattering process, with a multiplicity matched to the pileup profiles of the data. Finally, the response of the CMS detector is modeled with GEANT4 [50].

## 4 Event selection and background estimation

The selection criteria that target the leptonic  $W$  boson decay, a single electron or muon plus  $p_T^{\text{miss}}$  from a neutrino, are common for the SM and BSM analyses. Events are required to contain a tight muon with  $p_T > 26$  (30) GeV in 2016 and 2018 (2017) data, or a tight electron with  $p_T > 30$  (35) GeV in 2016 (2017–18) data. Events are rejected if they contain an additional electron or muon with  $p_T > 10$  GeV that satisfies the veto criteria. Events are also required to have  $p_T^{\text{miss}}$  larger than 30 GeV. In addition, in both the SM and BSM analyses, events must contain at least two AK4 jets (the VBS signature jets) that are not b-tagged, do not overlap with the Higgs boson decay products, and satisfy  $p_T > 30$  GeV,  $|\eta| < 4.7$ ,  $m_{jj} > 500$  GeV, and  $|\Delta\eta_{jj}| > 2.5$ , where  $m_{jj}$  is the invariant mass of the dijet system and  $\Delta\eta_{jj}$  is the difference in pseudorapidity between the jets.

The SM analysis is based on selecting two AK4 jets instead of a single AK8 jet to construct the Higgs boson candidate. Specifically, events are required to have two b-tagged AK4 jets with  $p_T > 30$  GeV,  $|\eta| < 2.5$ , and a dijet invariant mass ( $m_{bb}$ ) in the range  $50 < m_{bb} < 150$  GeV.

A BDT, referred to as the signal BDT, is employed to discriminate between the SM signal and the sum of all backgrounds. The signal events are assigned a target output of 1 and the background events are assigned a target output of 0. The BDT is trained using simulated events to regress the target output with the mean squared error loss function. The training and inference are performed with the XGBoost Python package [51]. The variables that are input to the sig-

nal BDT include the  $p_T$ ,  $\eta$ , and  $\phi$  of all selected leptons and jets; the  $p_T$  and  $\phi$  of  $\vec{p}_T^{\text{miss}}$ ; the b jet discriminator value of all selected jets; and  $m_{jj}$ ,  $\Delta\eta_{jj}$ , and  $m_{bb}$ . Finally, the SM signal region is defined by requiring the signal BDT output to be larger than 0.5, in addition to the  $m_{bb}$ ,  $m_{jj}$ , and  $\Delta\eta_{jj}$  selections already applied.

The background in the SM BDT output signal region is estimated from two control regions used to determine the overall rate of the  $W + \text{jets}$  and  $t\bar{t}$  processes. The distributions of these backgrounds, along with both the distributions and overall rates of other smaller backgrounds, are taken from simulation. The control region used to constrain the  $W + \text{jets}$  process is defined by inverting the BDT output requirement for the signal region. In this control region, a second BDT, referred to as the  $W + \text{jets}$  BDT, is trained to discriminate between  $W + \text{jets}$  and all other processes using the same set of input variables as the signal BDT. Then, the  $W + \text{jets}$  BDT distribution is used to extract the overall rate of  $W + \text{jets}$  production. The control region used to constrain the  $t\bar{t}$  process has the signal BDT output requirement removed and the signal region  $m_{jj}$  requirement modified to  $100 < m_{jj} < 500 \text{ GeV}$ . In this control region, the  $m_{jj}$  distribution is fit to extract the overall  $t\bar{t}$  production rate.

The signal region for the BSM analysis requires events to have one AK8 jet with  $p_T > 300 \text{ GeV}$ , an  $X \rightarrow b\bar{b}$  PARTICLENET score greater than 0.9,  $m > 50 \text{ GeV}$ , and  $40 < m_{SD} < 150 \text{ GeV}$ . Events are also required to have no b-tagged AK4 jets. Finally, each event must satisfy  $p_T(\ell) + p_T^{\text{miss}} + p_T(\text{H} \rightarrow b\bar{b} \text{ jet}) > 900 \text{ GeV}$ , and the requirements on the VBS jets are increased to  $m_{jj} > 600 \text{ GeV}$  and  $|\Delta\eta_{jj}| > 4$ .

The background in the BSM signal region is estimated using a modification of the ‘‘ABCD’’ method (e.g. [52, 53]), where two approximately independent variables are used to define four orthogonal regions: region A, the signal region, and regions B, C, and D, which are dominated by background events. In this work,  $\Delta\eta_{jj}$  and  $m_{SD}$  are used, such that inverting one or both selections on each variable gives the background-dominated regions:  $|\Delta\eta_{jj}| \leq 4$  and  $m_{SD} < 150 \text{ GeV}$  for region B,  $|\Delta\eta_{jj}| > 4$  and  $m_{SD} \geq 150 \text{ GeV}$  for region C, and  $|\Delta\eta_{jj}| \leq 4$  and  $m_{SD} \geq 150 \text{ GeV}$  for region D. The predicted background yield in the signal region  $A_{\text{data}}^{\text{pred}}$  is then obtained by the following relation:

$$A_{\text{data}}^{\text{pred}} = \left( B_{\text{data}} \frac{C_{\text{data}}}{D_{\text{data}}} \right) \left( \frac{A_{\text{MC}}/B_{\text{MC}}}{C_{\text{MC}}/D_{\text{MC}}} \right),$$

where  $B_{\text{data}}$ ,  $C_{\text{data}}$ , and  $D_{\text{data}}$  are the yields of the three regions in data, and the simulated background yields  $A_{\text{MC}}$ ,  $B_{\text{MC}}$ ,  $C_{\text{MC}}$ , and  $D_{\text{MC}}$  are used as a correction (right term) to the standard method (left term). This correction accounts for a small correlation between  $\Delta\eta_{jj}$  and  $m_{SD}$  for background events that causes an 11% discrepancy between the ABCD prediction in simulation and  $A_{\text{MC}}$ . This discrepancy is taken as a baseline for the systematic uncertainty in the prediction. However, the background composition varies across regions A, B, C, and D, and it is not known to high precision. As a result, the baseline systematic uncertainty is extended by varying the subleading backgrounds within their respective uncertainties, representing scenarios in which the contributions from each background are larger or smaller, and recalculating the discrepancy of the method.

Based on studies of the discrepancy in the various scenarios, we assign a systematic uncertainty of 13% in the background prediction. The yields in the BSM signal region, with  $\kappa_W = -1$ ,  $\kappa_Z = 1$ , are tabulated in Table 1 and the yields in regions A, B, C, and D are shown in Fig. 3.

Table 1: The background yield estimated from data and signal yield ( $\kappa_W = -1$ ,  $\kappa_Z = 1$ ) predicted by MC simulation in the BSM signal region are shown with their associated statistical and systematic uncertainties. The systematic uncertainty in the signal yield quoted here is the sum in quadrature of the independent relative systematic uncertainties, multiplied by the total yield. The observed data yield is also tabulated.

Type	Yield	Stat. Unc.	Syst. Unc.
Signal	366	3	68
Background	108	14	14
Observed	130		

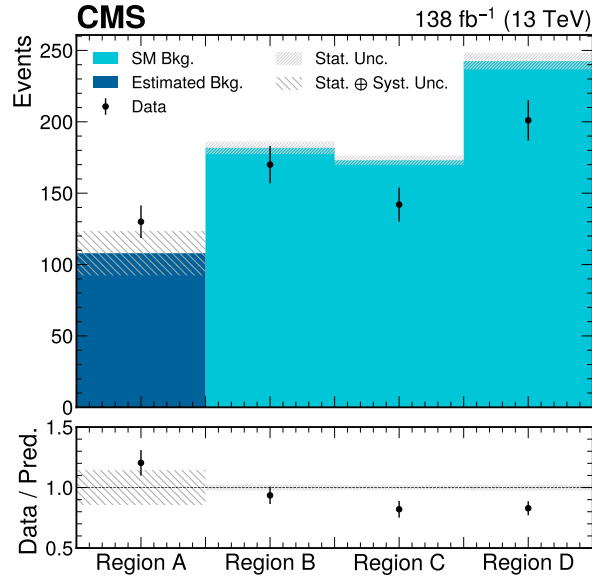


Figure 3: Event yields observed in the data (black points) for regions A, B, C, and D of the BSM analysis, where region A is the signal region. The simulated SM background event yields in the control regions B, C, and D are shown in light blue. The background in the signal region estimated from data in regions B, C, and D is plotted in dark blue. The lower panel shows the ratio of the data to the estimated background yields. The vertical bars on the points give the statistical uncertainty in the data, while the gray and hatched areas represent the statistical and total uncertainties in the estimated backgrounds, respectively.

## 5 Systematic uncertainties

Results are obtained from binned maximum likelihood fits of the signal and predicted background expectations to the data yields [54]. Three distributions— $m_{jj}$  in the  $t\bar{t}$  control region, the  $W + \text{jets}$  BDT in the  $W + \text{jets}$  control region, and the signal BDT in the signal region—are fit simultaneously in the SM analysis, whereas a single-bin counting experiment is performed for the BSM analysis. Several sources of systematic uncertainties are estimated for these measurements. Systematic uncertainties are constrained by log-normal functions, and correlations between sources of systematic uncertainties are included as nuisance parameters. Theoretical sources of uncertainty include the renormalization and factorization scales ( $\mu_R$  and  $\mu_F$ , respectively), the PDFs, and the modeling of initial- and final-state radiation. Experimental sources of uncertainty include the single-lepton trigger efficiency, lepton identification efficiency, jet energy scale and resolution [21], DEEPJET  $b$ -tagging efficiency, PARTICLENET  $X \rightarrow b\bar{b}$  tagger efficiency, and integrated luminosity measurement [55–57]. In the SM analysis, the finite statistical power of the simulated samples is considered as a source of uncertainty using the Barlow-



Beeston method [58]. In the BSM analysis, the statistical uncertainties in the background estimation method and the signal simulation are considered as two additional log-normal constraints. The leading systematic uncertainty in the SM signal yield comes from the uncertainty in the b jet tagging efficiency due to the purity of the b jet enriched region where the efficiency is measured in data. The rate of non-b jets in this region is subtracted based on simulation, so the uncertainty is determined by varying the size of the subtraction up and down by 20% [28]. The leading systematic uncertainty in the BSM signal yield comes from the variation of  $\mu_F$ . In particular,  $\mu_F$  is varied up and down by a factor of 2, and the largest difference in the signal yield is taken as the systematic uncertainty.

## 6 Results

The BDT distribution in the signal region for the SM analysis is shown in Fig. 4. The observed (expected) signal strength, the rate of the VBS WH signal relative to the SM, is  $3.0^{+5.9}_{-5.5}$  ( $1.0^{+4.3}_{-4.0}$ ). The observed (expected) signal significance is  $0.54\sigma$  ( $0.25\sigma$ ), where  $\sigma$  is a standard deviation. Finally, the observed (expected) 95% confidence level upper limit is 14.3 (9.0) times the SM prediction.

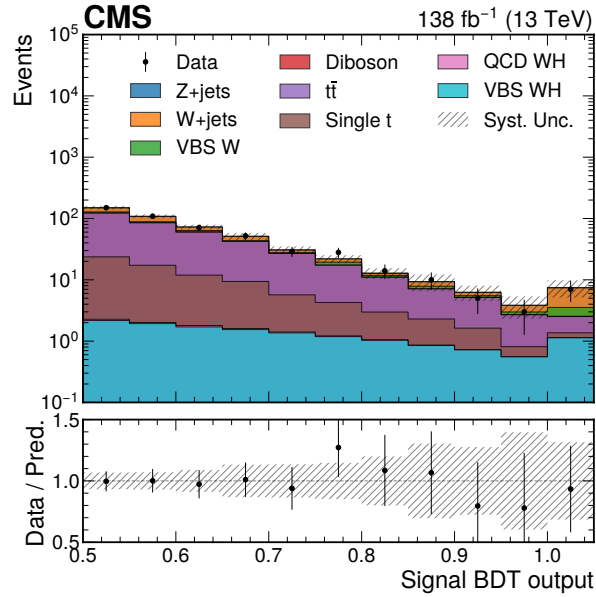


Figure 4: Observed and expected distributions of the BDT output in the signal region of the SM analysis. The data are shown by the points and the expected contributions from the various sources after the fit to the data by the colored histograms. The lower plot displays the ratio of the data to the sum of the predicted distributions. The vertical bars on the points indicate the statistical uncertainty in the data, and the hatched regions show the systematic uncertainty in the sum of the predicted yields. The rightmost bin includes overflow.

The limits in the BSM analysis are set following the procedure described in Section 3.2 of Ref. [59]. We find that the scenario where  $\lambda_{WZ} = \kappa_W / \kappa_Z = -1$ , with  $|\kappa_W| = 1$  and  $|\kappa_Z| = 1$ , is excluded at a confidence level (CL) higher than 99.99%, with an expected and observed significance beyond  $5\sigma$ . This procedure is repeated for 625 different values of  $\kappa_W$  and  $\kappa_Z$ . The exclusion significance regions in the two-dimensional  $\kappa_W$ - $\kappa_Z$  plane is shown in Fig. 5. The observed 95% CL ( $2\sigma$ ) and 99.99% ( $5\sigma$ ) contours are given by the dark and light blue colors, respectively, while the expected contours are given by the labeled yellow lines. The contours correspond to the conditions  $-2\Delta \log L < 6.18$  and  $< 28.7$ , respectively, where  $L$  is the value of

the likelihood function. We find that all of the opposite sign scenarios with  $\kappa_W$  and  $\kappa_Z$  values compatible with the current measurements,  $|\kappa_W| = 1.02 \pm 0.08$  and  $|\kappa_Z| = 1.04 \pm 0.07$  [8], are excluded at a CL higher than 99.99%.

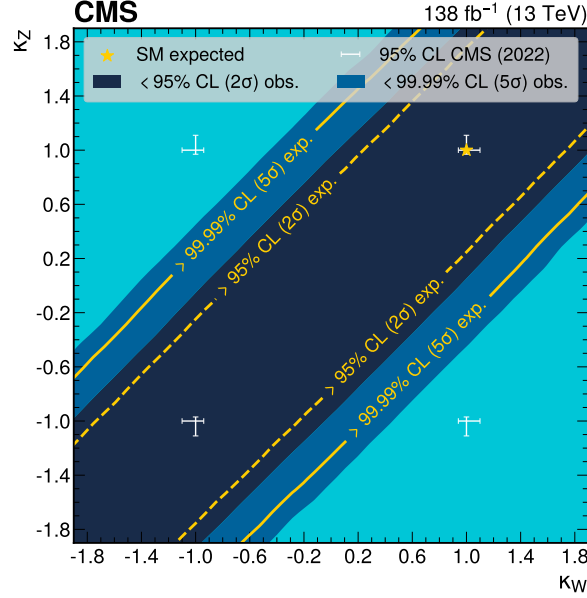


Figure 5: The  $>95\%$  ( $2\sigma$ ) and  $>99.99\%$  ( $5\sigma$ ) exclusion regions in the two-dimensional  $\kappa_W$ - $\kappa_Z$  plane are shown by the dark and light blue colors, respectively. Previous CMS measurements of the magnitude of  $\kappa_W$  and  $\kappa_Z$  at the 95% CL [8] are represented by the horizontal and vertical bars, and the SM expectation is given by the gold star.

## 7 Summary

In this Letter, we have reported the first study of WH production through vector boson scattering (VBS) using  $138 \text{ fb}^{-1}$  of data recorded with the CMS detector at the LHC between 2016 and 2018 at a center-of-mass energy of 13 TeV. We focused on both the standard model (SM) scenario and scenarios where  $\lambda_{WZ} = \kappa_W / \kappa_Z$ , with  $\kappa_W$  and  $\kappa_Z$  being the HWW and HZZ coupling modifiers, respectively, is modified from the SM value of 1. Events were selected by requiring exactly one isolated charged lepton (electron or muon) and the magnitude of the missing transverse momentum  $p_T^{\text{miss}}$  being consistent with the W boson leptonic decay, two jets consistent with a VBS interaction, and one or two additional jets consistent with the Higgs boson decay to  $b\bar{b}$ . Assuming a signal with SM features, the observed (expected) ratio between the measured rate of VBS WH and the expectation from the SM is  $3.0^{+5.9}_{-5.5}$  ( $1.0^{+4.3}_{-4.0}$ ), corresponding to an observed (expected) 95% confidence level upper limit of 14.3 (9.0) times the SM prediction. The BSM scenario where  $\lambda_{WZ} = -1$ , with  $|\kappa_W| = |\kappa_Z| = 1$ , and all the opposite-sign scenarios with  $\kappa_W$  and  $\kappa_Z$  values compatible with the current measurements are excluded with a significance greater than 5 standard deviations, corresponding to a confidence level higher than 99.99%.

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











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





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







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


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








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

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










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














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

























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












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




























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
























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






















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C. Dziwok , G. Flügge , T. Kress , A. Nowack , O. Pooth , A. Stahl , T. Ziemons , A. Zotz 










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















H. Aarup Petersen , M. Aldaya Martin , J. Alimena , S. Amoroso, Y. An , J. Bach , S. Baxter , M. Bayatmakou , H. Becerril Gonzalez , O. Behnke , A. Belvedere , F. Blekman<sup>25</sup> , K. Borrás<sup>26</sup> , A. Campbell , A. Cardini , C. Cheng, F. Colombina , M. De Silva , G. Eckerlin, D. Eckstein , L.I. Estevez Banos , O. Filatov , E. Gallo<sup>25</sup> , A. Geiser , V. Guglielmi , M. Guthoff , A. Hinzmann , L. Jeppe , B. Kaech , M. Kasemann , C. Kleinwort , R. Kogler , M. Komm , D. Krücker , W. Lange, D. Leyva Pernia , K. Lipka<sup>27</sup> , W. Lohmann<sup>28</sup> , F. Lorkowski , R. Mankel , I.-A. Melzer-Pellmann , M. Mendizabal Morentin , A.B. Meyer , G. Milella , K. Moral Figueroa , A. Mussgiller , L.P. Nair , J. Niedziela , A. Nürnberg , Y. Otariid, J. Park , E. Ranken , A. Raspereza , D. Rastorguev , J. Rübenach, L. Rygaard, A. Saggio , M. Scham<sup>29,26</sup> , S. Schnake<sup>26</sup> , P. Schütze , C. Schwanenberger<sup>25</sup> , D. Selivanova , K. Sharko , M. Shchedrolosiev , D. Stafford, F. Vazzoler , A. Ventura Barroso , R. Walsh , D. Wang , Q. Wang , Y. Wen , K. Wichmann, L. Wiens<sup>26</sup> , C. Wissing , Y. Yang , A. Zimmermann Castro Santos 

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



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

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B. Ujvari , G. Zilizi 















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














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








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













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





















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M. Felcini , M. Grunewald 





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














































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



















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




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









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








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










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































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












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









#### Universität Zürich, Zurich, Switzerland

C. Amsler<sup>62</sup> , P. Bärtshi , M.F. Canelli , K. Cormier , M. Huwiler , W. Jin , A. Jofrehei , B. Kilminster , S. Leontsinis , S.P. Liehti , A. Macchiolo , P. Meiring , F. Meng , U. Molinatti , J. Motta , A. Reimers , P. Robmann, M. Senger , E. Shokr, F. Stäger , R. Tramontano 

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C. Adloff<sup>63</sup>, D. Bhowmik, C.M. Kuo, W. Lin, P.K. Rout , P.C. Tiwari<sup>38</sup> , S.S. Yu 



















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L. Ceard, K.F. Chen , P.s. Chen, Z.g. Chen, A. De Iorio , W.-S. Hou , T.h. Hsu, Y.w. Kao, S. Karmakar , G. Kole , Y.y. Li , R.-S. Lu , E. Paganis , X.f. Su , J. Thomas-Wilsker , L.s. Tsai, D. Tsionou, H.y. Wu, E. Yazgan 


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S. Cerci<sup>67</sup> , B. Isildak<sup>76</sup> , D. Sunar Cerci , T. Yetkin 


















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

A. Boyaryntsev , B. Grynyov 

























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

L. Levchuk 














































#### University of Bristol, Bristol, United Kingdom

D. Anthony , J.J. Brooke , A. Bundock , F. Bury , E. Clement , D. Cussans , H. Flacher , M. Glowacki , J. Goldstein , H.F. Heath , M.-L. Holmberg , L. Kreczko , S. Paramesvaran , L. Robertshaw , S. Seif El Nasr-Storey , V.J. Smith , N. Stylianou<sup>77</sup> , K. Walkingshaw Pass






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

A.H. Ball , K.W. Bell , A. Belyaev<sup>78</sup> , C. Brew , R.M. Brown , D.J.A. Cockerill , C. Cooke , A. Elliot , K.V. Ellis , K. Harder , S. Harper , J. Linacre , K. Manolopoulos , D.M. Newbold , E. Olaiya , D. Petyt , T. Reis , A.R. Sahasransu , G. Salvi , T. Schuh , C.H. Shepherd-Themistocleous , I.R. Tomalin , K.C. Whalen , T. Williams 

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I. Andreou , R. Bainbridge , P. Bloch , C.E. Brown , O. Buchmuller , V. Cacchio , C.A. Carrillo Montoya , G.S. Chahal<sup>79</sup> , D. Colling , J.S. Dancu , I. Das , P. Dauncey , G. Davies , J. Davies , M. Della Negra , S. Fayer , G. Fedi , G. Hall , M.H. Hassanshahi , A. Howard , G. Iles , C.R. Knight , J. Langford , J. León Holgado , L. Lyons , A.-M. Magnan , S. Mallios , M. Mieskolainen , J. Nash<sup>80</sup> , M. Pesaresi , P.B. Pradeep , B.C. Radburn-Smith , A. Richards , A. Rose , K. Savva , C. Seez , R. Shukla , A. Tapper , K. Uchida , G.P. Uttley , L.H. Vage , T. Virdee<sup>30</sup> , M. Vojinovic , N. Wardle , D. Winterbottom 







#### **Brunel University, Uxbridge, United Kingdom**

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












#### **Baylor University, Waco, Texas, USA**

S. Abdullin , A. Brinkerhoff , E. Collins , J. Dittmann , K. Hatakeyama , J. Hiltbrand , B. McMaster , J. Samudio , S. Sawant , C. Sutantawibul , J. Wilson 





















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

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
















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A. Akpınar , C. Cosby , G. De Castro , Z. Demiragli , C. Erice , C. Fangmeier , C. Fernandez Madrazo , E. Fontanesi , D. Gastler , F. Golf , S. Jeon , J. O'cain , I. Reed , J. Rohlf , K. Salyer , D. Sperka , D. Spitzbart , I. Suarez , A. Tsatsos , A.G. Zecchinelli 







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G. Benelli , D. Cutts , L. Gouskos , M. Hadley , U. Heintz , J.M. Hogan<sup>82</sup> , T. Kwon , G. Landsberg , K.T. Lau , D. Li , J. Luo , S. Mondal , N. Pervan , T. Russell , S. Sagir<sup>83</sup> , F. Simpson , M. Stamenkovic , N. Venkatasubramanian , X. Yan 

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S. Abbott , C. Brainerd , R. Breedon , H. Cai , M. Calderon De La Barca Sanchez , M. Chertok , M. Citron , J. Conway , P.T. Cox , R. Erbacher , F. Jensen , O. Kukral , G. Mocellin , M. Mulhearn , S. Ostrom , W. Wei , Y. Yao , S. Yoo , F. Zhang 

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












M. Bachtis , R. Cousins , A. Datta , G. Flores Avila , J. Hauser , M. Ignatenko 

M.A. Iqbal , T. Lam , E. Manca , A. Nunez Del Prado, D. Saltzberg , V. Valuev 

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R. Clare , J.W. Gary , M. Gordon, G. Hanson , W. Si 










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
















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A. Barzdukas , L. Brennan , C. Campagnari , K. Downham , C. Grieco , J. Incandela , J. Kim , A.J. Li , P. Masterson , H. Mei , J. Richman , S.N. Santpur , U. Sarica , R. Schmitz , F. Setti , J. Sheplock , D. Stuart , T.Á. Vami , S. Wang , D. Zhang















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

S. Bhattacharya , A. Bornheim , O. Cerri, A. Latorre, J. Mao , H.B. Newman , G. Reales Gutiérrez, M. Spiropulu , J.R. Vlimant , C. Wang , S. Xie , R.Y. Zhu 
















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

J. Alison , S. An , P. Bryant , M. Cremonesi, V. Dutta , T. Ferguson , T.A. Gómez Espinosa , A. Harilal , A. Kallil Tharayil, C. Liu , T. Mudholkar , S. Murthy , P. Palit , K. Park, M. Paulini , A. Roberts , A. Sanchez , W. Terrill 








































































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

J.P. Cumalat , W.T. Ford , A. Hart , A. Hassani , G. Karathanasis , N. Manganelli , J. Pearkes , C. Savard , N. Schonbeck , K. Stenson , K.A. Ulmer , S.R. Wagner , N. Zipper , D. Zuolo 











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








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

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













M. Albrow , M. Alyari , O. Amram , G. Apollinari , A. Apresyan , L.A.T. Bauerdick , D. Berry , J. Berryhill , P.C. Bhat , K. Burkett , J.N. Butler , A. Canepa , G.B. Cerati , H.W.K. Cheung , F. Chlebana , G. Cummings , J. Dickinson , I. Dutta , V.D. Elvira , Y. Feng , J. Freeman , A. Gandrakota , Z. Gecse , L. Gray , D. Green, A. Grummer , S. Grünendahl , D. Guerrero , 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 , D. Noonan , S. Norberg, V. Papadimitriou , N. Pastika , K. Pedro , C. Pena<sup>84</sup> , F. Ravera , A. Reinsvold Hall<sup>85</sup> , L. Ristori , M. Safdari , E. Sexton-Kennedy , N. Smith , A. Soha , L. Spiegel , S. Stoynev , J. Strait , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger , E.W. Vaandering , I. Zoi 

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






C. Aruta , P. Avery , D. Bourilkov , P. Chang , V. Cherepanov , R.D. Field, E. Koenig , M. Kolosova , J. Konigsberg , A. Korytov , K. Matchev , N. Menendez , G. Mit-

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


















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

T. Adams , A. Al Kadhim , A. Askew , S. Bower , V. Hagopian , R. Hashmi , R.S. Kim , S. Kim , T. Kolberg , G. Martinez, H. Prosper , P.R. Prova, M. Wulansatiti , R. Yohay , J. Zhang











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

B. Alsufyani, M.M. Baarmand , S. Butalla , S. Das , T. Elkafrawy<sup>86</sup> , M. Hohlmann , E. Yanes












#### **University of Illinois Chicago, Chicago, USA, Chicago, USA**

M.R. Adams , A. Baty , C. Bennett, R. Cavanaugh , R. Escobar Franco , O. Evdokimov , C.E. Gerber , M. Hawksworth, A. Hingrajiya, D.J. Hofman , J.h. Lee , D. S. Lemos , A.H. Merrit , C. Mills , S. Nanda , G. Oh , B. Ozek , D. Pilipovic , R. Pradhan , E. Prifti, T. Roy , S. Rudrabhatla , M.B. Tonjes , N. Varelas , M.A. Wadud , Z. Ye , J. Yoo 
























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

M. Alhusseini , D. Blend, K. Dilsiz<sup>87</sup> , L. Emediato , G. Karaman , O.K. Köseyan , J.-P. Merlo, A. Mestvirishvili<sup>88</sup> , O. Neogi, H. Ogul<sup>89</sup> , Y. Onel , A. Penzo , C. Snyder, E. Tiras<sup>90</sup> 









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

B. Blumenfeld , L. Corcodilos , J. Davis , A.V. Gritsan , L. Kang , S. Kyriacou , P. Maksimovic , M. Roguljic , J. Roskes , S. Sekhar , M. Swartz 


















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

A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , S. Arteaga Escatel , P. Baringer , A. Bean , Z. Flowers , D. Grove , J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu , J. Marquez , M. Murray , M. Nickel , M. Pitt , S. Popescu<sup>91</sup> , C. Rogan , C. Royon , R. Salvatico , S. Sanders , C. Smith , G. Wilson 






















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

B. Allmond , R. Gujju Gurunadha , A. Ivanov , K. Kaadze , Y. Maravin , J. Natoli , D. Roy , G. Sorrentino 











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

A. Baden , A. Belloni , J. Bistany-riebman, Y.M. Chen , S.C. Eno , N.J. Hadley , S. Jabeen , R.G. Kellogg , T. Koeth , B. Kronheim, Y. Lai , S. Lascio , A.C. Mignerey , S. Nabili , C. Palmer , C. Papageorgakis , M.M. Paranjpe, E. Popova<sup>92</sup> , A. Shevelev , L. Wang 













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

J. Bendavid , I.A. Cali , P.c. Chou , M. D'Alfonso , J. Eysermans , C. Freer , G. Gomez-Ceballos , M. Goncharov, G. Grosso, P. Harris, D. Hoang, D. Kovalskyi , J. Krupa , L. Lavezzo , Y.-J. Lee , K. Long , C. MCGinn, A. Novak , C. Paus , C. Roland , G. Roland , S. Rothman , G.S.F. Stephans , Z. Wang , B. Wyslouch , T. J. Yang 











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

B. Crossman , B.M. Joshi , C. Kapsiak , M. Krohn , D. Mahon , J. Mans , B. Marzocchi , R. Rusack , R. Saradhy , N. Strobbe 

















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

K. Bloom , D.R. Claes , G. Haza , J. Hossain , C. Joo , I. Kravchenko , J.E. Siado , W. Tabb , A. Vagnerini , A. Wightman , F. Yan , D. Yu 

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

H. Bandyopadhyay , L. Hay , H.w. Hsia, I. Iashvili , A. Kalogeropoulos , A. Kharchilava , M. Morris , D. Nguyen , S. Rappoccio , H. Rejeb Sfar, A. Williams , P. Young 



























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

G. Alverson , E. Barberis , J. Bonilla , J. Dervan, Y. Haddad , Y. Han , A. Krishna , J. Li , M. Lu , G. Madigan , R. Mccarthy , D.M. Morse , V. Nguyen , T. Orimoto , A. Parker , L. Skinnari , D. Wood 









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

J. Bueghly, S. Dittmer , K.A. Hahn , Y. Liu , Y. Miao , D.G. Monk , M.H. Schmitt , A. Taliercio , M. Velasco

















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

G. Agarwal , R. Band , R. Bucci, S. Castells , A. Das , R. Goldouzian , M. Hildreth , K.W. Ho , K. Hurtado Anampa , T. Ivanov , C. Jessop , K. Lannon , J. Lawrence , N. Loukas , L. Lutton , J. Mariano, N. Marinelli, I. Mcalister, T. McCauley , C. Mcgrady , C. Moore , Y. Musienko<sup>17</sup> , H. Nelson , M. Osherson , A. Piccinelli , R. Ruchti , A. Townsend , Y. Wan, M. Wayne , H. Yockey, M. Zarucki , L. Zygala 

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

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



















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










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



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

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




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



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