

CERN-PH-EP/2013-037  
2014/12/31

CMS-HIG-13-025

# Searches for heavy Higgs bosons in two-Higgs-doublet models and for $t \rightarrow ch$ decay using multilepton and diphoton final states in pp collisions at 8 TeV

The CMS Collaboration\*

## Abstract

Searches are presented for heavy scalar (H) and pseudoscalar (A) Higgs bosons posited in the two doublet model (2HDM) extensions of the standard model (SM). These searches are based on a data sample of pp collisions collected with the CMS experiment at the LHC at a center-of-mass energy of  $\sqrt{s} = 8$  TeV and corresponding to an integrated luminosity of  $19.5 \text{ fb}^{-1}$ . The decays  $H \rightarrow hh$  and  $A \rightarrow Zh$ , where h denotes an SM-like Higgs boson, lead to events with three or more isolated charged leptons or with a photon pair accompanied by one or more isolated leptons. The search results are presented in terms of the H and A production cross sections times branching fractions and are further interpreted in terms of 2HDM parameters. We place 95% CL cross section upper limits of approximately 7 pb on  $\sigma\mathcal{B}$  for  $H \rightarrow hh$  and 2 pb for  $A \rightarrow Zh$ . Also presented are the results of a search for the rare decay of the top quark that results in a charm quark and an SM Higgs boson,  $t \rightarrow ch$ , the existence of which would indicate a nonzero flavor-changing Yukawa coupling of the top quark to the Higgs boson. We place a 95% CL upper limit of 0.56% on  $\mathcal{B}(t \rightarrow ch)$ .

*Published in Physical Review D as doi:10.1103/PhysRevD.90.112013.*



# 1 Introduction

The standard model (SM) has an outstanding record of consistency with experimental observations. It is not a complete theory, however, and since the recent discovery of a Higgs boson [1–3], attaining a better understanding of the mechanism responsible for electroweak symmetry breaking (EWSB) has become a central goal in particle physics. The experimental directions to pursue this goal include improved characterization of the Higgs boson properties, searches for new particles such as the members of an extended Higgs sector or the partners of the known elementary particles predicted by supersymmetric models, and searches for unusual processes such as rare decays of the top quark. Since the Higgs boson plays a critical role in EWSB, searches and studies of decays with the Higgs boson in the final state have become particularly attractive.

In many extensions of the SM, the Higgs sector includes two scalar doublets [4]. The two Higgs doublet model (2HDM) [5] is a specific example of such an SM extension. In this model five physical Higgs sector particles survive EWSB: two neutral CP-even scalars ( $h$ ,  $H$ ), one neutral CP-odd pseudoscalar ( $A$ ), and two charged scalars ( $H^+$ ,  $H^-$ ) [6]. For masses at or below the 1 TeV scale these particles can be produced at the LHC. Both the heavy scalar  $H$  and pseudoscalar  $A$  can decay into electroweak bosons, including the recently discovered Higgs boson. The branching fractions of  $H$  and  $A$  into final states containing one or more Higgs bosons  $h$  often dominate when kinematically accessible. For heavy scalars with masses below the top pair production threshold, the  $H \rightarrow hh$  and  $A \rightarrow Zh$  decays typically dominate over competing Yukawa decays to bottom quarks, while for heavy scalars with masses above the top pair production threshold, these decays are often comparable in rate to decays into top pairs and are potentially more distinctive.

We describe a search for two members of the extended Higgs sector,  $H$  and  $A$ , via their decays  $H \rightarrow hh$  and  $A \rightarrow Zh$ , where  $h$  denotes the recently discovered SM-like Higgs boson [1–3]. The final states used in this search consist of three or more charged leptons or a resonant photon pair accompanied by at least one charged lepton. (In the remainder of this paper, “lepton” refers to a charged lepton,  $e$ ,  $\mu$ , or hadronic decay of the  $\tau$ -lepton,  $\tau_h$ ). The  $H \rightarrow hh$  and  $A \rightarrow Zh$  decays can yield multileptonic final states when  $h$  decays to  $WW^*$ ,  $ZZ^*$ , or  $\tau\tau$ . Similarly, the resonant decay  $h \rightarrow \gamma\gamma$  can provide a final state that contains a photon pair and one or more leptons from the decay of the other daughter particle.

Using the same dataset and technique, we also investigate the process  $t \rightarrow ch$ , namely the flavor changing rare decay of the top quark to a Higgs boson accompanied by a charm quark in the  $t\bar{t} \rightarrow (bW)(ch)$  decay. The  $t \rightarrow ch$  process can occur at an observable rate for some parameters of the 2HDM [7]. Depending on how the  $h$  boson and  $t$  quark decay, both the multilepton and the lepton+diphoton final states can be produced. Both ATLAS [8] and CMS [9] have searched for this process using complementary techniques. The CMS upper limit for the branching fraction of 1.3% at 95% Confidence Level (CL) comes from an inclusive multilepton search that uses the dataset analyzed here. We describe here a  $t \rightarrow ch$  search using lepton+diphoton events and combine the results of the previously reported multilepton search with the present lepton+diphoton search. This combination results in a considerable improvement in the  $t \rightarrow ch$  search sensitivity.

In this paper, we first briefly describe the CMS detector, data collection, and the detector simulation scheme in Section 2. We then describe in Section 3 the selection of events that are relevant for the search signatures followed by the event classification in Section 4, which calls for the data sample to be subdivided in a number of mutually exclusive channels based on the number and flavor of leptons, the number of hadronically decaying  $\tau$  leptons, photons, the tagged

flavors of the jets, as well as the amount of missing transverse energy ( $E_T^{\text{miss}}$ ). A description of the SM background estimation in Section 5 precedes the channel-by-channel comparison of the observed number of events with the background estimation in Section 6. We next interpret in Section 7 these observations in terms of the standalone production and decay rates for H and A. Since these rates follow from the parameters of the 2HDM, we reexpress these results in terms of the appropriate 2HDM parameters. Finally, we selectively redeploy the H and A analysis procedure to search for the rare  $t \rightarrow ch$  decay.

The multilepton component of this analysis closely follows the previously mentioned CMS inclusive multilepton analysis [9]. In particular, the lepton reconstruction, SM background estimation procedures as well as the dataset used are identical in the two analyses and are therefore described minimally here.

## 2 Detector, data collection, and simulation

The central feature of the CMS detector is a superconducting solenoidal magnet of field strength 3.8 T. Within the field volume are a silicon pixel and strip tracker, a lead tungstate crystal calorimeter, and a brass-and-scintillator hadron calorimeter. The tracking detector covers the pseudorapidity region  $|\eta| < 2.5$  and the calorimeters  $|\eta| < 3.0$ . Muon detectors based on gas-ionization detectors lie outside the solenoid, covering  $|\eta| < 2.4$ . A steel-and-quartz-fiber forward calorimeter provides additional coverage between  $3 < |\eta| < 5.0$ . A detailed description of the detector as well as a description of the coordinate system and relevant kinematical variables can be found in Ref. [10].

The data sample used in this search corresponds to an integrated luminosity of  $19.5 \text{ fb}^{-1}$  recorded in 2012 with the CMS detector at the LHC. Dilepton triggers (dielectron, dimuon, muon-electron) and diphoton triggers are used for data collection. The transverse momentum ( $p_T$ ) threshold for dilepton triggers is 17 GeV for the leading lepton and 8 GeV for the subleading lepton. Similarly, the  $p_T$  thresholds for the diphoton trigger are 36 and 22 GeV.

The dominant SM backgrounds for this analysis such as  $t\bar{t}$  quark pairs and diboson production are simulated using the MADGRAPH (version 5.1.3.30) [11] generator. We use the CTEQ6L1 leading-order parton distribution function (PDF) set [12]. For the diboson + jets simulation, up to two jets are selected at the matrix element level in MADGRAPH. The detector simulation is performed with GEANT4 [13]. The generation of signal events is performed using both the MADGRAPH and PYTHIA generators, with the description of detector response based on the CMS fast simulation program [14].

## 3 Particle reconstruction and preliminary event selection

The CMS experiment uses a particle-flow (PF) based event reconstruction [15, 16], which takes into account information from all subdetectors, including charged-particle tracks from the tracking system and deposited energy from the electromagnetic and hadronic calorimeters. All particles in the event are classified into mutually exclusive types: electrons, muons,  $\tau$  leptons, photons, charged hadrons, and neutral hadrons.

Electron and muon candidates used in this search are reconstructed from the tracker, calorimeter, and muon system measurements. Details of reconstruction and identification can be found in Ref. [17, 18] for electrons and in Refs. [19, 20] for muons. The electron and muon candidates are required to have  $p_T \geq 10 \text{ GeV}$  and  $|\eta| < 2.4$ . For events triggered by the dilepton trigger, the leading electron or muon must have  $p_T > 20 \text{ GeV}$  in order to ensure maximal efficiency of the

dilepton trigger. Hadronic decays of the  $\tau$  lepton ( $\tau_h$ ) are reconstructed using the hadron-plus-strips (HPS) method [21] and must have the measured jet  $p_T$  of the jet tagged as a  $\tau_h$  candidate to be greater than 20 GeV and  $|\eta| \leq 2.3$ .

Photon candidates are reconstructed using the energy deposit clusters in the electromagnetic calorimeter [18, 22]. Candidate photons are required to satisfy shower shape requirements. In order to reject electrons misidentified as photons, the photon candidate must not match any of the tracks reconstructed with the pixel detector. Photon candidates are required to have  $p_T \geq 20$  GeV and  $|\eta| < 2.5$ . For events triggered by the diphoton trigger, the leading (subleading) photon must have  $p_T > 40(25)$  GeV.

Jets are reconstructed by clustering PF particles using the anti- $k_T$  algorithm [23] with a distance parameter of 0.5 and are required to have  $|\eta| \leq 2.5$ . Jets are further characterized as being “b-tagged” using the medium working point of the CMS Combined secondary-vertex (CSV) algorithm [24]. They typically result from the decays of the b quark. The total hadronic transverse energy,  $H_T$ , is the scalar sum of the  $p_T$  of all jets with  $p_T > 30$  GeV. The  $E_T^{\text{miss}}$  in an event is defined to be the magnitude of the vectorial  $p_T$  sum of all the PF candidates.

The primary vertex for a candidate event is defined as the reconstructed collision vertex with the highest  $p_T^2$  sum of the associated tracks. It also must be within 24 cm from the center of the detector, along the beam axis ( $z$  direction), and within 2 cm in a direction transverse to the beam line [25]. We require the candidate leptons to originate from within 0.5 cm in  $z$  of the primary vertex and that their impact parameters  $d_{xy}$  between the track and the primary vertex in the plane transverse to the beam axis be at most 0.02 cm.

For electrons and muons, we define the relative isolation  $I_{\text{rel}}$  of the candidate leptons to be the ratio of the  $p_T$  sum of all other PF candidates that are reconstructed in a cone defined by  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$  around the candidate to the  $p_T$  of the candidate, and require  $I_{\text{rel}} < 0.15$ . The photon isolation requirement is similar, but varies as a function of the candidate  $p_T$  and  $\eta$  [26]. For the isolation of the  $\tau_h$  candidates, we require that the  $p_T$  sum of all other particles in a cone of  $\Delta R < 0.5$  be less than 2 GeV. The isolation variable for leptons and photons is corrected for the contributions from pileup interactions [27]. The combined efficiency for trigger, reconstruction and identification are approximately 75% for electrons and 80% for muons. The identification and isolation efficiency for prompt leptons is measured in data using a “tag-and-probe” method based on an inclusive sample of  $Z + \text{jets}$  events [28]. The ratio of the efficiency in data and simulation parameterized by the different  $p_T$  and  $\eta$  values of the probed lepton is used to correct the selection efficiency in the simulated samples.

A leptonically-decaying  $Z$  boson can lead to a trilepton event when the final-state radiation undergoes (internal or external) conversion and one of the leptons escapes detection. Therefore, we reject trilepton events with low missing transverse energy ( $E_T^{\text{miss}} < 30$  GeV) when their three body invariant mass is consistent with the  $Z$  mass (i.e.  $m_{\ell^+\ell^-\ell^\pm}$  or  $m_{\ell^+\ell^-\ell^\pm}$  is between 75 and 105 GeV), even if  $m_{\ell^+\ell^-}$  is not ( $\ell = e, \mu$ ). Finally, SM background from abundant low-mass Drell–Yan production and low-mass resonances like  $J/\psi$  and  $Y$  is suppressed by rejecting an event if it contains a dilepton pair with  $m_{\ell^+\ell^-}$  below 12 GeV.

## 4 Event classification

We perform searches using a multi-channel counting experiment approach. A multilepton event consists of at least three isolated and prompt leptons ( $e, \mu, \tau_h$ ), of which at least two must be electrons or muons (“light” leptons). A photon pair together with at least one lepton makes

a lepton+diphoton event. The relatively low rates for multilepton and lepton+diphoton final states in SM allow this search to target rare signals.

#### 4.1 The $H \rightarrow hh$ , $A \rightarrow Zh$ , and $t \rightarrow ch$ signals

In the  $H \rightarrow hh$  search, seven combinations of the  $hh$  decays ( $WW^*WW^*$ ,  $WW^*ZZ^*$ ,  $WW^*\tau\tau$ ,  $ZZ^*ZZ^*$ ,  $ZZ^*\tau\tau$ ,  $ZZ^*bb$ , and  $\tau\tau\tau\tau$ ) can result in a final state containing multileptons and three combinations ( $\gamma\gamma WW^*$ ,  $\gamma\gamma ZZ^*$ , and  $\gamma\gamma\tau\tau$ ) can result in lepton+diphoton final states with appreciable rates.

In the  $A \rightarrow Zh$  search, the multilepton and diphoton signal events can result from the  $WW$ ,  $ZZ$ ,  $\tau\tau$  and  $\gamma\gamma$  decays of the  $h$ , when accompanied by the appropriate decays of the  $W$  and  $Z$  bosons and the  $\tau$  lepton. Five combinations of the  $Zh$  decays ( $Z \rightarrow \ell\ell$ ,  $h \rightarrow WW^*$ ;  $Z \rightarrow \ell\ell$ ,  $h \rightarrow ZZ^*$ ;  $Z \rightarrow \ell\ell$ ,  $h \rightarrow \tau\tau$ ;  $Z \rightarrow \nu\nu$ ,  $h \rightarrow ZZ^*$ ;  $Z \rightarrow qq$ ,  $h \rightarrow ZZ^*$ ) can result in a final state containing multileptons and one combination ( $Z \rightarrow \ell\ell$ ,  $h \rightarrow \gamma\gamma$ ) leads to lepton+diphoton states with substantial rates.

For the  $t \rightarrow ch$  search, three combinations in the decay chain  $t\bar{t} \rightarrow (bW)(ch) \rightarrow (b\ell\nu)(ch)$  can lead to multilepton final states, namely  $h \rightarrow WW^*$ ,  $h \rightarrow ZZ^*$ , and  $h \rightarrow \tau\tau$ . The  $bWch$  channel can also result in a lepton+diphoton final state when the Higgs boson decays to a photon pair. Finally, given the parent  $t\bar{t}$  state, the amount of hadronic activity in the  $t \rightarrow ch$  signal events is expected to be quite large.

#### 4.2 Multilepton search channels

A three-lepton event must contain exactly three isolated and prompt leptons ( $e$ ,  $\mu$ ,  $\tau_h$ ), of which two must be electrons or muons. Similarly, a four-lepton event must contain at least four leptons, of which three must be electrons or muons. With the goal of segregating SM backgrounds, these events are classified on the basis of the lepton flavor, their relative charges, as well as charge and flavor combinations and other kinematic quantities such as dilepton invariant mass and  $E_T^{\text{miss}}$ , as follows.

Events with  $\tau_h$  are grouped separately because narrow jets are frequently misidentified as  $\tau_h$ , leading to larger SM backgrounds for channels with  $\tau_h$ . Similarly, the presence of a  $b$ -tagged jet in an event calls for a separate grouping in order to isolate the  $t\bar{t}$  background.

The next classification criterion is the maximum number of opposite-sign and same-flavor (OSSF) dilepton pairs that can be constructed in an event using each light lepton only once. For example, both  $\mu^+\mu^-\mu^-$  and  $\mu^+\mu^-e^-$  are said to be OSSF1, and a  $\mu^+e^-\tau_h$  would be OSSF0. Both  $e^+e^+\mu^-$  and  $\mu^+\mu^+\tau_h$  are OSSF0(SS), where SS additionally indicates the presence of same-signed electron or muon pairs. Similarly,  $\mu^+\mu^-e^+e^-$  is OSSF2. An event with an OSSF pair is said to be “on-Z” if the invariant mass of at least one of the OSSF pair is between 75 GeV and 105 GeV, otherwise it is “off-Z”. An OSSF1 off-Z event is “below-Z” or “above-Z” depending on whether the mass of the pair is less than 75 GeV or more than 105 GeV, respectively. An on-Z OSSF2 event may be a “one on-Z” or a “two on-Z” event.

Finally, the three-lepton events are classified in five  $E_T^{\text{miss}}$  bins:  $< 50$ , 50–100, 100–150, 150–200, and  $> 200$  GeV and the four-lepton events are classified in four  $E_T^{\text{miss}}$  bins:  $< 30$ , 30–50, 50–100, and  $> 100$  GeV. This results in a total of 70 three-lepton channels and 72 four-lepton channels which are listed explicitly when we later present the tables of event yields and background predictions (Tables 1 and 2).

### 4.3 Lepton+diphoton search channels

A diphoton pair together with at least one lepton makes a lepton+diphoton event. The diphoton invariant mass of the  $h \rightarrow \gamma\gamma$  candidates must be between 120 and 130 GeV. The search channels are  $\gamma\gamma\ell\ell$ ,  $\gamma\gamma\ell\tau_h$ ,  $\gamma\gamma\ell$ , and  $\gamma\gamma\tau_h$ . Depending on the relative dilepton flavor and invariant mass, the  $\gamma\gamma\ell\ell$  events can be OSSF0, OSSF1 on-Z, or OSSF1 off-Z. The SM background decreases with increasing  $E_T^{\text{miss}}$ , therefore the events are further classified, when appropriate, in three bins:  $E_T^{\text{miss}} < 30$ ,  $30\text{--}50$ , and  $>50$  GeV.

The  $t \rightarrow ch$  signal populates the  $\gamma\gamma\ell$  and  $\gamma\gamma\tau_h$  channels but not the dilepton+diphoton channels. Since the  $t \rightarrow ch$  signal events always contain a b quark from the conventional bW decay of one of the top quarks, the  $\gamma\gamma\ell$  and  $\gamma\gamma\tau_h$  search channels are further classified based on the presence of a b-tagged jet. For these channels, we also split the last  $E_T^{\text{miss}}$  bin into two:  $50\text{--}100$  GeV and  $>100$  GeV.

The overall lepton+diphoton channel count in this search is seven for  $\gamma\gamma\ell\ell$ , three for  $\gamma\gamma\ell\tau_h$ , and eight each for  $\gamma\gamma\ell$  and  $\gamma\gamma\tau_h$ . They are listed explicitly when we present the tables of event yields and background predictions later (Tables 6 and 7).

## 5 Background estimation

### 5.1 Multilepton background estimation

Significant sources of multilepton SM background are Z + jets, diboson production ( $VV$  + jets;  $V = W, Z$ ),  $t\bar{t}$  production, and rare processes such as  $t\bar{t}V$  + jets. The techniques we use here to estimate these backgrounds are identical to those used in Ref. [9] and are described briefly below.

WZ and ZZ diboson production can yield events with three or four intrinsically prompt and isolated leptons that can be accompanied by significant  $E_T^{\text{miss}}$  and  $H_T$ . To estimate these background contributions, we use a simulation validated after kinematic comparisons with appropriately enriched data samples.

Processes such as Z + jets and  $W^+W^-$  + jets can yield events with two prompt leptons. These can be accompanied by jets that may also contain leptons from the semileptonic decays of hadrons, or other objects that are misreconstructed as prompt leptons, leading to a three-lepton SM background. Since the simulation of the rare fluctuations that lead to such a misidentified prompt lepton can be unreliable, we use the data with two reconstructed leptons to estimate this SM background using the number of isolated prompt tracks in the dilepton dataset.

The  $t\bar{t}$  decay can result in two prompt leptons and is a source of background when the decay of one of the daughter b quarks reconstructs as the third prompt lepton candidate. This background is estimated from a  $t\bar{t}$  Monte Carlo sample and using the probability of occurrence of a misidentified third lepton derived from data.

For search channels that contain  $\tau_h$ , we estimate the probability of a (sparse) jet misidentified as a  $\tau_h$  candidate by extrapolating the isolation distribution of the  $\tau_h$  candidates. Since the shape of this distribution is sensitive to the extent of jet activity, the extrapolation is carried out as a function of the hadronic activity in the sample as determined by the summed  $p_T$  of all tracks as well as the leading jet  $p_T$  in the event.

Finally, minor backgrounds from rare processes such as  $t\bar{t}V$  + jets or SM Higgs production including its associated production with W, Z, or  $t\bar{t}$  are estimated using simulation.

## 5.2 Lepton+diphoton background estimation

We use a 120–130 GeV diphoton invariant mass window to capture the  $h \rightarrow \gamma\gamma$  signal. With the requirement of at least one lepton in these lepton+diphoton channels, the SM background tends to be small and is estimated by interpolating the diphoton mass sidebands of the signal window. We assume the background distribution shape to be a falling exponential as a function of the diphoton invariant mass over the 100–200 GeV mass range.

Figure 1 (Left) shows the exponential fit to the 100–120 and 130–200 GeV sidebands in the mass distribution for  $\gamma\gamma\tau_h$  events with  $E_T^{\text{miss}} < 30$  GeV. We choose this sample to determine the exponent because it is a high-statistics sample. This exponent is used for background determination in all diphoton channels, allowing only the normalization to float from channel to channel. Figure 1 (Right) shows an example of such a fit for the  $\gamma\gamma\ell$  sample with a 30–50 GeV  $E_T^{\text{miss}}$  requirement along with an exponential fit where both the exponent and normalization are allowed to float. We assign a 50% systematic uncertainty for background determination in the 120–130 GeV Higgs boson mass region. The figure also shows the expected signal multiplied by a factor of three for clarity for  $m_H = 300$  GeV, assuming that the production cross section  $\sigma$  for  $m_H = 300$  GeV is equal to the Standard Model Higgs gluon fusion value of 3.59 pb at this mass given by the LHC Higgs Cross Section Working Group in Ref. [29], and a branching fraction  $\mathcal{B}(H \rightarrow hh) = 1$ .

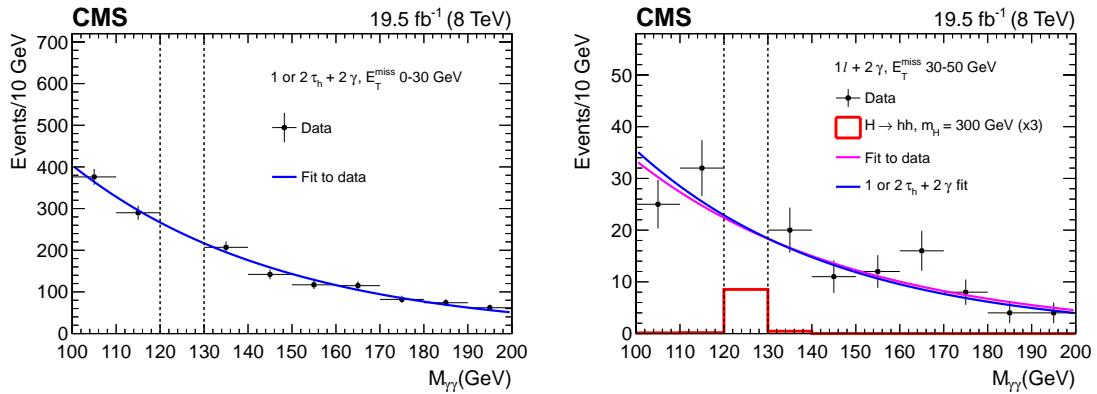


Figure 1: Left: diphoton invariant mass distribution for  $\gamma\gamma\tau_h$  events with  $E_T^{\text{miss}} < 30$  GeV with an exponential fit derived from the 100–120 and 130–200 GeV sidebands regions. Right: the same distribution for the  $\gamma\gamma\ell$  events with  $E_T^{\text{miss}}$  in 30–50 GeV range with an exponential fit (blue curve) where the exponent is fixed to the value obtained from the fit shown in the left figure. Also shown for comparison purposes is an actual fit (magenta curve) to the shown data distribution. An example signal distribution (in red), assuming  $\sigma\mathcal{B}(pp \rightarrow H \rightarrow hh)$  to be equal to three times 3.59 pb, as described in the text, shows that the signal is well-contained in the 120–130 GeV window.

## 6 Observations

Tables 1 and 2 list the observed number of events for the three-lepton and four-lepton search channels, respectively. The number of expected events from SM processes are also shown together with the combined statistical and systematic uncertainties. Table 3 lists the sources of systematic effects and the resultant uncertainties in estimating the expected events from the SM. All search channels share systematic uncertainties for luminosity, renormalization scale, PDF, and trigger efficiency.



Table 1: Observed (Obs.) yields and SM expectations (Exp.) for three-lepton events. See text for the description of event classification by the number and invariant mass of opposite-sign, same-flavor lepton pairs that are on- or below-Z (see Section 4.2), presence of  $\tau_h$ , tagged b jets, and the  $E_T^{\text{miss}}$  in the event. The 70 channels are exclusive.

3 leptons	$m_{\ell^+\ell^-}$	$E_T^{\text{miss}}$ (GeV)	$N_{\tau_h} = 0, N_b = 0$		$N_{\tau_h} = 1, N_b = 0$		$N_{\tau_h} = 0, N_b \geq 1$		$N_{\tau_h} = 1, N_b \geq 1$	
			Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.
OSSF0(SS)	—	(200, $\infty$ )	1	$1.3 \pm 0.6$	2	$1.4 \pm 0.5$	0	$0.70 \pm 0.36$	0	$0.7 \pm 0.5$
OSSF0(SS)	—	(150, 200)	2	$2.1 \pm 0.9$	0	$3.0 \pm 1.1$	1	$2.1 \pm 1.0$	0	$1.5 \pm 0.6$
OSSF0(SS)	—	(100, 150)	9	$10.0 \pm 4.9$	4	$9.9 \pm 3.0$	12	$12.0 \pm 5.9$	4	$6.3 \pm 2.8$
OSSF0(SS)	—	(50, 100)	34	$37 \pm 15$	54	$66 \pm 14$	32	$32 \pm 15$	24	$22 \pm 10$
OSSF0(SS)	—	(0, 50)	47	$46 \pm 11$	196	$221 \pm 51$	28	$24 \pm 11$	21	$31.0 \pm 9.6$
OSSF0	—	(200, $\infty$ )	—	—	5	$4.8 \pm 2.4$	—	—	6	$5.9 \pm 3.1$
OSSF0	—	(150, 200)	—	—	12	$18.0 \pm 9.1$	—	—	21	$20 \pm 10$
OSSF0	—	(100, 150)	—	—	94	$96 \pm 47$	—	—	91	$121 \pm 61$
OSSF0	—	(50, 100)	—	—	351	$329 \pm 173$	—	—	300	$322 \pm 163$
OSSF0	—	(0, 50)	—	—	682	$767 \pm 207$	—	—	230	$232 \pm 118$
OSSF1	Below-Z	(200, $\infty$ )	2	$2.5 \pm 0.9$	4	$2.1 \pm 1.0$	1	$1.9 \pm 0.7$	2	$2.4 \pm 1.2$
OSSF1	On-Z	(200, $\infty$ )	17	$19.0 \pm 6.3$	4	$5.6 \pm 1.9$	1	$2.4 \pm 0.8$	3	$2.1 \pm 0.9$
OSSF1	Below-Z	(150, 200)	7	$4.4 \pm 1.7$	11	$9.3 \pm 4.6$	3	$4.7 \pm 2.1$	7	$11.0 \pm 5.9$
OSSF1	On-Z	(150, 200)	38	$32.0 \pm 8.5$	10	$11.0 \pm 3.6$	4	$5.4 \pm 1.7$	2	$5.7 \pm 2.7$
OSSF1	Below-Z	(100, 150)	21	$26.0 \pm 9.9$	45	$56 \pm 27$	20	$23 \pm 11$	56	$66 \pm 33$
OSSF1	On-Z	(100, 150)	134	$129 \pm 29$	43	$51 \pm 16$	20	$18 \pm 6$	24	$28 \pm 14$
OSSF1	Below-Z	(50, 100)	157	$129 \pm 30$	383	$380 \pm 104$	58	$60 \pm 28$	166	$173 \pm 87$
OSSF1	On-Z	(50, 100)	862	$732 \pm 141$	1360	$1230 \pm 323$	80	$62 \pm 17$	117	$101 \pm 48$
OSSF1	Below-Z	(0, 50)	543	$559 \pm 93$	10200	$9170 \pm 2710$	40	$52 \pm 14$	257	$256 \pm 79$
OSSF1	On-Z	(0, 50)	4040	$4060 \pm 691$	51400	$51400 \pm 15300$	181	$181 \pm 28$	1000	$1010 \pm 286$

Table 2: Observed (Obs.) yields and SM expectation (Exp.) for four-lepton events. See text for the description of event classification by the number and invariant mass of opposite-sign, same-flavor lepton pairs that are on- or off-Z, presence of  $\tau_h$ , tagged b jets, and the total  $E_T^{\text{miss}}$  in the event. The 72 channels are exclusive.

$\geq 4$ leptons	$m_{\ell^+\ell^-}$	$E_T^{\text{miss}}$ (GeV)	$N_{\tau_h} = 0, N_b = 0$		$N_{\tau_h} = 1, N_b = 0$		$N_{\tau_h} = 0, N_b \geq 1$		$N_{\tau_h} = 1, N_b \geq 1$	
			Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.
OSSF0	—	(100, $\infty$ )	0	$0.07 \pm 0.07$	0	$0.18 \pm 0.09$	0	$0.05 \pm 0.05$	0	$0.16 \pm 0.10$
OSSF0	—	(50, 100)	0	$0.07 \pm 0.06$	2	$0.80 \pm 0.35$	0	$0.00^{+0.03}_{-0.00}$	0	$0.43 \pm 0.22$
OSSF0	—	(30, 50)	0	$0.001^{+0.020}_{-0.001}$	0	$0.47 \pm 0.24$	0	$0.00^{+0.02}_{-0.00}$	0	$0.11 \pm 0.09$
OSSF0	—	(0, 30)	0	$0.007^{+0.020}_{-0.007}$	1	$0.40 \pm 0.16$	0	$0.001^{+0.020}_{-0.001}$	0	$0.02^{+0.04}_{-0.02}$
OSSF1	Off-Z	(100, $\infty$ )	0	$0.07 \pm 0.04$	4	$1.00 \pm 0.33$	0	$0.14 \pm 0.09$	0	$0.46 \pm 0.20$
OSSF1	On-Z	(100, $\infty$ )	2	$0.6 \pm 0.2$	2	$3.4 \pm 0.8$	1	$0.80 \pm 0.41$	0	$0.60 \pm 0.26$
OSSF1	Off-Z	(50, 100)	0	$0.21 \pm 0.09$	5	$2.6 \pm 0.6$	0	$0.21 \pm 0.11$	1	$0.70 \pm 0.32$
OSSF1	On-Z	(50, 100)	2	$1.30 \pm 0.39$	10	$12.0 \pm 2.5$	2	$0.60 \pm 0.33$	1	$0.8 \pm 0.3$
OSSF1	Off-Z	(30, 50)	1	$0.16 \pm 0.07$	4	$2.4 \pm 0.5$	0	$0.06 \pm 0.06$	0	$0.47 \pm 0.21$
OSSF1	On-Z	(30, 50)	3	$1.20 \pm 0.35$	11	$14.0 \pm 3.1$	0	$0.22 \pm 0.12$	0	$0.80 \pm 0.31$
OSSF1	Off-Z	(0, 30)	1	$0.38 \pm 0.18$	11	$5.7 \pm 1.7$	0	$0.05 \pm 0.04$	0	$0.50 \pm 0.26$
OSSF1	On-Z	(0, 30)	1	$2.0 \pm 0.5$	32	$30.0 \pm 9.2$	1	$0.19 \pm 0.11$	3	$1.30 \pm 0.42$
OSSF2	Two on-Z	(100, $\infty$ )	0	$0.02 \pm 0.15$	—	—	0	$0.21 \pm 0.13$	—	—
OSSF2	One on-Z	(100, $\infty$ )	1	$0.43 \pm 0.15$	—	—	0	$0.50 \pm 0.29$	—	—
OSSF2	Off-Z	(100, $\infty$ )	0	$0.06 \pm 0.03$	—	—	0	$0.09 \pm 0.07$	—	—
OSSF2	Two on-Z	(50, 100)	3	$2.8 \pm 2.1$	—	—	0	$0.33 \pm 0.11$	—	—
OSSF2	One on-Z	(50, 100)	1	$2.0 \pm 0.7$	—	—	1	$0.50 \pm 0.28$	—	—
OSSF2	Off-Z	(50, 100)	2	$0.20 \pm 0.14$	—	—	0	$0.12 \pm 0.10$	—	—
OSSF2	Two on-Z	(30, 50)	19	$22 \pm 9$	—	—	2	$0.70 \pm 0.24$	—	—
OSSF2	One on-Z	(30, 50)	6	$6.5 \pm 2.4$	—	—	0	$0.32 \pm 0.12$	—	—
OSSF2	Off-Z	(30, 50)	3	$1.4 \pm 0.6$	—	—	1	$0.15 \pm 0.08$	—	—
OSSF2	Two on-Z	(0, 30)	118	$109 \pm 28$	—	—	3	$2.0 \pm 0.5$	—	—
OSSF2	One on-Z	(0, 30)	24	$29.0 \pm 7.6$	—	—	1	$0.60 \pm 0.17$	—	—
OSSF2	Off-Z	(0, 30)	5	$7.8 \pm 2.3$	—	—	0	$0.18 \pm 0.06$	—	—

Table 3: A compilation of significant sources of systematic uncertainties in the event yield estimation. Note that a given uncertainty may pertain only to specific sources of background. The listed values are representative and the impact of an uncertainty varies from search channel to channel.

Source of uncertainty	Magnitude (%)
Luminosity	2.6
PDF	10
$E_T^{\text{miss}} (> 50 \text{ GeV})$ resolution correction	4
Jet energy scale	0.5
b-tag scale factor ( $t\bar{t}$ )	6
$e(\mu)$ ID/isolation (at $p_T = 30 \text{ GeV}$ )	0.6 (0.2)
Trigger efficiency	5
$t\bar{t}$ misidentification	50
$t\bar{t}, WZ, ZZ$ cross sections	10, 15, 15
$\tau_h$ misidentification	30
Diphoton background	50

The observations listed in the tables generally agree with the expectations within the uncertainties. Given the large number of channels being investigated simultaneously, certain deviations between observations and expected values are to be anticipated. We discuss one such deviation later in the context of the H search.

Figure 2 shows observations and background decomposition for some of the most sensitive channels for the  $H \rightarrow hh$  search. The amount of signal for  $m_H = 300 \text{ GeV}$ , as described above in the context of Fig. 1, is also shown. This information is also listed in Table 4. Figure 3 and Table 5 shows the same for the  $A \rightarrow Zh$  search for  $m_A = 300 \text{ GeV}$ , assuming the same cross section and  $\mathcal{B}(A \rightarrow Zh) = 1$ .

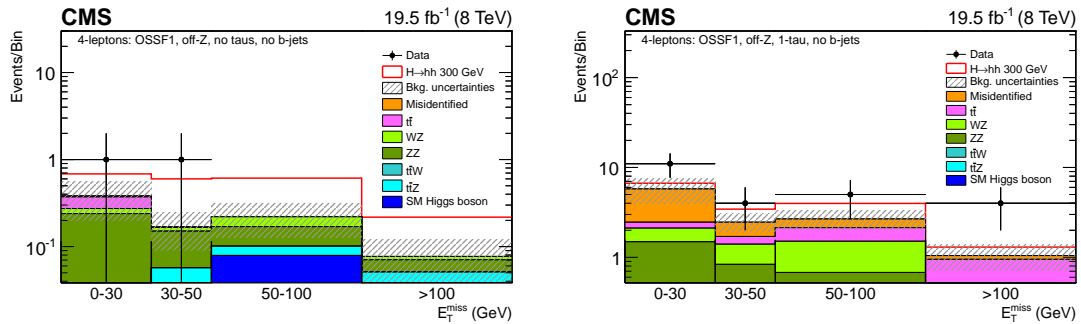


Figure 2: The  $E_T^{\text{miss}}$  distributions for four-lepton events with an off-Z OSSF1 dilepton pair, no b-tagged jet, and no  $\tau_h$  (left), and one  $\tau_h$  (right). These non-resonant (off-Z) channels are sensitive to the  $H \rightarrow hh$  signal which is shown stacked on top of the background distributions, assuming  $\sigma\mathcal{B}(pp \rightarrow H \rightarrow hh) = 3.59 \text{ pb}$ , as described in the text.

The lepton+diphoton results are summarized in Tables 6 and 7. The observations agree with the expectations within the uncertainties.

Table 4: Observed (Obs.) yields and SM expectation (Exp.) for selected four-lepton channels in the  $H \rightarrow hh$  search. These are also shown in Fig. 2. See text for the description of event classification. The  $H \rightarrow hh$  signal (Sig.) is also listed, assuming  $\sigma\mathcal{B}(pp \rightarrow H \rightarrow hh) = 3.59$  pb.

Channel	$E_T^{\text{miss}}$ (GeV)	Obs.	Exp.	Sig.
$4\ell$ (OSSF1, off-Z) (no $\tau_h$ , no b-jets)	(0, 30)	1	$0.38 \pm 0.18$	0.30
	(30, 50)	1	$0.16 \pm 0.07$	0.43
	(50, 100)	0	$0.21 \pm 0.09$	0.39
	(100, $\infty$ )	0	$0.07 \pm 0.04$	0.14
$4\ell$ (OSSF1, off-Z) (1- $\tau_h$ , no b-jets)	(0, 30)	11	$5.7 \pm 1.7$	0.91
	(30, 50)	4	$2.4 \pm 0.5$	0.98
	(50, 100)	5	$2.6 \pm 0.6$	1.31
	(100, $\infty$ )	4	$1.00 \pm 0.33$	0.25

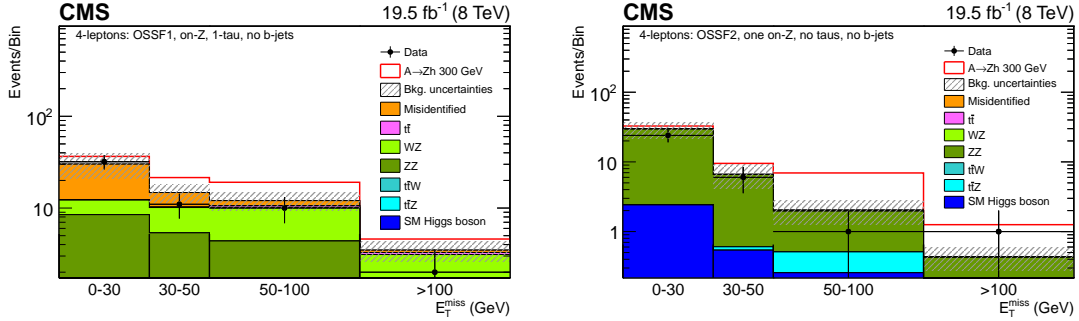


Figure 3: The  $E_T^{\text{miss}}$  distributions for four-lepton events without b-tagged jets which contain an on-Z OSSF1 dilepton pair and one  $\tau_h$  (left), and an OSSF2 dilepton pairs with one Z candidate and no  $\tau_h$  (right). These resonant (containing a Z) channels are sensitive to the  $A \rightarrow Zh$  signal which is shown stacked on top of the background distributions, assuming  $\sigma\mathcal{B}(pp \rightarrow A \rightarrow Zh) = 3.59$  pb, as described in the text.

Table 5: Observed (Obs.) yields and SM expectation (Exp.) for selected four-lepton channels in the  $A \rightarrow Zh$  search. These are also shown in Fig. 3. See text for the description of event classification. The  $A \rightarrow Zh$  signal (Sig.) is also listed, assuming  $\sigma\mathcal{B}(pp \rightarrow A \rightarrow Zh) = 3.59$  pb.

Channel	$E_T^{\text{miss}}$ (GeV)	Obs.	Exp.	Sig.
$4\ell$ (OSSF1, on-Z) (1- $\tau_h$ , no b-jets)	(0, 30)	32	$30.0 \pm 9.2$	6.46
	(30, 50)	11	$14.0 \pm 3.1$	6.72
	(50, 100)	10	$12.0 \pm 2.5$	7.05
	(100, $\infty$ )	2	$3.4 \pm 0.8$	1.12
$4\ell$ (OSSF2, one on-Z) (no $\tau_h$ , no b-jets)	(0, 30)	24	$29.0 \pm 7.6$	3.15
	(30, 50)	6	$6.5 \pm 2.4$	2.91
	(50, 100)	1	$2.0 \pm 0.7$	4.92
	(100, $\infty$ )	1	$0.43 \pm 0.15$	0.82

## 7 Interpretation of results

### 7.1 Statistical procedure

No significant disagreement is found between our observations and the corresponding SM expectations. We derive limits on the production cross-section times branching fraction for the new physics scenarios under consideration, and use them to constrain parameters of the models. We set 95% CL upper limits on the cross sections using the modified frequentist construc-

Table 6: Observed yields and SM expectations for dilepton+diphoton events. The diphoton invariant mass is required to be in the 120–130 GeV window. The ten channels are exclusive.

Channel	$E_T^{\text{miss}}$ (GeV)	Obs.	Exp.
$\gamma\gamma\ell\ell$ (OSSF1, off-Z)	(50, $\infty$ )	0	$0.19^{+0.25}_{-0.19}$
	(30, 50)	1	$0.17^{+0.25}_{-0.17}$
	(0, 30)	1	$1.20 \pm 0.74$
$\gamma\gamma\ell\ell$ (OSSF1, on-Z)	(50, $\infty$ )	0	$0.10^{+0.17}_{-0.10}$
	(30, 50)	1	$0.33 \pm 0.28$
	(0, 30)	0	$1.01 \pm 0.55$
$\gamma\gamma\ell\ell$ (OSSF0)	All	0	$0.00^{+0.17}_{-0.00}$
$\gamma\gamma\ell\tau_h$	(50, $\infty$ )	0	$0.16^{+0.66}_{-0.16}$
	(30, 50)	0	$0.50^{+0.57}_{-0.50}$
	(0, 30)	0	$0.76 \pm 0.60$

Table 7: Observed yields and SM expectations for single lepton+diphoton events. The diphoton invariant mass is required to be in the 120–130 GeV window. The eight channels are exclusive.

Channel	$E_T^{\text{miss}}$ (GeV)	$N_b = 0$		$N_b \geq 1$	
		Obs.	Exp.	Obs.	Exp.
$\gamma\gamma\ell$	(100, $\infty$ )	1	$2.2 \pm 1.0$	0	$0.5 \pm 0.4$
	(50, 100)	7	$9.5 \pm 4.4$	1	$2.3 \pm 1.2$
	(30, 50)	29	$21 \pm 10$	2	$1.1 \pm 0.6$
	(0, 30)	72	$77 \pm 38$	2	$2.1 \pm 1.1$
$\gamma\gamma\tau_h$	(100, $\infty$ )	1	$0.24^{+0.25}_{-0.24}$	0	$0.35 \pm 0.28$
	(50, 100)	14	$9.3 \pm 4.7$	1	$1.5 \pm 0.8$
	(30, 50)	71	$67 \pm 34$	2	$2.1 \pm 1.2$
	(0, 30)	229	$235 \pm 117$	6	$6.4 \pm 3.3$

tion CL [30, 31]. We compute the single-channel CL limits for each channel and then obtain the combined upper limit.

## 7.2 $H \rightarrow hh$ and $A \rightarrow Zh$ model-independent interpretations

Figure 4 (left) shows 95% CL observed and expected  $\sigma\mathcal{B}$  upper limit for the gluon fusion production of heavy scalar  $H$ , with the decay  $H \rightarrow hh$  along with one and two standard deviation bands around the expected limits using only the multilepton channels. Figure 4 (right) shows the same using both multilepton and diphoton channels. In placing these model-independent limits, we explicitly assume that  $h$  is the recently discovered SM-like Higgs boson [1–3] particularly in regards to the branching fraction of its various decay modes as predicted in the SM.

For low masses, there is an almost two standard deviation discrepancy between the expected and observed 95% CL limits in Fig. 4. Its origin traces back to three four-lepton channels listed in Table 2, which can also be located in Fig. 2 (right). They consist of events with a  $\tau_h$  and three light leptons containing an off-Z OSSF dilepton pair, but not a b-tagged jet. The  $H \rightarrow hh$  signal resides almost entirely in the 0–100 GeV range in  $E_T^{\text{miss}}$  which is spanned by these three channels collectively. The observed (expected) number of events is 11 ( $5.7 \pm 1.7$ ), 4 ( $2.4 \pm 0.5$ ) and 5 ( $2.6 \pm 0.6$ ) for  $E_T^{\text{miss}}$  in ranges 0–30, 30–50, and 50–100 GeV, respectively. Summing over the three channels, the observed count is 20 with an expectation of  $10.7 \pm 1.9$ , giving the probability

of observing 20 events over the 0–100 GeV  $E_T^{\text{miss}}$  range to be approximately 2.2%. Systematic uncertainties and their correlations are taken into account when evaluating this probability. The observed discrepancy in the limits shown in Fig. 4 is thus consistent with a broad fluctuation in the observed  $E_T^{\text{miss}}$  distribution. Given the large number of channels under scrutiny in this search, fluctuations at this level are to be expected. No such deviation is observed in the  $E_T^{\text{miss}}$  distribution for other search channels.

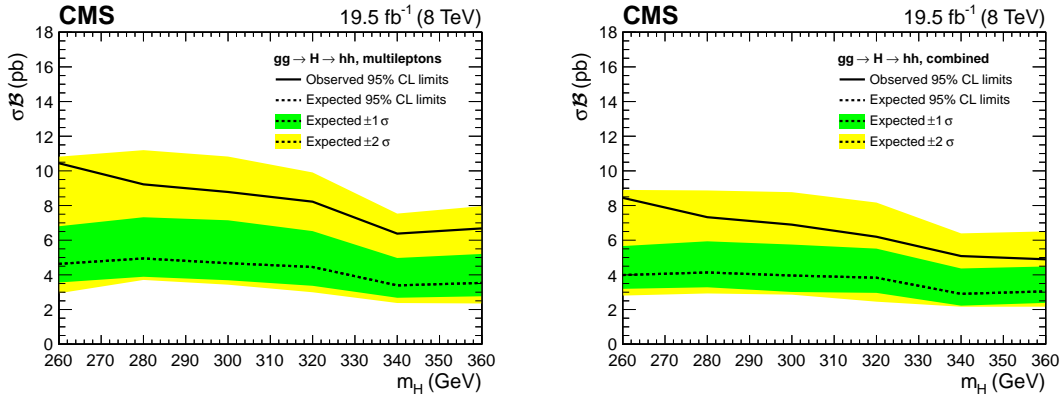


Figure 4: Left: observed and expected 95% CL  $\sigma\mathcal{B}$  limits for gluon fusion production of H and the decay  $H \rightarrow hh$  with one and two standard deviation bands shown. These limits are based only on multilepton channels. The h branching fractions are assumed to have SM values. Right: the same, but also including lepton+diphoton channels.

Next we probe the sensitivity to gluon fusion production of the heavy pseudoscalar A with the decay  $A \rightarrow Zh$ . Figure 5 (left) shows 95% CL upper limits on  $\sigma\mathcal{B}$  for  $A \rightarrow Zh$  search along with one and two standard deviation bands around the expected contour using only the multilepton channels. Figure 5 (right) shows the same signal probed with both multilepton and diphoton channels. The observed and expected exclusions are consistent.

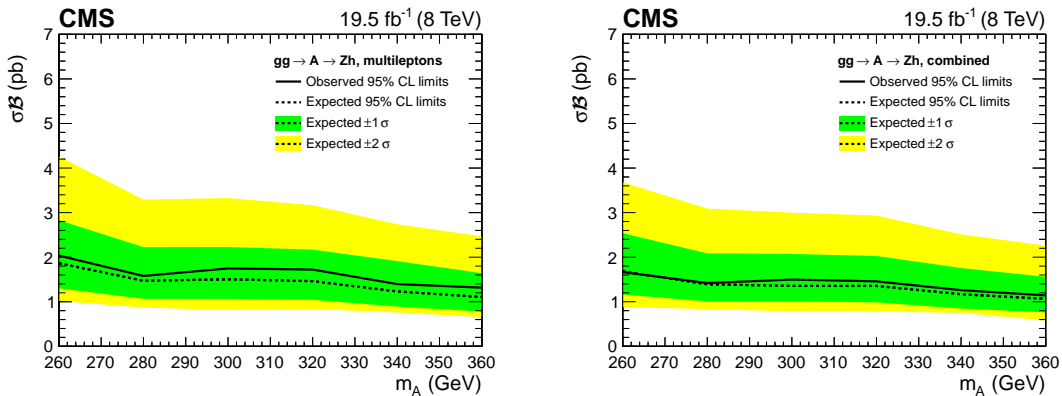


Figure 5: Left: observed and expected 95% CL  $\sigma\mathcal{B}$  limits for gluon fusion production of A and the decay  $A \rightarrow Zh$  with one and two standard deviation bands shown. These limits are based only on multilepton channels. The h branching fraction are assumed to have SM values. Right: the same, but also including lepton+diphoton channels.

### 7.3 Interpretations in the context of two-Higgs-doublet models

General models with two Higgs doublets may exhibit new tree-level contributions to flavor-changing neutral currents that are strongly constrained by low-energy experiments. Prohibitive flavor violation is avoided in a 2HDM if all fermions of a given representation receive their

masses through renormalizable Yukawa couplings to a single Higgs doublet, as in the case of supersymmetry. There are four such possible distinct assignments of fermion couplings in models with two Higgs doublets, the most commonly considered of which are called Type I and Type II models. In Type I models all fermions receive their masses through Yukawa couplings to a single Higgs doublet, while in Type II models the up-type quarks receive their masses through couplings to one doublet and down-type quarks and leptons couple to the second doublet. In either type, after electroweak symmetry breaking the physical Higgs scalars are linear combinations of these two electroweak Higgs doublets, so that fermion couplings to the physical states depend on the type of 2HDM, the mixing angle  $\alpha$ , and the ratio of vacuum expectation values  $\tan\beta$ . We next present search interpretations in the context of Type I and Type II 2HDMs [5]. In these models, the production cross sections for H and A as well as the branching fractions for them to decay to two SM-like Higgs bosons depend on parameters  $\alpha$  and  $\tan\beta$ . The mixing angle between H and h is given by  $\alpha$ , whereas  $\tan\beta$  gives the relative contribution of each Higgs doublet to electroweak symmetry breaking. In obtaining these model-dependent limits, the daughter h is assumed to be the recently discovered SM-like Higgs boson, but the branching fractions to its various decay modes are assumed to be dictated by the parameters  $\alpha$  and  $\tan\beta$  of the 2HDM, as described below.

We use the SUSHi [32] program to obtain the 2HDM cross sections. The branching fraction for SM-like Higgs boson are calculated using the 2HDMC [33] program. The 2HDMC results are consistent with those provided by the LHC Higgs cross section working group [34]. A detailed list of couplings of H and A to SM fermions and massive gauge bosons in Type I and II 2HDMs has been tabulated in Ref. [6]. Figure 6 (top left and bottom left) shows observed and expected 95% CL upper limits for gluon fusion production of a heavy Higgs boson H of mass 300 GeV for Type I and Type II 2HDMs, respectively, along with the  $\sigma\mathcal{B}$  theoretical predictions (right) adopted from Ref. [35] for the two models. Figure 7 (top left and bottom left) shows similar results for the pseudoscalar A Higgs boson of mass 300 GeV. The branching fractions for the SM-like Higgs boson daughters of the H and A vary across the  $\tan\beta$  versus  $\cos(\beta - \alpha)$  plane and are incorporated in the upper limit calculations.

Finally, we further improve constraints on the 2HDM parameters using the simultaneous null findings for the H and A. Figure 8 shows exclusion in  $\tan\beta$  versus  $\cos(\beta - \alpha)$  plane for the combined gluon fusion signal for Type I (left) and Type II (right) 2HDMs, assuming H and A to be mass degenerate with a mass of 300 GeV. Once again, the branching fractions of the SM-like h daughters are allowed to vary across the plane.

#### 7.4 $t \rightarrow ch$ search results

The  $t \rightarrow ch$  signal predominantly populates lepton+diphoton channels with a b-tag and  $\ell\ell\ell$  (no  $\tau_h$ ) multilepton channels that lack an OSSF dilepton pair or have an off-Z OSSF pair. Beyond the fact that the presence of charm quark increases the likelihood of an event being classified as being b-tagged, no special effort is made to identify the charm quark present in the signal. The observations and SM expectations for the ten most sensitive channels are listed in Table 8 along with the signal yield for a nominal value of  $\mathcal{B}(t \rightarrow ch) = 1\%$ . No significant excess is observed.

The statistical procedure yields an observed limit of  $\mathcal{B}(t \rightarrow ch) = 0.56\%$  and an expected limit of  $\mathcal{B}(t \rightarrow ch) = (0.65^{+0.29}_{-0.19})\%$  from SM  $t\bar{t}$  production followed by either  $t \rightarrow ch$  or its charge-conjugate decay. The  $t \rightarrow ch$  branching fraction is related to the left- and right-handed top flavor changing Yukawa couplings  $\lambda_{tc}^h$  and  $\lambda_{ct}^h$ , respectively, by  $\mathcal{B}(t \rightarrow ch) \simeq 0.29 (|\lambda_{tc}^h|^2 + |\lambda_{ct}^h|^2)$  [7], so that the observed limit corresponds to a limit on the couplings of  $\sqrt{|\lambda_{tc}^h|^2 + |\lambda_{ct}^h|^2} < 0.14$ .

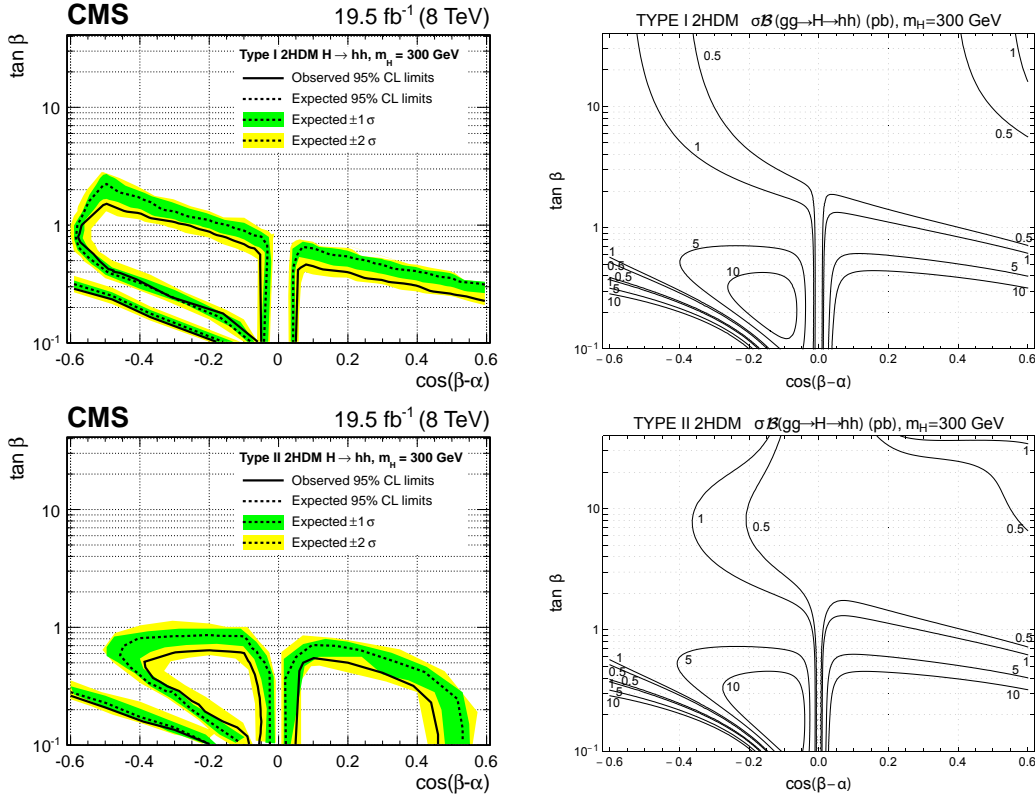


Figure 6: Left: observed and expected 95% CL upper limits for gluon fusion production of a heavy Higgs boson H of mass 300 GeV as a function of parameters  $\tan\beta$  and  $\cos(\beta-\alpha)$  of the Type I (upper) and II (lower) 2HDM. The parameters determine the H production cross section as well as the branching fractions  $\mathcal{B}(H \rightarrow hh)$  and  $\mathcal{B}(h \rightarrow WW^*, ZZ^*, \tau\tau, \gamma\gamma)$ , which are relevant to this search. Right: the  $\sigma\mathcal{B}(H \rightarrow hh)$  contours for Type I (upper) and II (lower) 2HDM adopted from Ref. [35]. The excluded regions are either below the open limit contours or within the closed ones.

Table 8: The ten most sensitive search channels for  $t \rightarrow ch$ , along with the number of observed (Obs.), expected SM background (Exp.), and expected signal (Sig.) events (assuming  $\mathcal{B}(t \rightarrow ch) = 1\%$ ). The three-lepton channels are taken from Ref. [9], have  $H_T < 200$  GeV and do not contain a  $\tau_h$ . The stated uncertainties contain both systematic and statistical components.

Channel	$E_T^{\text{miss}}$ (GeV)	$N_b$	Obs.	Exp.	Sig.
$\gamma\gamma\ell$	(50, 100)	$\geq 1$	1	$2.3 \pm 1.2$	$2.88 \pm 0.39$
	(30, 50)	$\geq 1$	2	$1.1 \pm 0.6$	$2.16 \pm 0.30$
	(0, 30)	$\geq 1$	2	$2.1 \pm 1.1$	$1.76 \pm 0.24$
	(50, 100)	0	7	$9.5 \pm 4.4$	$2.22 \pm 0.31$
	(100, $\infty$ )	$\geq 1$	0	$0.5 \pm 0.4$	$0.92 \pm 0.14$
	(100, $\infty$ )	0	1	$2.2 \pm 1.0$	$0.94 \pm 0.17$
$lll$ (OSSF1, below-Z)	(50, 100)	$\geq 1$	48	$48 \pm 23$	$9.5 \pm 2.3$
	(0, 50)	$\geq 1$	34	$42 \pm 11$	$5.9 \pm 1.2$
$lll$ (OSSF0)	(50, 100)	$\geq 1$	29	$26 \pm 13$	$5.9 \pm 1.3$
	(0, 50)	$\geq 1$	29	$23 \pm 10$	$4.3 \pm 1.1$

To facilitate interpretations in broader contexts [36], we also provide limits on  $\mathcal{B}(t \rightarrow ch)$  from

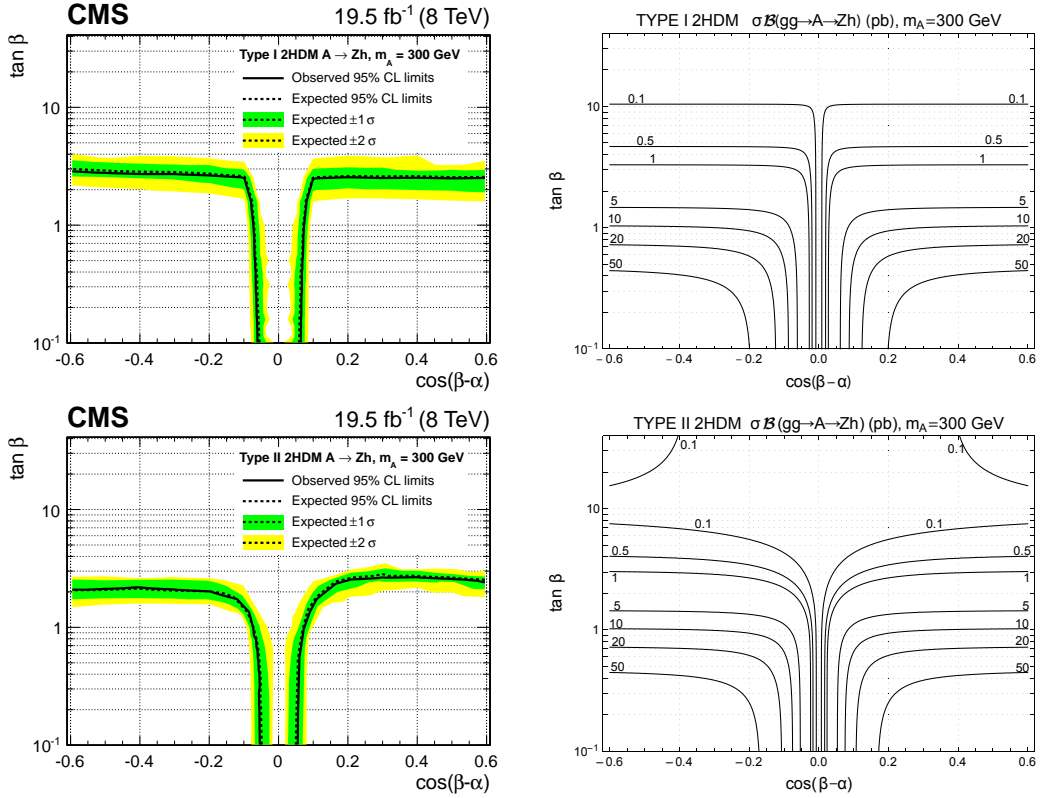


Figure 7: Left: observed and expected 95% CL upper limits for gluon fusion production of an A boson of mass 300 GeV as a function of parameters  $\tan\beta$  and  $\cos(\beta - \alpha)$  of the Type I (upper) and II (lower) 2HDM. The parameters determine the A production cross section as well as the branching fractions  $\mathcal{B}(A \rightarrow Zh)$  and  $\mathcal{B}(h \rightarrow WW^*, ZZ^*, \tau\tau, \gamma\gamma)$  which are relevant to this search. Right: the  $\sigma\mathcal{B}(A \rightarrow Zh)$  contours for Type I (upper) and II (lower) 2HDM adopted from Ref. [35]. The excluded regions are below the open limit contours.

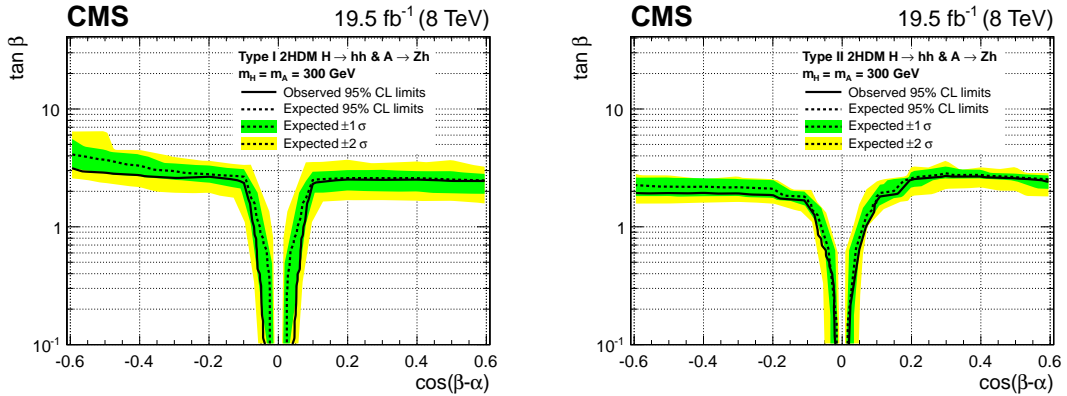


Figure 8: Combined observed and expected 95% upper limits for gluon fusion production of a heavy Higgs boson H and A of mass 300 GeV for Type I (left) and Type II (right) 2HDM as a function of parameters  $\tan\beta$  and  $\cos(\beta - \alpha)$ . The parameters determine the H and A production cross sections as well as the branching fractions  $\mathcal{B}(H \rightarrow hh)$ ,  $\mathcal{B}(A \rightarrow Zh)$ , and  $\mathcal{B}(h \rightarrow WW^*, ZZ^*, \tau\tau, \gamma\gamma)$ , which are relevant to this search.

individual Higgs boson decay modes. For this purpose, we assume the SM branching fraction for the Higgs boson decay mode [37] under consideration, and ignore other decay modes. Table 9 shows the results, illustrating the analysis sensitivity for the  $t \rightarrow ch$  decay in each of the



Higgs boson decay modes.

Table 9: Comparison of the observed and expected 95% CL limits on  $\mathcal{B}(t \rightarrow ch)$  from individual Higgs boson decay modes along with the 68% CL uncertainty ranges.

Higgs boson decay mode	Upper limits on $\mathcal{B}(t \rightarrow ch)$		
	Obs.	Exp.	68% CL range
$\mathcal{B}(h \rightarrow WW^*) = 23.1\%$	1.58%	1.57%	(1.02–2.22)%
$\mathcal{B}(h \rightarrow \tau\tau) = 6.15\%$	7.01%	4.99%	(3.53–7.74)%
$\mathcal{B}(h \rightarrow ZZ^*) = 2.89\%$	5.31%	4.11%	(2.85–6.45)%
Combined multileptons ( $WW^*, \tau\tau, ZZ^*$ )	1.28%	1.17%	(0.85–1.73)%
$\mathcal{B}(h \rightarrow \gamma\gamma) = 0.23\%$	0.69%	0.81%	(0.60–1.17)%
Combined multileptons + diphotons	0.56%	0.65%	(0.46–0.94)%

## 8 Summary

We have performed a search for the  $H \rightarrow hh$  and  $A \rightarrow Zh$  decays of heavy scalar (H) and pseudoscalar (A) Higgs bosons, respectively, which occur in the extended Higgs sector described by the 2HDM. This is the first search for these decays carried out at the LHC. We used multilepton and diphoton final states from a dataset corresponding to an integrated luminosity of  $19.5 \text{ fb}^{-1}$  of data recorded in 2012 from pp collisions at a center-of-mass energy of 8 TeV. We find no significant deviation from the SM expectations and place 95% CL cross section upper limits of approximately 7 pb on  $\sigma\mathcal{B}$  for  $H \rightarrow hh$  and 2 pb for  $A \rightarrow Zh$ . We further interpret these limits in the context of Type I and Type II 2HDMs, presenting exclusion contours in the  $\tan\beta$  versus  $\cos(\beta - \alpha)$  plane.

Using diphoton and multilepton search channels that are sensitive to the decay  $t \rightarrow ch$ , we place an upper limit of 0.56% on  $\mathcal{B}(t \rightarrow ch)$ , where the expected limit is 0.65%. This is a significant improvement over the earlier limit of 1.3% from the multilepton search alone [9].

## Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: the Austrian Federal Ministry of Science, Research and Economy and the Austrian Science Fund; the Belgian Fonds de la Recherche Scientifique, and Fonds voor Wetenschappelijk Onderzoek; the Brazilian Funding Agencies (CNPq, CAPES, FAPERJ, and FAPESP); the Bulgarian Ministry of Education and Science; CERN; the Chinese Academy of Sciences, Ministry of Science and Technology, and National Natural Science Foundation of China; the Colombian Funding Agency (COLCIENCIAS); the Croatian Ministry of Science, Education and Sport, and the Croatian Science Foundation; the Research Promotion Foundation, Cyprus; the Ministry of Education and Research, Estonian Research Council via IUT23-4 and IUT23-6 and European Regional Development Fund, Estonia; the Academy of Finland, Finnish Ministry of Education and Culture, and Helsinki Institute of Physics; the Institut National de Physique Nucléaire et de Physique des Particules / CNRS, and Commissariat à l'Énergie Atomique et aux Énergies Alternatives / CEA,

France; the Bundesministerium für Bildung und Forschung, Deutsche Forschungsgemeinschaft, and Helmholtz-Gemeinschaft Deutscher Forschungszentren, Germany; the General Secretariat for Research and Technology, Greece; the National Scientific Research Foundation, and National Innovation Office, Hungary; the Department of Atomic Energy and the Department of Science and Technology, India; the Institute for Studies in Theoretical Physics and Mathematics, Iran; the Science Foundation, Ireland; the Istituto Nazionale di Fisica Nucleare, Italy; the Korean Ministry of Education, Science and Technology and the World Class University program of NRF, Republic of Korea; the Lithuanian Academy of Sciences; the Ministry of Education, and University of Malaya (Malaysia); the Mexican Funding Agencies (CINVESTAV, CONACYT, SEP, and UASLP-FAI); the Ministry of Business, Innovation and Employment, New Zealand; the Pakistan Atomic Energy Commission; the Ministry of Science and Higher Education and the National Science Centre, Poland; the Fundação para a Ciência e a Tecnologia, Portugal; JINR, Dubna; the Ministry of Education and Science of the Russian Federation, the Federal Agency of Atomic Energy of the Russian Federation, Russian Academy of Sciences, and the Russian Foundation for Basic Research; the Ministry of Education, Science and Technological Development of Serbia; the Secretaría de Estado de Investigación, Desarrollo e Innovación and Programa Consolider-Ingenio 2010, Spain; the Swiss Funding Agencies (ETH Board, ETH Zurich, PSI, SNF, UniZH, Canton Zurich, and SER); the Ministry of Science and Technology, Taipei; the Thailand Center of Excellence in Physics, the Institute for the Promotion of Teaching Science and Technology of Thailand, Special Task Force for Activating Research and the National Science and Technology Development Agency of Thailand; the Scientific and Technical Research Council of Turkey, and Turkish Atomic Energy Authority; the National Academy of Sciences of Ukraine, and State Fund for Fundamental Researches, Ukraine; the Science and Technology Facilities Council, UK; the US Department of Energy, and the US National Science Foundation.

Individuals have received support from the Marie-Curie programme and the European Research Council and EPLANET (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS programme of Foundation for Polish Science, cofinanced from European Union, Regional Development Fund; the Compagnia di San Paolo (Torino); the Consorzio per la Fisica (Trieste); MIUR project 20108T4XTM (Italy); the Thalís and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; and the National Priorities Research Program by Qatar National Research Fund.

## References

- [1] ATLAS Collaboration, "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC", *Phys. Lett. B* **716** (2012) 1, doi:10.1016/j.physletb.2012.08.020, arXiv:1207.7214v2.
- [2] CMS Collaboration, "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC", *Phys. Lett. B* **716** (2012) 30, doi:10.1016/j.physletb.2012.08.021, arXiv:1207.7235v2.
- [3] CMS Collaboration, "Observation of a new boson with mass near 125 GeV in pp collisions at  $\sqrt{s} = 7$  and 8 TeV", *JHEP* **06** (2013) 081,

- doi:10.1007/JHEP06(2013)081, arXiv:1303.4571.
- [4] G. C. Branco et al., “Theory and phenomenology of two-Higgs-doublet models”, *Phys. Rept.* **516** (2012) 1, doi:10.1016/j.physrep.2012.02.002, arXiv:1106.0034v3.
- [5] N. Craig and S. Thomas, “Exclusive Signals of an Extended Higgs Sector”, *JHEP* **11** (2012) 083, doi:10.1007/JHEP11(2012)083, arXiv:1207.4835v2.
- [6] N. Craig et al., “Multi-lepton signals of multiple Higgs bosons”, *JHEP* **02** (2013) 033, doi:10.1007/JHEP02(2013)033, arXiv:1210.0559v1.
- [7] N. Craig et al., “Searching for  $t \rightarrow cH$  with Multi-Leptons”, *Phys. Rev. D* **86** (2012) 075002, doi:10.1103/PhysRevD.86.075002, arXiv:1207.6794v2.
- [8] ATLAS Collaboration, “Search for top quark decays  $t \rightarrow qH$  with  $H \rightarrow \gamma\gamma$  using the ATLAS detector”, *JHEP* **1406** (2014) 008, doi:10.1007/JHEP06(2014)008, arXiv:1403.6293v1.
- [9] CMS Collaboration, “Search for anomalous production of events with three or more leptons in pp collisions at  $\sqrt{s} = 8$  TeV”, *Phys. Rev. D* **90** (2014) 032006, doi:10.1103/PhysRevD.90.032006, arXiv:1404.5801.
- [10] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [11] F. Maltoni and T. Stelzer, “MadEvent: Automatic event generation with MADGRAPH”, *JHEP* **02** (2003) 027, doi:10.1088/1126-6708/2003/02/027, arXiv:hep-ph/0208156v1.
- [12] S. Kretzer, H. L. Lai, F. I. Olness, and W. K. Tung, “CTEQ6 parton distributions with heavy quark mass effects”, *Phys. Rev. D* **69** (2004) 114005, doi:10.1103/PhysRevD.69.114005, arXiv:hep-ph/0307022v1.
- [13] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [14] CMS Collaboration, “Fast simulation of the CMS detector”, *J. Phys. Conf. Ser.* **219** (2010) 032053, doi:10.1088/1742-6596/219/3/032053.
- [15] CMS Collaboration, “Particle-Flow Event Reconstruction in CMS and Performance for Jets,  $T_{\text{aus}}$ , and  $E_{\text{T}}^{\text{miss}}$ ”, CMS Physics Analysis Summary CMS-PAS-PFT-09-001, 2009.
- [16] CMS Collaboration, “Commissioning of the Particle-flow Event Reconstruction with the first LHC collisions recorded in the CMS detector”, CMS Physics Analysis Summary CMS-PAS-PFT-10-001, 2010.
- [17] CMS Collaboration, “Electron Reconstruction and Identification at  $\sqrt{s} = 7$  TeV”, CMS Physics Analysis Summary CMS-PAS-EGM-10-004, 2010.
- [18] CMS Collaboration, “Energy Calibration and Resolution of the CMS Electromagnetic Calorimeter in pp Collisions at  $\sqrt{s} = 7$  TeV”, *JINST* **8** (2013) P09009, doi:10.1088/1748-0221/8/09/P09009, arXiv:1306.2016v2.
- [19] CMS Collaboration, “Performance of muon identification in pp collisions at  $\sqrt{s} = 7$  TeV”, CMS Physics Analysis Summary CMS-PAS-MUO-10-002, 2010.

- [20] CMS Collaboration, “Performance of CMS muon reconstruction in pp collision events at  $\sqrt{s} = 7$  TeV”, *JINST* **7** (2012) P10002, doi:10.1088/1748-0221/7/10/P10002, arXiv:1206.4071v2.
- [21] CMS Collaboration, “Performance of  $\tau$ -lepton reconstruction and identification in CMS”, *JINST* **7** (2012) P01001, doi:10.1088/1748-0221/7/01/P01001, arXiv:1109.6034v1.
- [22] CMS Collaboration, “Photon reconstruction and identification at  $\sqrt{s} = 7$  TeV”, CMS Physics Analysis Summary CMS-PAS-EGM-10-005, 2010.
- [23] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- $k_T$  jet clustering algorithm”, *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189v2.
- [24] CMS Collaboration, “Identification of b-quark jets with the CMS experiment”, *JINST* **8** (2013) P04013, doi:10.1088/1748-0221/8/04/P04013, arXiv:1211.4462.
- [25] CMS Collaboration, “Measurement of the  $t\bar{t}$  production cross section in the dilepton channel in pp collisions at  $\sqrt{s} = 7$  TeV”, *JHEP* **11** (2012) 067, doi:10.1007/JHEP11(2012)067, arXiv:1208.2671v2.
- [26] CMS Collaboration, “Observation of the diphoton decay of the Higgs boson and measurement of its properties”, *Eur. Phys. J. C* **74** (2014) 3076, doi:10.1140/epjc/s10052-014-3076-z, arXiv:1407.0558v2.
- [27] M. Cacciari and G. P. Salam, “Pileup subtraction using jet areas”, *Phys. Lett. B* **659** (2008) 119, doi:10.1016/j.physletb.2007.09.077, arXiv:0707.1378v2.
- [28] CMS Collaboration, “Measurement of the Inclusive W and Z Production Cross Sections in pp Collisions at  $\sqrt{s} = 7$  TeV”, *JHEP* **10** (2011) 132, doi:10.1007/JHEP10(2011)132, arXiv:1107.4789v1.
- [29] S. Heinemeyer et al., “Handbook of LHC Higgs cross sections: 3. Higgs properties”, CERN Report CERN-2013-004, 2013. doi:10.5170/CERN-2013-004, arXiv:1307.1347.
- [30] T. Junk, “Confidence Level Computation for Combining Searches with Small Statistics”, *Nucl. Instrum. Meth. A* **434** (1999) 435, doi:10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006v1.
- [31] A. L. Read, “Presentation of search results: The  $CL_s$  technique”, *J. Phys. G* **28** (2002) 2693, doi:10.1088/0954-3899/28/10/313.
- [32] R. V. Harlander, S. Liebler, and H. Mantler, “SusHi: A program for the calculation of Higgs production in gluon fusion and bottom-quark annihilation in the Standard Model and the MSSM”, *Comput. Phys. Commun.* **184** (2013) 1605, doi:10.1016/j.cpc.2013.02.006, arXiv:1212.3249v2.
- [33] D. Eriksson, J. Rathsman, and O. Stal, “2HDMC: Two-Higgs-Doublet Model Calculator Physics and Manual”, *Comput. Phys. Commun.* **181** (2010) 189, doi:10.1016/j.cpc.2009.09.011, arXiv:0902.0851v2.
- [34] LHC Higgs Cross Section Working Group Collaboration, “Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables”, (2011). arXiv:1101.0593v3. Unpublished.

- 
- [35] N. Craig, J. Galloway, and S. Thomas, “Searching for Signs of the Second Higgs Doublet”, (2013). [arXiv:1305.2424v1](#).
- [36] K.-F. Chen, W.-S. Hou, C. Kao, and M. Kohda, “When the Higgs meets the Top: Search for  $t \rightarrow ch^0$  at the LHC”, *Phys. Lett. B* **725** (2013) 378, [doi:10.1016/j.physletb.2013.07.060](#), [arXiv:1304.8037v2](#).
- [37] CMS Collaboration, “Measurement of the properties of a Higgs boson in the four-lepton final state”, *Phys. Rev. D* **89** (2014) 092007, [doi:10.1103/PhysRevD.89.092007](#), [arXiv:1312.5353v3](#).



## A The CMS Collaboration

### Yerevan Physics Institute, Yerevan, Armenia

V. Khachatryan, A.M. Sirunyan, A. Tumasyan

### Institut für Hochenergiephysik der OeAW, Wien, Austria

W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan<sup>1</sup>, M. Friedl, R. Frühwirth<sup>1</sup>, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler<sup>1</sup>, W. Kiesenhofer, V. Knünz, M. Krammer<sup>1</sup>, I. Krätschmer, D. Liko, I. Mikulec, D. Rabady<sup>2</sup>, B. Rahbaran, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz<sup>1</sup>

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

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

### Universiteit Antwerpen, Antwerpen, Belgium

S. Alderweireldt, M. Bansal, S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, S. Luyckx, S. Ochesanu, B. Roland, R. Rougny, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

### Vrije Universiteit Brussel, Brussel, Belgium

F. Blekman, S. Blyweert, J. D'Hondt, N. Daci, N. Heracleous, J. Keaveney, S. Lowette, M. Maes, A. Olbrechts, Q. Python, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Vilella

### Université Libre de Bruxelles, Bruxelles, Belgium

C. Caillol, B. Clerbaux, G. De Lentdecker, D. Dobur, L. Favart, A.P.R. Gay, A. Grebenyuk, A. Léonard, A. Mohammadi, L. Perniè<sup>2</sup>, T. Reis, T. Seva, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang

### Ghent University, Ghent, Belgium

V. Adler, K. Beernaert, L. Benucci, A. Cimmino, S. Costantini, S. Crucy, S. Dildick, A. Fagot, G. Garcia, J. Mccartin, A.A. Ocampo Rios, D. Ryckbosch, S. Salva Diblen, M. Sigamani, N. Strobbe, F. Thyssen, M. Tytgat, E. Yazgan, N. Zaganidis

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

S. Basegmez, C. Beluffi<sup>3</sup>, G. Bruno, R. Castello, A. Caudron, L. Ceard, G.G. Da Silveira, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco<sup>4</sup>, J. Hollar, P. Jez, M. Komm, V. Lemaitre, C. Nuttens, D. Pagano, L. Perrini, A. Pin, K. Piotrkowski, A. Popov<sup>5</sup>, L. Quertenmont, M. Selvaggi, M. Vidal Marono, J.M. Vizan Garcia

### Université de Mons, Mons, Belgium

N. Bely, T. Caebergs, E. Daubie, G.H. Hammad

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

W.L. Aldá Júnior, G.A. Alves, L. Brito, M. Correa Martins Junior, T. Dos Reis Martins, C. Mora Herrera, M.E. Pol

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

W. Carvalho, J. Chinellato<sup>6</sup>, A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, J. Santaolalla, A. Santoro, A. Sznajder, E.J. Tonelli Manganote<sup>6</sup>, A. Vilela Pereira

**Universidade Estadual Paulista <sup>a</sup>, Universidade Federal do ABC <sup>b</sup>, São Paulo, Brazil**

C.A. Bernardes<sup>b</sup>, S. Dogra<sup>a</sup>, T.R. Fernandez Perez Tomei<sup>a</sup>, E.M. Gregores<sup>b</sup>, P.G. Mercadante<sup>b</sup>, S.F. Novaes<sup>a</sup>, Sandra S. Padula<sup>a</sup>

**Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria**

A. Aleksandrov, V. Genchev<sup>2</sup>, P. Iaydjiev, A. Marinov, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, M. Vutova

**University of Sofia, Sofia, Bulgaria**

A. Dimitrov, I. Glushkov, R. Hadjiiska, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

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

J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, R. Du, C.H. Jiang, S. Liang, R. Plestina<sup>7</sup>, J. Tao, X. Wang, Z. Wang

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

C. Asawatangtrakuldee, Y. Ban, Y. Guo, Q. Li, W. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, L. Zhang, W. Zou

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

C. Avila, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

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

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

**University of Split, Faculty of Science, Split, Croatia**

Z. Antunovic, M. Kovac

**Institute Rudjer Boskovic, Zagreb, Croatia**

V. Brigljevic, K. Kadija, J. Luetic, D. Mekterovic, L. Sudic

**University of Cyprus, Nicosia, Cyprus**

A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis

**Charles University, Prague, Czech Republic**

M. Bodlak, M. Finger, M. Finger Jr.<sup>8</sup>

**Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt**

Y. Assran<sup>9</sup>, A. Ellithi Kamel<sup>10</sup>, M.A. Mahmoud<sup>11</sup>, A. Radi<sup>12,13</sup>

**National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**

M. Kadastik, M. Murumaa, M. Raidal, A. Tiko

**Department of Physics, University of Helsinki, Helsinki, Finland**

P. Eerola, G. Fedi, M. Voutilainen

**Helsinki Institute of Physics, Helsinki, Finland**

J. Härkönen, V. Karimäki, R. Kinnunen, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, L. Wendland

**Lappeenranta University of Technology, Lappeenranta, Finland**

T. Tuuva



**DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France**

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, C. Favaro, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M. Titov

**Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France**

S. Baffioni, F. Beaudette, P. Busson, C. Charlot, T. Dahms, M. Dalchenko, L. Dobrzynski, N. Filipovic, A. Florent, R. Granier de Cassagnac, L. Mastrolorenzo, P. Miné, C. Mironov, I.N. Naranjo, M. Nguyen, C. Ochando, P. Paganini, S. Regnard, R. Salerno, J.B. Sauvan, Y. Sirois, C. Veelken, Y. Yilmaz, A. Zabi

**Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France**

J.-L. Agram<sup>14</sup>, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte<sup>14</sup>, J.-C. Fontaine<sup>14</sup>, D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, P. Van Hove

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

S. Gadrat

**Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France**

S. Beauceron, N. Beaupere, G. Boudoul<sup>2</sup>, E. Bouvier, S. Brochet, C.A. Carrillo Montoya, J. Chasserat, R. Chierici, D. Contardo<sup>2</sup>, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, J.D. Ruiz Alvarez, D. Sabes, L. Sgandurra, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret, H. Xiao

**Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia**

Z. Tsamalaidze<sup>8</sup>

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

C. Autermann, S. Beranek, M. Bontenackels, M. Edelhoff, L. Feld, O. Hindrichs, K. Klein, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, H. Weber, B. Wittmer, V. Zhukov<sup>5</sup>

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

M. Ata, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, S. Knutzen, P. Kreuzer, M. Merschmeyer, A. Meyer, P. Millet, M. Olschewski, K. Padeken, P. Papacz, H. Reithler, S.A. Schmitz, L. Sonnenschein, D. Teyssier, S. Thüer, M. Weber

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

V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, A. Heister, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, J. Lingemann<sup>2</sup>, A. Nowack, I.M. Nugent, L. Perchalla, O. Pooth, A. Stahl

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

I. Asin, N. Bartosik, J. Behr, W. Behrenhoff, U. Behrens, A.J. Bell, M. Bergholz<sup>15</sup>, A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, S. Choudhury, F. Costanza, C. Diez Pardos, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, T. Eichhorn, G. Flucke, J. Garay Garcia, A. Geiser, P. Gunnellini, J. Hauk, M. Hempel, D. Horton, H. Jung, A. Kalogeropoulos, M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, D. Krücker, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann<sup>15</sup>, B. Lutz, R. Mankel, I. Marfin, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, S. Naumann-Emme, A. Nayak, O. Novgorodova, F. Nowak,

E. Ntomari, H. Perrey, D. Pitzl, R. Placakyte, A. Raspereza, P.M. Ribeiro Cipriano, E. Ron, M.Ö. Sahin, J. Salfeld-Nebgen, P. Saxena, R. Schmidt<sup>15</sup>, T. Schoerner-Sadenius, M. Schröder, C. Seitz, S. Spannagel, A.D.R. Vargas Trevino, R. Walsh, C. Wissing

**University of Hamburg, Hamburg, Germany**

M. Aldaya Martin, V. Blobel, M. Centis Vignali, A.R. Draeger, J. Erfle, E. Garutti, K. Goebel, M. Görner, J. Haller, M. Hoffmann, R.S. Höing, H. Kirschenmann, R. Klanner, R. Kogler, J. Lange, T. Lapsien, T. Lenz, I. Marchesini, J. Ott, T. Peiffer, N. Pietsch, J. Poehlsen, T. Poehlsen, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, D. Troendle, E. Usai, L. Vanelderen

**Institut für Experimentelle Kernphysik, Karlsruhe, Germany**

C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, F. Frensch, M. Giffels, F. Hartmann<sup>2</sup>, T. Hauth<sup>2</sup>, U. Husemann, I. Katkov<sup>5</sup>, A. Kornmayer<sup>2</sup>, E. Kuznetsova, P. Lobelle Pardo, M.U. Mozer, Th. Müller, A. Nürnberg, G. Quast, K. Rabbertz, F. Ratnikov, S. Röcker, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, R. Wolf

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

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

**University of Athens, Athens, Greece**

A. Agapitos, A. Panagiotou, N. Saoulidou, E. Stiliaris

**University of Ioánnina, Ioánnina, Greece**

X. Aslanoglou, I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, E. Paradass

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

G. Bencze, C. Hajdu, P. Hidas, D. Horvath<sup>16</sup>, F. Sikler, V. Veszpremi, G. Vesztergombi<sup>17</sup>, A.J. Zsigmond

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

N. Beni, S. Czellar, J. Karancsi<sup>18</sup>, J. Molnar, J. Palinkas, Z. Szillasi

**University of Debrecen, Debrecen, Hungary**

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

**National Institute of Science Education and Research, Bhubaneswar, India**

S.K. Swain

**Panjab University, Chandigarh, India**

S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, U. Bhawandeep, A.K. Kalsi, M. Kaur, M. Mittal, N. Nishu, J.B. Singh

**University of Delhi, Delhi, India**

Ashok Kumar, Arun Kumar, S. Ahuja, A. Bhardwaj, B.C. Choudhary, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, V. Sharma

**Saha Institute of Nuclear Physics, Kolkata, India**

S. Banerjee, S. Bhattacharya, K. Chatterjee, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, A. Modak, S. Mukherjee, D. Roy, S. Sarkar, M. Sharan

**Bhabha Atomic Research Centre, Mumbai, India**

A. Abdulsalam, D. Dutta, S. Kailas, V. Kumar, A.K. Mohanty<sup>2</sup>, L.M. Pant, P. Shukla, A. Topkar

**Tata Institute of Fundamental Research, Mumbai, India**

T. Aziz, S. Banerjee, S. Bhowmik<sup>19</sup>, R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu<sup>20</sup>, G. Kole, S. Kumar, M. Maity<sup>19</sup>, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage<sup>21</sup>

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

H. Bakhshiansohi, H. Behnamian, S.M. Etesami<sup>22</sup>, A. Fahim<sup>23</sup>, R. Goldouzian, A. Jafari, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, B. Safarzadeh<sup>24</sup>, M. Zeinali

**University College Dublin, Dublin, Ireland**

M. Felcini, M. Grunewald

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

M. Abbrescia<sup>a,b</sup>, L. Barbone<sup>a,b</sup>, C. Calabria<sup>a,b</sup>, S.S. Chhibra<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>, L. Fiore<sup>a</sup>, G. Iaselli<sup>a,c</sup>, G. Maggi<sup>a,c</sup>, M. Maggi<sup>a</sup>, S. My<sup>a,c</sup>, S. Nuzzo<sup>a,b</sup>, A. Pompili<sup>a,b</sup>, G. Pugliese<sup>a,c</sup>, R. Radogna<sup>a,b,2</sup>, G. Selvaggi<sup>a,b</sup>, L. Silvestris<sup>a,2</sup>, G. Singh<sup>a,b</sup>, R. Venditti<sup>a,b</sup>, P. Verwilligen<sup>a</sup>, G. Zito<sup>a</sup>

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

G. Abbiendi<sup>a</sup>, A.C. Benvenuti<sup>a</sup>, D. Bonacorsi<sup>a,b</sup>, S. Braibant-Giacomelli<sup>a,b</sup>, L. Brigliadori<sup>a,b</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>, G. Codispoti<sup>a,b</sup>, M. Cuffiani<sup>a,b</sup>, G.M. Dallavalle<sup>a</sup>, F. Fabbri<sup>a</sup>, A. Fanfani<sup>a,b</sup>, D. Fasanella<sup>a,b</sup>, P. Giacomelli<sup>a</sup>, C. Grandi<sup>a</sup>, L. Guiducci<sup>a,b</sup>, S. Marcellini<sup>a</sup>, G. Masetti<sup>a,2</sup>, A. Montanari<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>, N. Tosi<sup>a,b</sup>, R. Travaglini<sup>a,b</sup>

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

S. Albergo<sup>a,b</sup>, G. Cappello<sup>a</sup>, M. Chiorboli<sup>a,b</sup>, S. Costa<sup>a,b</sup>, F. Giordano<sup>a,2</sup>, R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b</sup>, C. Tuve<sup>a,b</sup>

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

G. Barbagli<sup>a</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>, E. Gallo<sup>a</sup>, S. Gozzi<sup>a,b</sup>, V. Gori<sup>a,b,2</sup>, P. Lenzi<sup>a,b</sup>, M. Meschini<sup>a</sup>, S. Paoletti<sup>a</sup>, G. Sguazzoni<sup>a</sup>, A. Tropiano<sup>a,b</sup>

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

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

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

F. Ferro<sup>a</sup>, M. Lo Vetere<sup>a,b</sup>, E. Robutti<sup>a</sup>, S. Tosi<sup>a,b</sup>

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

M.E. Dinardo<sup>a,b</sup>, S. Fiorendi<sup>a,b,2</sup>, S. Gennai<sup>a,2</sup>, R. Gerosa<sup>a,b,2</sup>, A. Ghezzi<sup>a,b</sup>, P. Govoni<sup>a,b</sup>, M.T. Lucchini<sup>a,b,2</sup>, S. Malvezzi<sup>a</sup>, R.A. Manzoni<sup>a,b</sup>, A. Martelli<sup>a,b</sup>, B. Marzocchi<sup>a,b</sup>, D. Menasce<sup>a</sup>, L. Moroni<sup>a</sup>, M. Paganoni<sup>a,b</sup>, D. Pedrini<sup>a</sup>, S. Ragazzi<sup>a,b</sup>, N. Redaelli<sup>a</sup>, T. Tabarelli de Fatis<sup>a,b</sup>

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

S. Buontempo<sup>a</sup>, N. Cavallo<sup>a,c</sup>, S. Di Guida<sup>a,d,2</sup>, F. Fabozzi<sup>a,c</sup>, A.O.M. Iorio<sup>a,b</sup>, L. Lista<sup>a</sup>, S. Meola<sup>a,d,2</sup>, M. Merola<sup>a</sup>, P. Paolucci<sup>a,2</sup>

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

P. Azzi<sup>a</sup>, N. Bacchetta<sup>a</sup>, D. Bisello<sup>a,b</sup>, A. Branca<sup>a,b</sup>, R. Carlin<sup>a,b</sup>, P. Checchia<sup>a</sup>, M. Dall'Osso<sup>a,b</sup>, T. Dorigo<sup>a</sup>, M. Galanti<sup>a,b</sup>, F. Gasparini<sup>a,b</sup>, U. Gasparini<sup>a,b</sup>, P. Giubilato<sup>a,b</sup>, F. Gonella<sup>a</sup>, A. Gozzelino<sup>a</sup>, K. Kanishchev<sup>a,c</sup>, S. Lacaprara<sup>a</sup>, M. Margoni<sup>a,b</sup>, A.T. Meneguzzo<sup>a,b</sup>, J. Pazzini<sup>a,b</sup>, N. Pozzobon<sup>a,b</sup>, P. Ronchese<sup>a,b</sup>, F. Simonetto<sup>a,b</sup>, E. Torassa<sup>a</sup>, M. Tosi<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>, Università di Pavia <sup>b</sup>, Pavia, Italy**

M. Gabusi<sup>a,b</sup>, S.P. Ratti<sup>a,b</sup>, C. Riccardi<sup>a,b</sup>, P. Salvini<sup>a</sup>, P. Vitulo<sup>a,b</sup>

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

M. Biasini<sup>a,b</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>, G. Mantovani<sup>a,b</sup>, M. Menichelli<sup>a</sup>, F. Romeo<sup>a,b</sup>, A. Saha<sup>a</sup>, A. Santocchia<sup>a,b</sup>, A. Spiezia<sup>a,b,2</sup>

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

K. Androsov<sup>a,25</sup>, P. Azzurri<sup>a</sup>, G. Bagliesi<sup>a</sup>, J. Bernardini<sup>a</sup>, T. Boccali<sup>a</sup>, G. Broccoli<sup>a,c</sup>, R. Castaldi<sup>a</sup>, M.A. Ciocci<sup>a,25</sup>, R. Dell'Orso<sup>a</sup>, S. Donato<sup>a,c</sup>, F. Fiori<sup>a,c</sup>, L. Foà<sup>a,c</sup>, A. Giassi<sup>a</sup>, M.T. Grippo<sup>a,25</sup>, F. Ligabue<sup>a,c</sup>, T. Lomtadze<sup>a</sup>, L. Martini<sup>a,b</sup>, A. Messineo<sup>a,b</sup>, C.S. Moon<sup>a,26</sup>, F. Palla<sup>a,2</sup>, A. Rizzi<sup>a,b</sup>, A. Savoy-Navarro<sup>a,27</sup>, A.T. Serban<sup>a</sup>, P. Spagnolo<sup>a</sup>, P. Squillacioti<sup>a,25</sup>, R. Tenchini<sup>a</sup>, G. Tonelli<sup>a,b</sup>, A. Venturi<sup>a</sup>, P.G. Verdini<sup>a</sup>, C. Vernieri<sup>a,c,2</sup>

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

L. Barone<sup>a,b</sup>, F. Cavallari<sup>a</sup>, G. D'imperio<sup>a,b</sup>, D. Del Re<sup>a,b</sup>, M. Diemoz<sup>a</sup>, M. Grassi<sup>a,b</sup>, C. Jorda<sup>a</sup>, E. Longo<sup>a,b</sup>, F. Margaroli<sup>a,b</sup>, P. Meridiani<sup>a</sup>, F. Micheli<sup>a,b,2</sup>, S. Nourbakhsh<sup>a,b</sup>, G. Organtini<sup>a,b</sup>, R. Paramatti<sup>a</sup>, S. Rahatlou<sup>a,b</sup>, C. Rovelli<sup>a</sup>, F. Santanastasio<sup>a,b</sup>, L. Soffi<sup>a,b,2</sup>, P. Traczyk<sup>a,b</sup>

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

N. Amapane<sup>a,b</sup>, R. Arcidiacono<sup>a,c</sup>, S. Argiro<sup>a,b,2</sup>, M. Arneodo<sup>a,c</sup>, R. Bellan<sup>a,b</sup>, C. Biino<sup>a</sup>, N. Cartiglia<sup>a</sup>, S. Casasso<sup>a,b,2</sup>, M. Costa<sup>a,b</sup>, A. Degano<sup>a,b</sup>, N. Demaria<sup>a</sup>, L. Finco<sup>a,b</sup>, C. Mariotti<sup>a</sup>, S. Maselli<sup>a</sup>, E. Migliore<sup>a,b</sup>, V. Monaco<sup>a,b</sup>, M. Musich<sup>a</sup>, M.M. Obertino<sup>a,c,2</sup>, G. Ortona<sup>a,b</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>, A. Potenza<sup>a,b</sup>, A. Romero<sup>a,b</sup>, M. Ruspa<sup>a,c</sup>, R. Sacchi<sup>a,b</sup>, A. Solano<sup>a,b</sup>, A. Staiano<sup>a</sup>, U. Tamponi<sup>a</sup>

**INFN Sezione di Trieste <sup>a</sup>, 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>, G. Della Ricca<sup>a,b</sup>, B. Gobbo<sup>a</sup>, C. La Licata<sup>a,b</sup>, M. Marone<sup>a,b</sup>, D. Montanino<sup>a,b</sup>, A. Schizzi<sup>a,b,2</sup>, T. Umer<sup>a,b</sup>, A. Zanetti<sup>a</sup>

**Kangwon National University, Chunchon, Korea**

S. Chang, A. Kropivnitskaya, S.K. Nam

**Kyungpook National University, Daegu, Korea**

D.H. Kim, G.N. Kim, M.S. Kim, D.J. Kong, S. Lee, Y.D. Oh, H. Park, A. Sakharov, D.C. Son

**Chonbuk National University, Jeonju, Korea**

T.J. Kim

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

J.Y. Kim, S. Song

**Korea University, Seoul, Korea**

S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, Y. Kim, B. Lee, K.S. Lee, S.K. Park, Y. Roh

**University of Seoul, Seoul, Korea**

M. Choi, J.H. Kim, I.C. Park, S. Park, G. Ryu, M.S. Ryu

**Sungkyunkwan University, Suwon, Korea**

Y. Choi, Y.K. Choi, J. Goh, D. Kim, E. Kwon, J. Lee, H. Seo, I. Yu

**Vilnius University, Vilnius, Lithuania**

A. Juodagalvis

**National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia**

J.R. Komaragiri, M.A.B. Md Ali

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

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz<sup>28</sup>, R. Lopez-Fernandez, A. Sanchez-Hernandez

**Universidad Iberoamericana, Mexico City, Mexico**

S. Carrillo Moreno, F. Vazquez Valencia

**Benemerita Universidad Autonoma de Puebla, Puebla, Mexico**

I. Pedraza, H.A. Salazar Ibarguen

**Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico**

E. Casimiro Linares, A. Morelos Pineda

**University of Auckland, Auckland, New Zealand**

D. Krofcheck

**University of Canterbury, Christchurch, New Zealand**

P.H. Butler, S. Reucroft

**National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan**

A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, S. Khalid, W.A. Khan, T. Khurshid, M.A. Shah, M. Shoaib

**National Centre for Nuclear Research, Swierk, Poland**

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, P. Zalewski

**Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland**

G. Brona, K. Bunkowski, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, W. Wolszczak

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

P. Bargassa, C. Beirão Da Cruz E Silva, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, F. Nguyen, J. Rodrigues Antunes, J. Seixas, J. Varela, P. Vischia

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

S. Afanasiev, M. Gavrilenko, I. Golutvin, A. Kamenev, V. Karjavin, V. Konoplyanikov, A. Lanev, A. Malakhov, V. Matveev<sup>29</sup>, P. Moisezenz, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, A. Zarubin

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

V. Golovtsov, Y. Ivanov, V. Kim<sup>30</sup>, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

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

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

**Institute for Theoretical and Experimental Physics, Moscow, Russia**

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, A. Spiridonov, V. Stolin, E. Vlasov, A. Zhokin

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

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, G. Mesyats, S.V. Rusakov, A. Vinogradov

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

A. Belyaev, E. Boos, V. Bunichev, M. Dubinin<sup>31</sup>, L. Dudko, A. Ershov, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

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

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

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

P. Adzic<sup>32</sup>, M. Ekmedzic, J. Milosevic, V. Rekovic

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

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

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

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

**Universidad de Oviedo, Oviedo, Spain**

H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias

**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, G. Gomez, A. Graziano, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, R. Vilar Cortabitarte

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

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, A. Benaglia, J. Bendavid, L. Benhabib, J.F. Benitez, C. Bernet<sup>7</sup>, G. Bianchi, P. Bloch, A. Bocci, A. Bonato, O. Bondu, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, S. Colafranceschi<sup>33</sup>, M. D'Alfonso, D. d'Enterria, A. Dabrowski, A. David, F. De Guio, A. De Roeck, S. De Visscher, M. Dobson, M. Dordevic, N. Dupont-Sagorin, A. Elliott-Peisert, J. Eugster, G. Franzoni, W. Funk, D. Gigi, K. Gill, D. Giordano, M. Girone, F. Glege, R. Guida, S. Gundacker, M. Guthoff, J. Hammer,

M. Hansen, P. Harris, J. Hegeman, V. Innocente, P. Janot, K. Kousouris, K. Krajczar, P. Lecoq, C. Lourenço, N. Magini, L. Malgeri, M. Mannelli, J. Marrouche, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, P. Musella, L. Orsini, L. Pape, E. Perez, L. Perrozzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, M. Plagge, A. Racz, G. Rolandi<sup>34</sup>, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas<sup>35</sup>, D. Spiga, J. Steggemann, B. Stieger, M. Stoye, D. Treille, A. Tsirou, G.I. Veres<sup>17</sup>, J.R. Vlimant, N. Wardle, H.K. Wöhri, H. Wollny, W.D. Zeuner

**Paul Scherrer Institut, Villigen, Switzerland**

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

**Institute for Particle Physics, ETH Zurich, Zurich, Switzerland**

F. Bachmair, L. Bäni, L. Bianchini, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, P. Eller, C. Grab, D. Hits, W. Luster, B. Mangano, A.C. Marini, P. Martinez Ruiz del Arbol, D. Meister, N. Mohr, C. Nägeli<sup>36</sup>, F. Nessi-Tedaldi, F. Pandolfi, F. Pauss, M. Peruzzi, M. Quittnat, L. Rebane, M. Rossini, A. Starodumov<sup>37</sup>, M. Takahashi, K. Theofilatos, R. Wallny, H.A. Weber

**Universität Zürich, Zurich, Switzerland**

C. Amsler<sup>38</sup>, M.F. Canelli, V. Chiochia, A. De Cosa, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, B. Millan Mejias, J. Ngadiuba, P. Robmann, F.J. Ronga, S. Taroni, M. Verzetti, Y. Yang

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

M. Cardaci, K.H. Chen, C. Ferro, C.M. Kuo, W. Lin, Y.J. Lu, R. Volpe, S.S. Yu

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

P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, U. Grundler, W.-S. Hou, K.Y. Kao, Y.J. Lei, Y.F. Liu, R.-S. Lu, D. Majumder, E. Petrakou, Y.M. Tzeng, R. Wilken

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

B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

**Cukurova University, Adana, Turkey**

A. Adiguzel, M.N. Bakirci<sup>39</sup>, S. Cerci<sup>40</sup>, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, A. Kayis Topaksu, G. Onengut<sup>41</sup>, K. Ozdemir, S. Ozturk<sup>39</sup>, A. Polatoz, K. Sogut<sup>42</sup>, D. Sunar Cerci<sup>40</sup>, B. Tali<sup>40</sup>, H. Topakli<sup>39</sup>, M. Vergili

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

I.V. Akin, B. Bilin, S. Bilmis, H. Gamsizkan, G. Karapinar<sup>43</sup>, K. Ocalan, S. Sekmen, U.E. Surat, M. Yalvac, M. Zeyrek

**Bogazici University, Istanbul, Turkey**

E. Gülmez, B. Isildak<sup>44</sup>, M. Kaya<sup>45</sup>, O. Kaya<sup>46</sup>

**Istanbul Technical University, Istanbul, Turkey**

H. Bahtiyar<sup>47</sup>, E. Barlas, K. Cankocak, F.I. Vardarli, M. Yücel

**National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine**

L. Levchuk, P. Sorokin

**University of Bristol, Bristol, United Kingdom**

J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, Z. Meng, D.M. Newbold<sup>48</sup>, S. Paramesvaran, A. Poll, S. Senkin, V.J. Smith, T. Williams

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

K.W. Bell, A. Belyaev<sup>49</sup>, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, W.J. Womersley, S.D. Worm

**Imperial College, London, United Kingdom**

M. Baber, R. Bainbridge, O. Buchmuller, D. Burton, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, G. Davies, M. Della Negra, P. Dunne, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, G. Hall, G. Iles, M. Jarvis, G. Karapostoli, M. Kenzie, R. Lane, R. Lucas<sup>48</sup>, L. Lyons, A.-M. Magnan, S. Malik, B. Mathias, J. Nash, A. Nikitenko<sup>37</sup>, J. Pela, M. Pesaresi, K. Petridis, D.M. Raymond, S. Rogerson, A. Rose, C. Seez, P. Sharp<sup>†</sup>, A. Tapper, M. Vazquez Acosta, T. Virdee

**Brunel University, Uxbridge, United Kingdom**

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

**Baylor University, Waco, USA**

J. Dittmann, K. Hatakeyama, A. Kasmi, H. Liu, T. Scarborough

**The University of Alabama, Tuscaloosa, USA**

O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio

**Boston University, Boston, USA**

A. Avetisyan, T. Bose, C. Fantasia, P. Lawson, C. Richardson, J. Rohlf, D. Sperka, J. St. John, L. Sulak

**Brown University, Providence, USA**

J. Alimena, E. Berry, S. Bhattacharya, G. Christopher, D. Cutts, Z. Demiragli, A. Ferapontov, A. Garabedian, U. Heintz, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, M. Segala, T. Sinthuprasith, T. Speer, J. Swanson

**University of California, Davis, Davis, USA**

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, M. Gardner, W. Ko, R. Lander, T. Miceli, M. Mulhearn, D. Pellett, J. Pilot, F. Ricci-Tam, M. Searle, S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay

**University of California, Los Angeles, USA**

R. Cousins, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, G. Rakness, E. Takasugi, V. Valuev, M. Weber

**University of California, Riverside, Riverside, USA**

J. Babb, K. Burt, R. Clare, J. Ellison, J.W. Gary, G. Hanson, J. Heilman, M. Ivova Rikova, P. Jandir, E. Kennedy, F. Lacroix, H. Liu, O.R. Long, A. Luthra, M. Malberti, H. Nguyen, M. Olmedo Negrete, A. Shrinivas, S. Sumowidagdo, S. Wimpenny

**University of California, San Diego, La Jolla, USA**

W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, R.T. D'Agnolo, D. Evans, A. Holzner, R. Kelley, D. Klein, M. Lebourgeois, J. Letts, I. Macneill, D. Olivito, S. Padhi, C. Palmer, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, C. Welke, F. Würthwein, A. Yagil, J. Yoo

**University of California, Santa Barbara, Santa Barbara, USA**

D. Barge, J. Bradmiller-Feld, C. Campagnari, T. Danielson, A. Dishaw, K. Flowers, M. Franco



---

Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Incandela, C. Justus, N. Mccoll, J. Richman, D. Stuart, W. To, C. West

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

A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, E. Di Marco, J. Duarte, A. Mott, H.B. Newman, C. Pena, C. Rogan, M. Spiropulu, V. Timciuc, R. Wilkinson, S. Xie, R.Y. Zhu

**Carnegie Mellon University, Pittsburgh, USA**

V. Azzolini, A. Calamba, B. Carlson, T. Ferguson, Y. Iiyama, M. Paulini, J. Russ, H. Vogel, I. Vorobiev

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

J.P. Cumalat, W.T. Ford, A. Gaz, E. Luiggi Lopez, U. Nauenberg, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner

**Cornell University, Ithaca, USA**

J. Alexander, A. Chatterjee, J. Chu, S. Dittmer, N. Eggert, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Ryd, E. Salvati, L. Skinnari, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Tucker, Y. Weng, L. Winstrom, P. Wittich

**Fairfield University, Fairfield, USA**

D. Winn

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

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, H.W.K. Cheung, F. Chlebana, S. Cihangir, V.D. Elvira, I. Fisk, J. Freeman, Y. Gao, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, D. Hare, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, K. Kaadze, B. Klima, B. Kreis, S. Kwan, J. Linacre, D. Lincoln, R. Lipton, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, V.I. Martinez Outschoorn, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko<sup>29</sup>, S. Nahn, C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, S. Sharma, A. Soha, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, A. Whitbeck, J. Whitmore, F. Yang

**University of Florida, Gainesville, USA**

D. Acosta, P. Avery, D. Bourilkov, M. Carver, T. Cheng, D. Curry, S. Das, M. De Gruttola, G.P. Di Giovanni, R.D. Field, M. Fisher, I.K. Furic, J. Hugon, J. Konigsberg, A. Korytov, T. Kypreos, J.F. Low, K. Matchev, P. Milenov<sup>50</sup>, G. Mitselmakher, L. Muniz, A. Rinkevicius, L. Shchutka, M. Snowball, J. Yelton, M. Zakaria

**Florida International University, Miami, USA**

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

**Florida State University, Tallahassee, USA**

T. Adams, A. Askew, J. Bochenek, B. Diamond, J. Haas, S. Hagopian, V. Hagopian, K.F. Johnson, H. Prosper, V. Veeraraghavan, M. Weinberg

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

M.M. Baarmand, M. Hohlmann, H. Kalakhety, F. Yumiceva

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

M.R. Adams, L. Apanasevich, V.E. Bazterra, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, P. Kurt, D.H. Moon, C. O'Brien, C. Silkworth, P. Turner, N. Varelas

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

E.A. Albayrak<sup>47</sup>, B. Bilki<sup>51</sup>, W. Clarida, K. Dilsiz, F. Duru, M. Haytmyradov, J.-P. Merlo, H. Mermerkaya<sup>52</sup>, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok<sup>47</sup>, A. Penzo, R. Rahmat, S. Sen, P. Tan, E. Tiras, J. Wetzel, T. Yetkin<sup>53</sup>, K. Yi

**Johns Hopkins University, Baltimore, USA**

B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, A.V. Gritsan, P. Maksimovic, C. Martin, M. Swartz

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

P. Baringer, A. Bean, G. Benelli, C. Bruner, J. Gray, R.P. Kenny III, M. Malek, M. Murray, D. Noonan, S. Sanders, J. Sekaric, R. Stringer, Q. Wang, J.S. Wood

**Kansas State University, Manhattan, USA**

A.F. Barfuss, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, L.K. Saini, S. Shrestha, N. Skhirtladze, I. Svintradze

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

J. Gronberg, D. Lange, F. Rebassoo, D. Wright

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

A. Baden, A. Belloni, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, R.G. Kellogg, T. Kolberg, Y. Lu, M. Marionneau, A.C. Mignerey, K. Pedro, A. Skuja, M.B. Tonjes, S.C. Tonwar

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

A. Apyan, R. Barbieri, G. Bauer, W. Busza, I.A. Cali, M. Chan, L. Di Matteo, V. Dutta, G. Gomez Ceballos, M. Goncharov, D. Gulhan, M. Klute, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, T. Ma, C. Paus, D. Ralph, C. Roland, G. Roland, G.S.F. Stephans, F. Stöckli, K. Sumorok, D. Velicanu, J. Veverka, B. Wyslouch, M. Yang, M. Zanetti, V. Zhukova

**University of Minnesota, Minneapolis, USA**

B. Dahmes, A. Gude, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, N. Pastika, R. Rusack, A. Singovsky, N. Tambe, J. Turkewitz

**University of Mississippi, Oxford, USA**

J.G. Acosta, S. Oliveros

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

E. Avdeeva, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, R. Gonzalez Suarez, J. Keller, D. Knowlton, I. Kravchenko, J. Lazo-Flores, S. Malik, F. Meier, G.R. Snow

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

J. Dolen, A. Godshalk, I. Iashvili, A. Kharchilava, A. Kumar, S. Rappoccio

**Northeastern University, Boston, USA**

G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, J. Haley, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, D. Trocino, R.-J. Wang, D. Wood, J. Zhang

**Northwestern University, Evanston, USA**

K.A. Hahn, A. Kubik, N. Mucia, N. Odell, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, K. Sung, M. Velasco, S. Won

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

A. Brinkerhoff, K.M. Chan, A. Drozdetskiy, M. Hildreth, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, W. Luo, S. Lynch, N. Marinelli, T. Pearson, M. Planer, R. Ruchti, N. Valls, M. Wayne, M. Wolf, A. Woodard

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

L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, D. Puigh, M. Rodenburg, G. Smith, B.L. Winer, H. Wolfe, H.W. Wulsin

**Princeton University, Princeton, USA**

O. Driga, P. Elmer, P. Hebda, A. Hunt, S.A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, H. Saka, D. Stickland<sup>2</sup>, C. Tully, J.S. Werner, S.C. Zenz, A. Zuranski

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

E. Brownson, H. Mendez, J.E. Ramirez Vargas

**Purdue University, West Lafayette, USA**

E. Alagoz, V.E. Barnes, D. Benedetti, G. Bolla, D. Bortoletto, M. De Mattia, Z. Hu, M.K. Jha, M. Jones, K. Jung, M. Kress, N. Leonardo, D. Lopes Pegna, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, B.C. Radburn-Smith, X. Shi, I. Shipsey, D. Silvers, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu, H.D. Yoo, J. Zablocki, Y. Zheng

**Purdue University Calumet, Hammond, USA**

N. Parashar, J. Stupak

**Rice University, Houston, USA**

A. Adair, B. Akgun, K.M. Ecklund, F.J.M. Geurts, W. Li, B. Michlin, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

**University of Rochester, Rochester, USA**

B. Betchart, A. Bodek, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, A. Khukhunaishvili, G. Petrillo, D. Vishnevskiy

**The Rockefeller University, New York, USA**

R. Ciesielski, L. Demortier, K. Goulianos, G. Lungu, C. Mesropian

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

S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, N. Craig, D. Duggan, J. Evans, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, A. Lath, S. Panwalkar, M. Park, R. Patel, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

**University of Tennessee, Knoxville, USA**

K. Rose, S. Spanier, A. York

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

O. Bouhali<sup>54</sup>, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon<sup>55</sup>, V. Khotilovich, V. Krutelyov, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Rose, A. Safonov, T. Sakuma, I. Suarez, A. Tatarinov

**Texas Tech University, Lubbock, USA**

N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Duderu, J. Faulkner, K. Kovitanggoon, S. Kunori, S.W. Lee, T. Libeiro, I. Volobouev

**Vanderbilt University, Nashville, USA**

E. Appelt, A.G. Delannoy, S. Greene, A. Gurrola, W. Johns, C. Maguire, Y. Mao, A. Melo, M. Sharma, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

**University of Virginia, Charlottesville, USA**

M.W. Arenton, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Lin, C. Neu, J. Wood

**Wayne State University, Detroit, USA**

C. Clarke, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, J. Sturdy

**University of Wisconsin, Madison, USA**

D.A. Belknap, D. Carlsmith, M. Cepeda, S. Dasu, L. Dodd, S. Duric, E. Friis, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, C. Lazaridis, A. Levine, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, I. Ross, T. Sarangi, A. Savin, W.H. Smith, C. Vuosalo, N. Woods

†: Deceased

- 1: Also at Vienna University of Technology, Vienna, Austria
- 2: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 3: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
- 4: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
- 5: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- 6: Also at Universidade Estadual de Campinas, Campinas, Brazil
- 7: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
- 8: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 9: Also at Suez University, Suez, Egypt
- 10: Also at Cairo University, Cairo, Egypt
- 11: Also at Fayoum University, El-Fayoum, Egypt
- 12: Also at British University in Egypt, Cairo, Egypt
- 13: Now at Ain Shams University, Cairo, Egypt
- 14: Also at Université de Haute Alsace, Mulhouse, France
- 15: Also at Brandenburg University of Technology, Cottbus, Germany
- 16: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 17: Also at Eötvös Loránd University, Budapest, Hungary
- 18: Also at University of Debrecen, Debrecen, Hungary
- 19: Also at University of Visva-Bharati, Santiniketan, India
- 20: Now at King Abdulaziz University, Jeddah, Saudi Arabia
- 21: Also at University of Ruhuna, Matara, Sri Lanka
- 22: Also at Isfahan University of Technology, Isfahan, Iran
- 23: Also at Sharif University of Technology, Tehran, Iran
- 24: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
- 25: Also at Università degli Studi di Siena, Siena, Italy
- 26: Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France
- 27: Also at Purdue University, West Lafayette, USA
- 28: Also at Universidad Michoacana de San Nicolas de Hidalgo, Morelia, Mexico
- 29: Also at Institute for Nuclear Research, Moscow, Russia
- 30: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 31: Also at California Institute of Technology, Pasadena, USA
- 32: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 33: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
- 34: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy

- 
- 35: Also at University of Athens, Athens, Greece  
36: Also at Paul Scherrer Institut, Villigen, Switzerland  
37: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia  
38: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland  
39: Also at Gaziosmanpasa University, Tokat, Turkey  
40: Also at Adiyaman University, Adiyaman, Turkey  
41: Also at Cag University, Mersin, Turkey  
42: Also at Mersin University, Mersin, Turkey  
43: Also at Izmir Institute of Technology, Izmir, Turkey  
44: Also at Ozyegin University, Istanbul, Turkey  
45: Also at Marmara University, Istanbul, Turkey  
46: Also at Kafkas University, Kars, Turkey  
47: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey  
48: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom  
49: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom  
50: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia  
51: Also at Argonne National Laboratory, Argonne, USA  
52: Also at Erzincan University, Erzincan, Turkey  
53: Also at Yildiz Technical University, Istanbul, Turkey  
54: Also at Texas A&M University at Qatar, Doha, Qatar  
55: Also at Kyungpook National University, Daegu, Korea