



# Constraints on the Higgs boson width from off-shell production and decay to Z-boson pairs



CMS Collaboration\*

CERN, Switzerland

## ARTICLE INFO

### Article history:

Received 14 May 2014  
 Received in revised form 12 June 2014  
 Accepted 30 June 2014  
 Available online 3 July 2014  
 Editor: M. Doser

### Keywords:

CMS  
 Physics  
 Higgs  
 Diboson  
 Properties

## ABSTRACT

Constraints are presented on the total width of the recently discovered Higgs boson,  $\Gamma_H$ , using its relative on-shell and off-shell production and decay rates to a pair of Z bosons, where one Z boson decays to an electron or muon pair, and the other to an electron, muon, or neutrino pair. The analysis is based on the data collected by the CMS experiment at the LHC in 2011 and 2012, corresponding to integrated luminosities of  $5.1 \text{ fb}^{-1}$  at a center-of-mass energy  $\sqrt{s} = 7 \text{ TeV}$  and  $19.7 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$ . A simultaneous maximum likelihood fit to the measured kinematic distributions near the resonance peak and above the Z-boson pair production threshold leads to an upper limit on the Higgs boson width of  $\Gamma_H < 22 \text{ MeV}$  at a 95% confidence level, which is 5.4 times the expected value in the standard model at the measured mass of  $m_H = 125.6 \text{ GeV}$ .

© 2014 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/3.0/>). Funded by SCOAP<sup>3</sup>.

The discovery of a new boson consistent with the standard model (SM) Higgs boson by the ATLAS and CMS Collaborations was recently reported [1–3]. The mass of the new boson ( $m_H$ ) was measured to be near 125 GeV, and the spin-parity properties were further studied by both experiments, favoring the scalar,  $J^{PC} = 0^{++}$ , hypothesis [4–7]. The measurements were found to be consistent with a single narrow resonance, and an upper limit of 3.4 GeV at a 95% confidence level (CL) on its decay width ( $\Gamma_H$ ) was reported by the CMS experiment in the four-lepton decay channel [7]. A direct width measurement at the resonance peak is limited by experimental resolution, and is only sensitive to values far larger than the expected width of around 4 MeV for the SM Higgs boson [8,9].

It was recently proposed [10] to constrain the Higgs boson width using its off-shell production and decay to two Z bosons away from the resonance peak [11]. In the dominant gluon fusion production mode the off-shell production cross section is known to be sizable. This arises from an enhancement in the decay amplitude from the vicinity of the Z-boson pair production threshold. A further enhancement comes, in gluon fusion production, from the top-quark pair production threshold. The zero-width approximation is inadequate and the ratio of the off-shell cross section above  $2m_Z$  to the on-shell signal is of the order of 8% [11,12]. Further developments to the measurement of the Higgs boson width were proposed in Refs. [13,14].

The gluon fusion production cross section depends on  $\Gamma_H$  through the Higgs boson propagator

$$\frac{d\sigma_{gg \rightarrow H \rightarrow ZZ}}{dm_{ZZ}^2} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}, \quad (1)$$

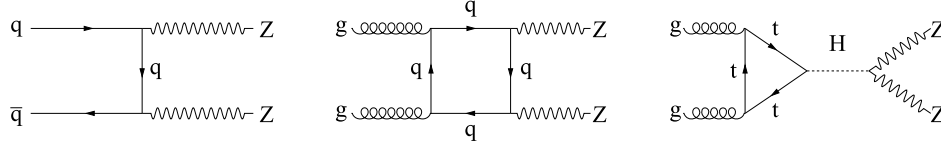
where  $g_{ggH}$  and  $g_{HZZ}$  are the couplings of the Higgs boson to gluons and Z bosons, respectively. Integrating either in a small region around  $m_H$ , or above the mass threshold  $m_{ZZ} > 2m_Z$ , where  $(m_{ZZ} - m_H) \gg \Gamma_H$ , the cross sections are, respectively,

$$\sigma_{gg \rightarrow H \rightarrow ZZ}^{\text{on-shell}} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{m_H \Gamma_H} \quad \text{and} \quad \sigma_{gg \rightarrow H^* \rightarrow ZZ}^{\text{off-shell}} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{(2m_Z)^2}. \quad (2)$$

From Eq. (2), it is clear that a measurement of the relative off-shell and on-shell production in the  $H \rightarrow ZZ$  channel provides direct information on  $\Gamma_H$ , as long as the coupling ratios remain unchanged, i.e. the gluon fusion production is dominated by the top-quark loop and there are no new particles contributing. In particular, the on-shell production cross section is unchanged under a common scaling of the squared product of the couplings and of the total width  $\Gamma_H$ , while the off-shell production cross section increases linearly with this scaling factor.

The dominant contribution for the production of a pair of Z bosons comes from the quark-initiated process,  $q\bar{q} \rightarrow ZZ$ , the diagram for which is displayed in Fig. 1(left). The gluon-induced diboson production involves the  $gg \rightarrow ZZ$  continuum background production from the box diagrams, as illustrated in Fig. 1(center). An

\* E-mail address: cms-publication-committee-chair@cern.ch.



**Fig. 1.** Lowest order contributions to the main ZZ production processes: (left) quark-initiated production,  $q\bar{q} \rightarrow ZZ$ , (center)  $gg$  continuum background production,  $gg \rightarrow ZZ$ , and (right) Higgs-mediated  $gg$  production,  $gg \rightarrow H \rightarrow ZZ$ , the signal.

example of the signal production diagram is shown in Fig. 1(right). The interference between the two gluon-induced contributions is significant at high  $m_{ZZ}$  [15], and is taken into account in the analysis of the off-shell signal.

Vector boson fusion (VBF) production, which contributes at the level of about 7% to the on-shell cross section, is expected to increase above  $2m_Z$ . The above formalism describing the ratio of off-shell and on-shell cross sections is applicable to the VBF production mode. In this analysis we constrain the fraction of VBF production using the properties of the events in the on-shell region. The other main Higgs boson production mechanisms,  $t\bar{t}H$  and  $VH$  ( $V = Z, W$ ), which contribute at the level of about 5% to the on-shell signal, are not expected to produce a significant off-shell contribution as they are suppressed at high mass [8,9]. They are therefore neglected in the off-shell analysis.

In this Letter, we present constraints on the Higgs boson width using its off-shell production and decay to Z-boson pairs, in the final states where one Z boson decays to an electron or a muon pair and the other to either an electron or a muon pair,  $H \rightarrow ZZ \rightarrow 4\ell$  ( $4\ell$  channel), or a pair of neutrinos,  $H \rightarrow ZZ \rightarrow 2\ell 2\nu$  ( $2\ell 2\nu$  channel). Relying on the observed Higgs boson signal in the resonance peak region [7], the simultaneous measurement of the signal in the high-mass region leads to constraints on the Higgs boson width  $\Gamma_H$  in the  $4\ell$  decay channel. The  $2\ell 2\nu$  decay channel, which benefits from a higher branching fraction [16,17], is used in the high-mass region to further increase the sensitivity to the Higgs boson width. The analysis is performed for the tree-level HVV coupling of a scalar Higgs boson, consistent with our observations [4,7], and implications for the anomalous HVV interactions are discussed. The Higgs boson mass is set to the measured value in the  $4\ell$  decay channel of  $m_H = 125.6$  GeV [7] and the Higgs boson width is set to the corresponding expected value in the SM of  $\Gamma_H^{SM} = 4.15$  MeV [8,9].

The measurement is based on pp collision data collected with the CMS detector at the LHC in 2011, corresponding to an integrated luminosity of  $5.1 \text{ fb}^{-1}$  at the center-of-mass energy of  $\sqrt{s} = 7$  TeV ( $4\ell$  channel), and in 2012, corresponding to an integrated luminosity of  $19.7 \text{ fb}^{-1}$  at  $\sqrt{s} = 8$  TeV ( $4\ell$  and  $2\ell 2\nu$  channels). The CMS detector, described in detail elsewhere [18], provides excellent resolution for the measurement of electron and muon transverse momenta ( $p_T$ ) over a wide range. The signal candidates are selected using well-identified and isolated prompt leptons. The online selection and event reconstruction are described elsewhere [2,3,7,16]. The analysis presented here is based on the same event selection as used in Refs. [7,16].

The analysis in the  $4\ell$  channel uses the four-lepton invariant mass distribution as well as a matrix element likelihood discriminant to separate the ZZ components originating from gluon and quark-initiated processes. We define the on-shell signal region as  $105.6 < m_{4\ell} < 140.6$  GeV and the off-shell signal region as  $m_{4\ell} > 220$  GeV. The analysis in the  $2\ell 2\nu$  channel relies on the transverse mass distribution  $m_T$ ,

$$m_T^2 = \left[ \sqrt{p_{T,2\ell}^2 + m_{2\ell}^2} + \sqrt{E_T^{\text{miss}^2} + m_{2\ell}^2} \right]^2 - \left[ \vec{p}_{T,2\ell} + \vec{E}_T^{\text{miss}} \right]^2, \quad (3)$$

where  $p_{T,2\ell}$  and  $m_{2\ell}$  are the measured transverse momentum and invariant mass of the dilepton system, respectively. The missing transverse energy,  $E_T^{\text{miss}}$ , is defined as the magnitude of the transverse momentum imbalance evaluated as the negative of the vectorial sum of transverse momenta of all the reconstructed particles in the event. In the  $2\ell 2\nu$  channel, the off-shell signal region is defined as  $m_T > 180$  GeV. The choice of the off-shell regions in both channels is done prior to looking at the data, based on the expected sensitivity.

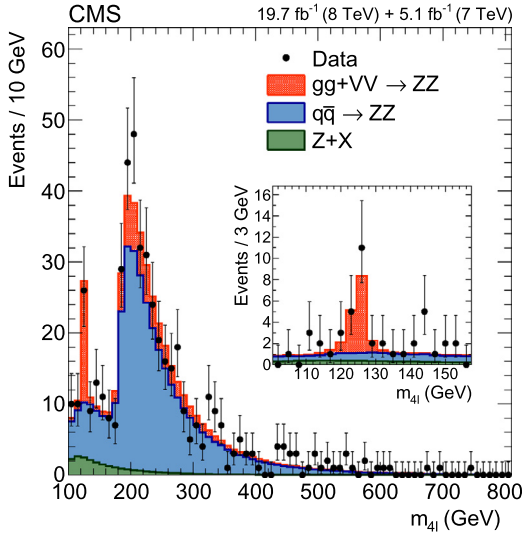
Simulated Monte Carlo (MC) samples of  $gg \rightarrow 4\ell$  and  $gg \rightarrow 2\ell 2\nu$  events are generated at leading order (LO) in perturbative quantum chromodynamics (QCD), including the Higgs boson signal, the continuum background, and the interference contributions using recent versions of two different MC generators, `GG2VV 3.1.5` [11,19] and `MCFM 6.7` [20], in order to cross-check theoretical inputs. The QCD renormalization and factorization scales are set to  $m_{ZZ}/2$  (dynamic scales) and MSTW2008 LO parton distribution functions (PDFs) [21] are used. Higher-order QCD corrections for the gluon fusion signal process are known to an accuracy of next-to-next-to-leading order (NNLO) and next-to-next-to-leading order (NNLO) for the total cross section [8,9] and to NNLO as a function of  $m_{ZZ}$  [14]. These correction factors to the LO cross section (K factors) are typically in the range of 2.0 to 2.5. After the application of the  $m_{ZZ}$ -dependent K factors, the event yield is normalized to the cross section from Refs. [8,9]. For the  $gg \rightarrow ZZ$  continuum background, although no exact calculation exists beyond LO, it has been recently shown [22] that the soft collinear approximation is able to describe the background cross section and therefore the interference term at NNLO. Following this calculation, we assign to the LO background cross section (and, consequently, to the interference contribution) a K factor equal to that used for the signal [14]. The limited theoretical knowledge of the background K factor at NNLO is taken into account by including an additional systematic uncertainty, the impact of which on the measurement is nevertheless small.

Vector boson fusion events are generated with `PHANTOM` [23]. Off-shell and interference effects with the nonresonant production are included at LO in these simulations. The event yield is normalized to the cross section at NNLO QCD and next-to-leading order (NLO) electroweak (EW) [8,9] accuracy, with a normalization factor shown to be independent of  $m_{ZZ}$ .

In order to parameterize and validate the distributions of all the components for both gluon fusion and VBF processes, specific simulated samples are also produced that describe only the signal or the continuum background, as well as several scenarios with scaled couplings and width. For the on-shell analysis, signal events are generated either with `POWHEG` [24–27] production at NLO in QCD and `JHUGEN` [28,29] decay (gluon fusion and VBF), or with `PYTHIA 6.4` [30] ( $VH$  and  $t\bar{t}H$  production).

In both the  $4\ell$  and  $2\ell 2\nu$  channels the dominant background is  $q\bar{q} \rightarrow ZZ$ . We assume SM production rates for this background, the contribution of which is evaluated by `POWHEG` simulation at NLO in QCD [31]. Next-to-leading order EW calculations [32,33], which predict negative and  $m_{ZZ}$ -dependent corrections to the  $q\bar{q} \rightarrow ZZ$  process for on-shell Z-boson pairs, are taken into account.

All simulated events undergo parton showering and hadronization using `PYTHIA`. As is done in Ref. [7] for LO samples, the parton



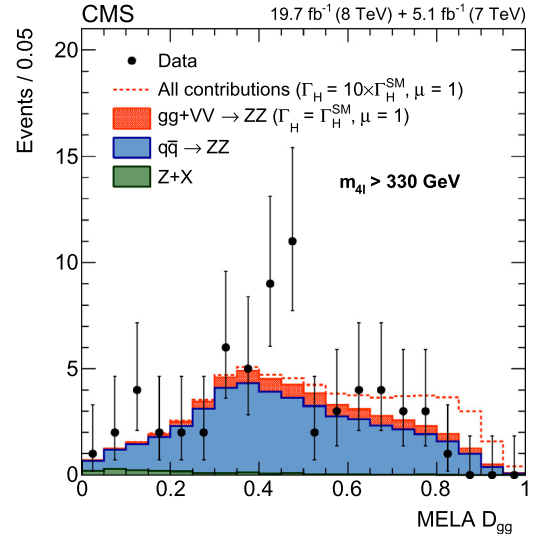
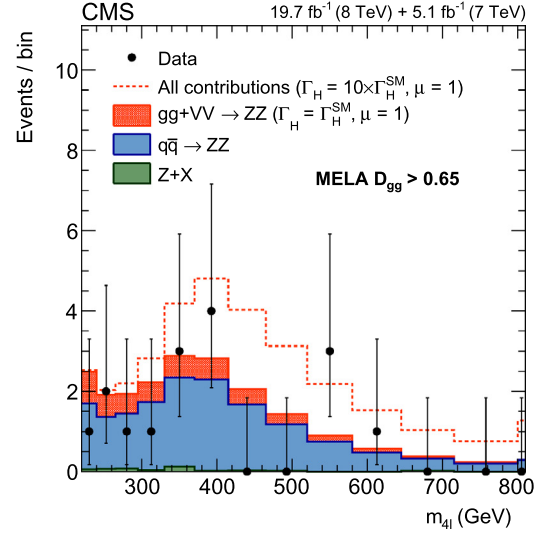
**Fig. 2.** Distribution of the four-lepton invariant mass in the range  $100 < m_{4\ell} < 800$  GeV. Points represent the data, filled histograms the expected contributions from the reducible ( $Z + X$ ) and  $q\bar{q}$  backgrounds, and from the sum of the gluon fusion ( $gg$ ) and vector boson fusion ( $VV$ ) processes, including the Higgs boson mediated contributions. The inset shows the distribution in the low mass region after a selection requirement on the MELA likelihood discriminant  $\mathcal{D}_{\text{bkg}}^{\text{kin}} > 0.5$  [7]. In this region, the contribution of the  $t\bar{t}$  and  $VH$  production processes is added to the dominant gluon fusion and VBF contributions.

showering settings are tuned to approximately reproduce the  $ZZ$   $p_T$  spectrum predicted at NNLO for the Higgs boson production [34]. Generated events are then processed with the detailed CMS detector simulation based on GEANT4 [35,36], and reconstructed using the same algorithms as used for the observed events.

The final state in the  $4\ell$  channel is characterized by four well-identified and isolated leptons forming two pairs of opposite-sign and same-flavor leptons consistent with two  $Z$  bosons. This channel benefits from a precise reconstruction of all final state leptons and from a very low instrumental background. The event selection and the reducible background evaluation are performed following the methods described in Ref. [7]. After the selection, the  $4\ell$  data sample is dominated by the quark-initiated  $q\bar{q} \rightarrow ZZ \rightarrow 4\ell$  ( $q\bar{q} \rightarrow 4\ell$ ) and  $gg \rightarrow 4\ell$  productions.

Fig. 2 presents the measured  $m_{4\ell}$  distribution over the full mass range,  $m_{4\ell} > 100$  GeV, together with the expected SM contributions. The  $gg \rightarrow 4\ell$  contribution is clearly visible in the on-shell signal region and at the  $Z$ -boson pair production threshold, above the  $q\bar{q} \rightarrow 4\ell$  background. The observed distribution is consistent with the expectation from SM processes. We observe 223 events in the off-shell signal region, while we expect  $217.6 \pm 9.5$  from SM processes, including the SM Higgs boson signal.

In order to enhance the sensitivity to the  $gg$  production in the off-shell region, a likelihood discriminant  $\mathcal{D}_{\text{gg}}$  is used, which characterizes the event topology in the  $4\ell$  center-of-mass frame using the observables  $(m_{Z_1}, m_{Z_2}, \vec{\Omega})$  for a given value of  $m_{4\ell}$ , where  $\vec{\Omega}$  denotes the five angles defined in Ref. [28]. The discriminant is built from the probabilities  $\mathcal{P}_{\text{tot}}^{\text{gg}}$  and  $\mathcal{P}_{\text{bkg}}^{\text{qq}}$  for an event to originate from either the  $gg \rightarrow 4\ell$  or the  $q\bar{q} \rightarrow 4\ell$  process. We use the matrix element likelihood approach (MELA) [2,29] for the probability computation using the mCFM matrix elements for both  $gg \rightarrow 4\ell$  and  $q\bar{q} \rightarrow 4\ell$  processes. The probability  $\mathcal{P}_{\text{tot}}^{\text{gg}}$  for the  $gg \rightarrow 4\ell$  process includes the signal ( $\mathcal{P}_{\text{sig}}^{\text{gg}}$ ), the background ( $\mathcal{P}_{\text{bkg}}^{\text{gg}}$ ), and their



**Fig. 3.** Distributions of (top) the four-lepton invariant mass after a selection requirement on the MELA likelihood discriminant  $\mathcal{D}_{\text{gg}} > 0.65$ , and (bottom) the  $\mathcal{D}_{\text{gg}}$  likelihood discriminant for  $m_{4\ell} > 330$  GeV in the  $4\ell$  channel. Points represent the data, filled histograms the expected contributions from the reducible ( $Z + X$ ) and  $q\bar{q}$  backgrounds, and from the gluon fusion ( $gg$ ) and vector boson fusion ( $VV$ ) SM processes (including the Higgs boson mediated contributions). The dashed line corresponds to the total expected yield for a Higgs boson width and a squared product of the couplings scaled by a factor 10 with respect to their SM values. In the top plot, the bin size varies from 20 to 85 GeV and the last bin includes all entries with masses above 800 GeV.

interference ( $\mathcal{P}_{\text{int}}^{\text{gg}}$ ), as introduced for the discriminant computation in Ref. [37]. The discriminant is defined as

$$\mathcal{D}_{\text{gg}} = \frac{\mathcal{P}_{\text{tot}}^{\text{gg}}}{\mathcal{P}_{\text{tot}}^{\text{gg}} + \mathcal{P}_{\text{bkg}}^{\text{qq}}} = \left[ 1 + \frac{\mathcal{P}_{\text{bkg}}^{\text{qq}}}{a \times \mathcal{P}_{\text{sig}}^{\text{gg}} + \sqrt{a} \times \mathcal{P}_{\text{int}}^{\text{gg}} + \mathcal{P}_{\text{bkg}}^{\text{gg}}} \right]^{-1}, \quad (4)$$

where the parameter  $a$  is the strength of the unknown anomalous  $gg$  contribution with respect to the expected SM contribution ( $a = 1$ ). We set  $a = 10$  in the definition of  $\mathcal{D}_{\text{gg}}$  according to the expected sensitivity. Studies show that the expected sensitivity does not change substantially when  $a$  is varied up or down by a factor of 2. It should be stressed that fixing the parameter  $a$  to a given value only affects the sensitivity of the analysis. To suppress the dominant  $q\bar{q} \rightarrow 4\ell$  background in the on-shell region, the analysis also employs a MELA likelihood discriminant  $\mathcal{D}_{\text{bkg}}^{\text{kin}}$  based on the JHUGEN and mCFM matrix element calculations for the signal and

**Table 1**

Expected and observed numbers of events in the  $4\ell$  and  $2\ell 2\nu$  channels in  $gg$ -enriched regions, defined by  $m_{4\ell} \geq 330$  GeV and  $\mathcal{D}_{gg} > 0.65$  ( $4\ell$ ), and by  $m_T > 350$  GeV and  $E_T^{\text{miss}} > 100$  GeV ( $2\ell 2\nu$ ). The numbers of expected events are given separately for the  $gg$  and VBF processes, and for a SM Higgs boson ( $\Gamma_H = \Gamma_H^{\text{SM}}$ ) and a Higgs boson width and squared product of the couplings scaled by a factor 10 with respect to their SM values. The unphysical expected contributions for the signal and background components are also reported separately, for the  $gg$  and VBF processes. For both processes, the sum of the signal and background components differs from the total due to the negative interferences. The quoted uncertainties include only the systematic sources.

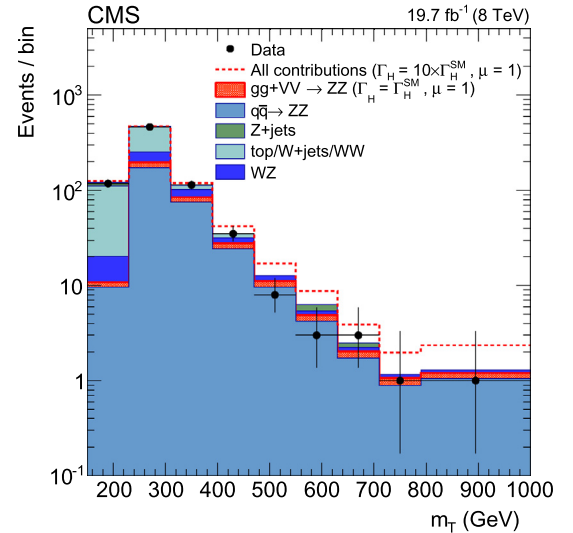
		$4\ell$	$2\ell 2\nu$
(a)	Total $gg$ ( $\Gamma_H = \Gamma_H^{\text{SM}}$ )	$1.8 \pm 0.3$	$9.6 \pm 1.5$
	gg Signal component ( $\Gamma_H = \Gamma_H^{\text{SM}}$ )	$1.3 \pm 0.2$	$4.7 \pm 0.6$
	gg Background component	$2.3 \pm 0.4$	$10.8 \pm 1.7$
(b)	Total $gg$ ( $\Gamma_H = 10 \times \Gamma_H^{\text{SM}}$ )	$9.9 \pm 1.2$	$39.8 \pm 5.2$
(c)	Total VBF ( $\Gamma_H = \Gamma_H^{\text{SM}}$ )	$0.23 \pm 0.01$	$0.90 \pm 0.05$
	VBF signal component ( $\Gamma_H = \Gamma_H^{\text{SM}}$ )	$0.11 \pm 0.01$	$0.32 \pm 0.02$
	VBF background component	$0.35 \pm 0.02$	$1.22 \pm 0.07$
(d)	Total VBF ( $\Gamma_H = 10 \times \Gamma_H^{\text{SM}}$ )	$0.77 \pm 0.04$	$2.40 \pm 0.14$
(e)	$q\bar{q}$ background	$9.3 \pm 0.7$	$47.6 \pm 4.0$
(f)	Other backgrounds	$0.05 \pm 0.02$	$35.1 \pm 4.2$
(a + c + e + f)	Total expected ( $\Gamma_H = \Gamma_H^{\text{SM}}$ )	$11.4 \pm 0.8$	$93.2 \pm 6.0$
(b + d + e + f)	Total expected ( $\Gamma_H = 10 \times \Gamma_H^{\text{SM}}$ )	$20.1 \pm 1.4$	$124.9 \pm 7.8$
	Observed	11	91

the background, as illustrated by the inset in Fig. 2 and used in Ref. [7].

As an illustration, Fig. 3(top) presents the  $4\ell$  invariant mass distribution for the off-shell signal region ( $m_{4\ell} > 220$  GeV) and for  $\mathcal{D}_{gg} > 0.65$ . The expected contributions from the  $q\bar{q} \rightarrow 4\ell$  and reducible backgrounds, as well as for the total gluon fusion ( $gg$ ) and vector boson fusion ( $VV$ ) contributions, including the Higgs boson signal, are shown. The distribution of the likelihood discriminant  $\mathcal{D}_{gg}$  for  $m_{4\ell} > 330$  GeV is shown in Fig. 3(bottom), together with the expected contributions from the SM. The expected  $m_{4\ell}$  and  $\mathcal{D}_{gg}$  distributions for the sum of all the processes, with a Higgs boson width  $\Gamma_H = 10 \times \Gamma_H^{\text{SM}}$  and a relative cross section with respect to the SM cross section equal to unity in both gluon fusion and VBF production modes ( $\mu = \mu_{ggH} = \mu_{VBF} = 1$ ), are also presented, showing the enhancement arising from the scaling of the squared product of the couplings. The expected and observed event yields in the off-shell  $gg$ -enriched region defined by  $m_{4\ell} \geq 330$  GeV and  $\mathcal{D}_{gg} > 0.65$  are reported in Table 1.

The  $2\ell 2\nu$  analysis is performed on the 8 TeV data set only. The final state in the  $2\ell 2\nu$  channel is characterized by two oppositely-charged leptons of the same flavor compatible with a Z boson, together with a large  $E_T^{\text{miss}}$  from the undetectable neutrinos. We require  $E_T^{\text{miss}} > 80$  GeV. The event selection and background estimation is performed as described in Ref. [16], with the exception that the jet categories defined in Ref. [16] are here grouped into a single category, i.e. the analysis is performed in an inclusive way. The  $m_T$  distribution in the off-shell signal region ( $m_T > 180$  GeV) is shown in Fig. 4. The expected and observed event yields in a  $gg$ -enriched region defined by  $m_T > 350$  GeV and  $E_T^{\text{miss}} > 100$  GeV are reported in Table 1.

Systematic uncertainties comprise experimental uncertainties on the signal efficiency and background yield evaluation, as well as uncertainties on the signal and background from theoretical predictions. Since the measurement is performed in wide  $m_{ZZ}$  regions, there are sources of systematic uncertainties that only affect the total normalization and others that affect both the normalization and the shape of the observables used in this analysis. In the  $4\ell$  final state, only the latter type of systematic uncertainty affects the measurement of  $\Gamma_H$ , since normalization uncertainties change the on-shell and off-shell yields by the same amount.



**Fig. 4.** Distribution of the transverse mass in the  $2\ell 2\nu$  channel. Points represent the data, filled histograms the expected contributions from the backgrounds, and from the gluon fusion ( $gg$ ) and vector boson fusion ( $VV$ ) SM processes (including the Higgs-mediated contributions). The dashed line corresponds to the total expected yield for a Higgs boson width and a squared product of the couplings scaled by a factor 10 with respect to their SM values. The bin size varies from 80 to 210 GeV and the last bin includes all entries with transverse masses above 1 TeV.

Among the signal uncertainties, experimental systematic uncertainties are evaluated from observed events for the trigger efficiency (1.5%), and combined object reconstruction, identification and isolation efficiencies (3–4% for muons, 5–11% for electrons) [7]. In the  $2\ell 2\nu$  final state, the effects of the lepton momentum scale (1–2%) and jet energy scale (1%) are taken into account and propagated to the evaluation of  $E_T^{\text{miss}}$ . The uncertainty in the b-jet veto (1–3%) is estimated from simulation using correction factors for the b-tagging and b-misidentification efficiencies as measured from the dijet and  $t\bar{t}$  decay control samples [38].

Theoretical uncertainties from QCD scales in the  $q\bar{q}$  background contribution are within 4–10% depending on  $m_{ZZ}$  [7]. An additional uncertainty of 2–6% is included to account for missing higher order contributions with respect to a full NLO QCD and NLO EW evaluation. The systematic uncertainty in the normal-



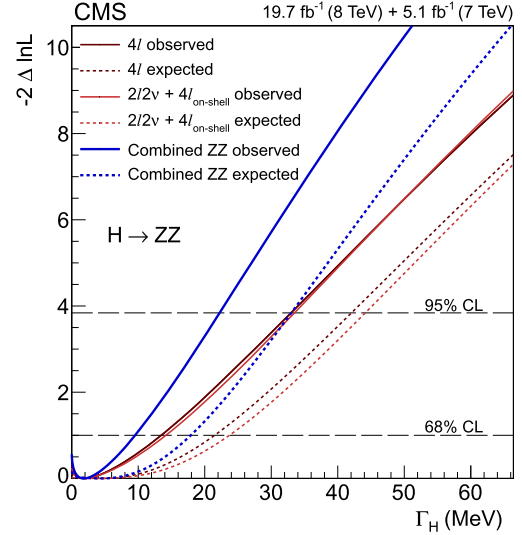
ization of the reducible backgrounds is evaluated following the methods described in Refs. [7,16]. In the  $2\ell 2\nu$  channel, for which these contributions are not negligible at high mass, the estimation from control samples for the  $Z$  + jets and for the sum of the  $t\bar{t}$ ,  $tW$  and  $WW$  contributions leads to uncertainties of 25% and 15% in the respective background yields. Theoretical uncertainties in the high mass contribution from the gluon-induced processes, which affect both the normalization and the shape, are especially important in this analysis (in particular for the signal and interference contributions that are scaled by large factors). However, these uncertainties partially cancel when measuring simultaneously the yield from the same process in the on-shell signal region. The remaining  $m_{ZZ}$ -dependent uncertainties in the QCD renormalization and factorization scales are derived using the  $K$  factor variations from Ref. [14], corresponding to a factor of two up or down from the nominal  $m_{ZZ}/2$  values, and amount to 2–4%. For the  $gg \rightarrow ZZ$  continuum background production, we assign a 10% additional uncertainty on the  $K$  factor, following Ref. [22] and taking into account the different mass ranges and selections on the specific final state. This uncertainty also affects the interference with the signal. The PDF uncertainties are estimated following Refs. [39,40] by changing the NLO PDF set from MSTW2008 to CT10 [41] and NNPDF2.1 [42], and the residual contribution is about 1%. For the VBF processes, no significant  $m_{ZZ}$ -dependence is found regarding the QCD scales and PDF uncertainties, which are in general much smaller than for the gluon fusion processes [8,9]. In the  $2\ell 2\nu$  final state, additional uncertainties on the yield arising from the theoretical description of the parton shower and underlying event are taken into account (6%).

We perform a simultaneous unbinned maximum likelihood fit of a signal-plus-background model to the measured distributions in the  $4\ell$  and  $2\ell 2\nu$  channels. In the  $4\ell$  channel the analysis is performed in the on-shell and off-shell signal regions defined above. In the on-shell region, a three-dimensional distribution  $\vec{x} = (m_{4\ell}, \mathcal{D}_{\text{bkg}}^{\text{kin}}, p_T^{4\ell}$  or  $\mathcal{D}_{\text{jet}})$  is analyzed, following the methodology described in Ref. [7], where the quantity  $\mathcal{D}_{\text{jet}}$  is a discriminant used to separate VBF from gluon fusion production. In the off-shell region, a two-dimensional distribution  $\vec{x} = (m_{4\ell}, \mathcal{D}_{\text{gg}})$  is analyzed. In the  $2\ell 2\nu$  channel, only the off-shell Higgs boson production is analyzed, using the  $\vec{x} = m_T$  distribution.

The probability distribution functions are built using the full detector simulation or data control regions, and are defined for the signal, the background, or the interference between the two contributions,  $\mathcal{P}_{\text{sig}}$ ,  $\mathcal{P}_{\text{bkg}}$ , or  $\mathcal{P}_{\text{int}}$ , respectively, as a function of the observables  $\vec{x}$  discussed above. Several production mechanisms are considered for the signal and the background, such as gluon fusion ( $gg$ ), VBF, and quark-antiquark annihilation ( $q\bar{q}$ ). The total probability distribution function for the off-shell region includes the interference of two contributions in each production process:

$$\begin{aligned} \mathcal{P}_{\text{tot}}^{\text{off-shell}}(\vec{x}) = & \left[ \mu_{\text{ggH}} \times (\Gamma_{\text{H}}/\Gamma_0) \times \mathcal{P}_{\text{sig}}^{\text{gg}}(\vec{x}) \right. \\ & + \sqrt{\mu_{\text{ggH}} \times (\Gamma_{\text{H}}/\Gamma_0)} \times \mathcal{P}_{\text{int}}^{\text{gg}}(\vec{x}) + \mathcal{P}_{\text{bkg}}^{\text{gg}}(\vec{x}) \\ & + \left[ \mu_{\text{VBF}} \times (\Gamma_{\text{H}}/\Gamma_0) \times \mathcal{P}_{\text{sig}}^{\text{VBF}}(\vec{x}) \right. \\ & + \sqrt{\mu_{\text{VBF}} \times (\Gamma_{\text{H}}/\Gamma_0)} \times \mathcal{P}_{\text{int}}^{\text{VBF}}(\vec{x}) + \mathcal{P}_{\text{bkg}}^{\text{VBF}}(\vec{x}) \\ & \left. + \mathcal{P}_{\text{bkg}}^{\text{q}\bar{\text{q}}}(\vec{x}) + \dots \right] \end{aligned} \quad (5)$$

The list of background processes is extended beyond those quoted depending on the final state ( $Z$  + X, top,  $W$  + jets,  $WW$ ,  $WZ$ ). The parameters  $\mu_{\text{ggH}}$  and  $\mu_{\text{VBF}}$  are the scale factors which modify the signal strength with respect to the reference parameterization in each production mechanism independently. The parameter  $(\Gamma_{\text{H}}/\Gamma_0)$  is the scale factor which modifies the observed width



**Fig. 5.** Scan of the negative log-likelihood,  $-2\Delta \ln \mathcal{L}$ , as a function of  $\Gamma_{\text{H}}$  for the combined fit of the  $4\ell$  and  $2\ell 2\nu$  channels (blue thick lines), for the  $4\ell$  channel alone in the off-shell and on-shell regions (dark red lines), and for the  $2\ell 2\nu$  channel in the off-shell region and  $4\ell$  channel in the on-shell region (light red lines). The solid lines represent the observed values, the dotted lines the expected values. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

with respect to the  $\Gamma_0$  value used in the reference parameterization.

In the on-shell region, the parameterization includes the small contribution of the  $t\bar{t}H$  and  $VH$  Higgs boson production mechanisms, which are related to the gluon fusion and VBF processes, respectively, because either the quark or the vector boson coupling to the Higgs boson is in common among those processes. Interference effects are negligible in the on-shell region. The total probability distribution function for the on-shell region is written as

$$\begin{aligned} \mathcal{P}_{\text{tot}}^{\text{on-shell}}(\vec{x}) = & \mu_{\text{ggH}} \times \left[ \mathcal{P}_{\text{sig}}^{\text{gg}}(\vec{x}) + \mathcal{P}_{\text{sig}}^{\text{t}\bar{\text{t}}\text{H}}(\vec{x}) \right] \\ & + \mu_{\text{VBF}} \left[ \mathcal{P}_{\text{sig}}^{\text{VBF}}(\vec{x}) + \mathcal{P}_{\text{sig}}^{\text{VH}}(\vec{x}) \right] \\ & + \mathcal{P}_{\text{bkg}}^{\text{q}\bar{\text{q}}}(\vec{x}) + \mathcal{P}_{\text{bkg}}^{\text{gg}}(\vec{x}) + \dots \end{aligned} \quad (6)$$

The above parameterizations in Eqs. (5, 6) are performed for the tree-level HVV interaction of a scalar Higgs boson, consistent with our observations [4,7]. We find that the presence of anomalous couplings in the HVV interaction would lead to enhanced off-shell production and a more stringent constraint on the width. It is evident that the parameterization in Eq. (5) relies on the modeling of the gluon fusion production with the dominant top-quark loop, therefore no possible new particles are considered in the loop. Further discussion can also be found in Refs. [43–45].

The three parameters  $\Gamma_{\text{H}}$ ,  $\mu_{\text{ggH}}$ , and  $\mu_{\text{VBF}}$  are left unconstrained in the fit. The  $\mu_{\text{ggH}}$  and  $\mu_{\text{VBF}}$  fitted values are found to be almost identical to those obtained in Ref. [7]. Systematic uncertainties are included as nuisance parameters and are treated according to the frequentist paradigm [46]. The shapes and normalizations of the signal and of each background component are allowed to vary within their uncertainties, and the correlations in the sources of systematic uncertainty are taken into account.

The fit results are shown in Fig. 5 as scans of the negative log-likelihood,  $-2\Delta \ln \mathcal{L}$ , as a function of  $\Gamma_{\text{H}}$ . Combining the two channels a limit is observed (expected) on the total width of  $\Gamma_{\text{H}} < 22$  MeV (33 MeV) at a 95% CL, which is 5.4 (8.0) times the expected value in the SM. The best fit value and 68% CL interval correspond to  $\Gamma_{\text{H}} = 1.8_{-1.8}^{+7.7}$  MeV. The result of the  $4\ell$  analysis

alone is an observed (expected) limit of  $\Gamma_H < 33$  MeV (42 MeV) at a 95% CL, which is 8.0 (10.1) times the SM value, and the result of the analysis combining the  $4\ell$  on-shell and  $2\ell 2\nu$  off-shell regions is  $\Gamma_H < 33$  MeV (44 MeV) at a 95% CL, which is 8.1 (10.6) times the SM value. The best fit values and 68% CL intervals are  $\Gamma_H = 1.9_{-1.9}^{+11.7}$  MeV and  $\Gamma_H = 1.8_{-1.8}^{+12.4}$  MeV for the  $4\ell$  analysis and for the analysis combining the  $4\ell$  on-shell and  $2\ell 2\nu$  off-shell regions, respectively.

The expected limit for the two channels combined without including the systematic uncertainties is  $\Gamma_H < 28$  MeV at a 95% CL. The effect of systematic uncertainties is driven by the  $2\ell 2\nu$  channel with larger experimental uncertainties in signal efficiencies and background estimation from control samples in data, while the result in the  $4\ell$  channel is largely dominated by the statistical uncertainty.

The statistical compatibility of the observed results with the expectation under the SM hypothesis corresponds to a p-value of 0.24. The statistical coverage of the results obtained in the likelihood scan has also been tested with the Feldman–Cousins approach [47] for the combined analysis leading to consistent although slightly tighter constraints. The analysis in the  $4\ell$  channel has also been performed in a one-dimensional fit using either  $m_{4\ell}$  or  $\mathcal{D}_{gg}$  and consistent results are found. The expected limit without using the MELA likelihood discriminant  $\mathcal{D}_{gg}$  is 40% larger in the  $4\ell$  channel.

In summary, we have presented constraints on the total Higgs boson width using its relative on-shell and off-shell production and decay rates to four leptons or two leptons and two neutrinos. The analysis is based on the 2011 and 2012 data sets corresponding to integrated luminosities of  $5.1 \text{ fb}^{-1}$  at  $\sqrt{s} = 7$  TeV and  $19.7 \text{ fb}^{-1}$  at  $\sqrt{s} = 8$  TeV. The four-lepton analysis uses the measured invariant mass distribution near the peak and above the Z-boson pair production threshold, as well as a likelihood discriminant to separate the gluon fusion ZZ production from the  $q\bar{q} \rightarrow ZZ$  background, while the two-lepton plus two-neutrino off-shell analysis relies on the transverse mass distribution. The presented analysis determines the independent contributions of the gluon fusion and VBF production mechanisms from the data in the on-shell region. It relies nevertheless on the knowledge of the coupling ratios between the off-shell and on-shell production, i.e. the dominance of the top quark loop in the gluon fusion production mechanism and the absence of new particle contribution in the loop. The presence of anomalous couplings in the HVV interaction would lead to enhanced off-shell production and would make our constraint tighter. The combined fit of the  $4\ell$  and  $2\ell 2\nu$  channels leads to an upper limit on the Higgs boson width of  $\Gamma_H < 22$  MeV at a 95% confidence level, which is 5.4 times the expected width of the SM Higgs boson. This result improves by more than two orders of magnitude upon previous experimental constraints on the new boson decay width from the direct measurement at the resonance peak.

## Acknowledgements

We wish to thank our theoretician colleagues and in particular Fabrizio Caola for providing the theoretical uncertainty in the  $gg \rightarrow ZZ$  background K factor, Tobias Kasprzik for providing the numerical calculations on the EW corrections for the  $q\bar{q} \rightarrow ZZ$  background process, Giampiero Passarino for his calculations of the  $m_{ZZ}$ -dependent K factor and its variations with renormalization and factorization scales, and Marco Zaro for checking the independence on  $m_{ZZ}$  of higher-order corrections in VBF processes. We also gratefully acknowledge Alessandro Ballestrero, John Campbell, Keith Ellis, Stefano Forte, Nikolas Kauer, Kirill Melnikov, and Ciaran Williams for their help in optimizing the Monte Carlo generators for this analysis.

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: BMWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); MoER, SF0690030s09 and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS and RFBR (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); ThEPCenter, IPST, STAR and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

## References

- [1] ATLAS Collaboration, Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC, Phys. Lett. B 716 (2012) 1, <http://dx.doi.org/10.1016/j.physletb.2012.08.020>, arXiv:1207.7214.
- [2] CMS Collaboration, Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, Phys. Lett. B 716 (2012) 30, <http://dx.doi.org/10.1016/j.physletb.2012.08.021>, arXiv:1207.7235.
- [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, [http://dx.doi.org/10.1007/JHEP06\(2013\)081](http://dx.doi.org/10.1007/JHEP06(2013)081), arXiv:1303.4571.
- [4] CMS Collaboration, Study of the mass and spin-parity of the Higgs boson candidate via its decays to Z boson pairs, Phys. Rev. Lett. 110 (2013) 081803, <http://dx.doi.org/10.1103/PhysRevLett.110.081803>, arXiv:1212.6639.
- [5] ATLAS Collaboration, Measurements of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC, Phys. Lett. B 726 (2013) 88, <http://dx.doi.org/10.1016/j.physletb.2013.08.010>, arXiv:1307.1427.
- [6] ATLAS Collaboration, Evidence for the spin-0 nature of the Higgs boson using ATLAS data, Phys. Lett. B 726 (2013) 120, <http://dx.doi.org/10.1016/j.physletb.2013.08.026>, arXiv:1307.1432.
- [7] CMS Collaboration, Measurement of the properties of a Higgs boson in the four-lepton final state, Phys. Rev. D 89 (2014) 092007, <http://dx.doi.org/10.1103/PhysRevD.89.092007>, arXiv:1312.5353.
- [8] LHC Higgs Cross Section Working Group, Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables, CERN Report CERN-2011-002, 2013, <http://dx.doi.org/10.5170/CERN-2011-002>, arXiv:1101.0593.
- [9] LHC Higgs Cross Section Working Group, Handbook of LHC Higgs Cross Sections: 3. Higgs Properties, CERN Report CERN-2013-004, 2013, <http://dx.doi.org/10.5170/CERN-2013-004>, arXiv:1307.1347.
- [10] F. Caola, K. Melnikov, Constraining the Higgs boson width with ZZ production at the LHC, Phys. Rev. D 88 (2013) 054024, <http://dx.doi.org/10.1103/PhysRevD.88.054024>, arXiv:1307.4935.
- [11] N. Kauer, G. Passarino, Inadequacy of zero-width approximation for a light Higgs boson signal, JHEP 08 (2012) 116, [http://dx.doi.org/10.1007/JHEP08\(2012\)116](http://dx.doi.org/10.1007/JHEP08(2012)116), arXiv:1206.4803.
- [12] N. Kauer, Inadequacy of zero-width approximation for a light Higgs boson signal, Mod. Phys. Lett. A 28 (2013) 1330015, <http://dx.doi.org/10.1142/S021773213300152>, arXiv:1305.2092.
- [13] J.M. Campbell, R.K. Ellis, C. Williams, Bounding the Higgs width at the LHC using full analytic results for  $gg \rightarrow e^+e^- \mu^+ \mu^-$ , arXiv:1311.3589, 2013.
- [14] G. Passarino, Higgs CAT, Eur. Phys. J. C 74 (2014) 2866, <http://dx.doi.org/10.1140/epjc/s10052-014-2866-7>, arXiv:1312.2397.
- [15] G. Passarino, Higgs interference effects in  $gg \rightarrow ZZ$  and their uncertainty, JHEP 08 (2012) 146, [http://dx.doi.org/10.1007/JHEP08\(2012\)146](http://dx.doi.org/10.1007/JHEP08(2012)146), arXiv:1206.3824.
- [16] CMS Collaboration, Search for a standard-model-like Higgs boson with a mass in the range 145 to 1000 GeV at the LHC, Eur. Phys. J. C 73 (2013) 2469, <http://dx.doi.org/10.1140/epjc/s10052-013-2469-8>, arXiv:1304.0213.

- [17] CMS Collaboration, Search for the standard model Higgs boson in the  $H \rightarrow ZZ \rightarrow 2\ell 2\nu$  channel in pp collisions at  $\sqrt{s} = 7$  TeV, JHEP 03 (2012) 040, [http://dx.doi.org/10.1007/JHEP03\(2012\)040](http://dx.doi.org/10.1007/JHEP03(2012)040).
- [18] S. Chatrchyan, et al., CMS, The CMS experiment at the CERN LHC, J. Instrum. 3 (2008) S08004, <http://dx.doi.org/10.1088/1748-0221/3/08/S08004>.
- [19] N. Kauer, Interference effects for  $H \rightarrow WW/ZZ \rightarrow \ell\bar{\nu}_\ell\ell\nu_\ell$  searches in gluon fusion at the LHC, JHEP 12 (2013) 082, [http://dx.doi.org/10.1007/JHEP12\(2013\)082](http://dx.doi.org/10.1007/JHEP12(2013)082), arXiv:1310.7011.
- [20] J.M. Campbell, R.K. Ellis, MCFM for the Tevatron and the LHC, Nucl. Phys. Proc. Suppl. 205 (2010) 10, <http://dx.doi.org/10.1016/j.nuclphysbps.2010.08.011>, arXiv:1007.3492.
- [21] A.D. Martin, W.J. Stirling, R.S. Thorne, G. Watt, Parton distributions for the LHC, Eur. Phys. J. C 63 (2009) 189, <http://dx.doi.org/10.1140/epjc/s10052-009-1072-5>, arXiv:0901.0002.
- [22] M. Bonvini, F. Caola, S. Forte, K. Melnikov, G. Ridolfi, Signal-background interference effects in  $gg \rightarrow H \rightarrow WW$  beyond leading order, Phys. Rev. D 88 (2013) 034032, <http://dx.doi.org/10.1103/PhysRevD.88.034032>, arXiv:1304.3053.
- [23] A. Ballestrero, A. Belhouari, G. Bevilacqua, V. Kashkan, E. Maina, PHANTOM: a Monte Carlo event generator for six parton final states at high energy colliders, Comput. Phys. Commun. 180 (2009) 401, <http://dx.doi.org/10.1016/j.cpc.2008.10.005>, arXiv:0801.3359.
- [24] S. Frixione, P. Nason, C. Oleari, Matching NLO QCD computations with parton shower simulations: the POWHEG method, JHEP 11 (2007) 070, <http://dx.doi.org/10.1088/1126-6708/2007/11/070>, arXiv:0709.2092.
- [25] S. Alioli, P. Nason, C. Oleari, E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX, JHEP 06 (2010) 043, [http://dx.doi.org/10.1007/JHEP06\(2010\)043](http://dx.doi.org/10.1007/JHEP06(2010)043), arXiv:1002.2581.
- [26] E. Bagnaschi, G. Degrossi, P. Slavich, A. Vicini, Higgs production via gluon fusion in the POWHEG approach in the SM and in the MSSM, JHEP 02 (2012) 088, [http://dx.doi.org/10.1007/JHEP02\(2012\)088](http://dx.doi.org/10.1007/JHEP02(2012)088), arXiv:1111.2854.
- [27] P. Nason, C. Oleari, NLO Higgs boson production via vector-boson fusion matched with shower in POWHEG, JHEP 02 (2010) 037, [http://dx.doi.org/10.1007/JHEP02\(2010\)037](http://dx.doi.org/10.1007/JHEP02(2010)037), arXiv:0911.5299.
- [28] Y. Gao, A.V. Gritsan, Z. Guo, K. Melnikov, M. Schulze, N.V. Tran, Spin determination of single-produced resonances at hadron colliders, Phys. Rev. D 81 (2010) 075022, <http://dx.doi.org/10.1103/PhysRevD.81.075022>, arXiv:1001.3396.
- [29] S. Bolognesi, Y. Gao, A.V. Gritsan, K. Melnikov, M. Schulze, N.V. Tran, A. Whitbeck, On the spin and parity of a single-produced resonance at the LHC, Phys. Rev. D 86 (2012) 095031, <http://dx.doi.org/10.1103/PhysRevD.86.095031>, arXiv:1208.4018.
- [30] T. Sjöstrand, S. Mrenna, P. Skands, PYTHIA 6.4 physics and manual, JHEP 05 (2006) 026, <http://dx.doi.org/10.1088/1126-6708/2006/05/026>, arXiv:hep-ph/0603175.
- [31] T. Melia, P. Nason, R. Rontsch, G. Zanderighi,  $W^+W^-$ , WZ and ZZ production in the POWHEG BOX, JHEP 11 (2011) 078, [http://dx.doi.org/10.1007/JHEP11\(2011\)078](http://dx.doi.org/10.1007/JHEP11(2011)078), arXiv:1107.5051.
- [32] A. Bierweiler, T. Kasprzik, J.H. Kühn, Vector-boson pair production at the LHC to  $\mathcal{O}(\alpha^3)$  accuracy, JHEP 12 (2013) 071, [http://dx.doi.org/10.1007/JHEP12\(2013\)071](http://dx.doi.org/10.1007/JHEP12(2013)071), arXiv:1305.5402.
- [33] J. Baglio, L.D. Ninh, M.M. Weber, Massive gauge boson pair production at LHC: a next-to-leading order story, Phys. Rev. D 88 (2013) 113005, <http://dx.doi.org/10.1103/PhysRevD.88.113005>, arXiv:1307.4331.
- [34] D. De Florian, G. Ferrera, M. Grazzini, D. Tommasini, Higgs boson production at the LHC: transverse momentum resummation effects in the  $H \rightarrow \gamma\gamma$ ,  $H \rightarrow WW \rightarrow \ell\nu\ell\nu$  and  $H \rightarrow ZZ \rightarrow 4\ell$  decay modes, JHEP 06 (2012) 132, [http://dx.doi.org/10.1007/JHEP06\(2012\)132](http://dx.doi.org/10.1007/JHEP06(2012)132), arXiv:1203.6321v1.
- [35] S. Agostinelli, et al., GEANT4, GEANT4—a simulation toolkit, Nucl. Instrum. Methods, Sect. A 506 (2003) 250, [http://dx.doi.org/10.1016/S0168-9002\(03\)01368-8](http://dx.doi.org/10.1016/S0168-9002(03)01368-8).
- [36] J. Allison, et al., GEANT4 developments and applications, IEEE Trans. Nucl. Sci. 53 (2006) 270, <http://dx.doi.org/10.1109/TNS.2006.869826>.
- [37] I. Anderson, S. Bolognesi, F. Caola, Y. Gao, A.V. Gritsan, C.B. Martin, K. Melnikov, M. Schulze, N.V. Tran, A. Whitbeck, Y. Zhou, Constraining anomalous HVV interactions at proton and lepton colliders, Phys. Rev. D 89 (2014) 035007, <http://dx.doi.org/10.1103/PhysRevD.89.035007>, arXiv:1309.4819.
- [38] CMS Collaboration, Identification of b-quark jets with the CMS experiment, J. Instrum. 8 (2013) P04013, <http://dx.doi.org/10.1088/1748-0221/8/04/P04013>, arXiv:1211.4462.
- [39] M. Botje, et al., The PDF4LHC working group interim recommendations, arXiv:1101.0538, 2011.
- [40] S. Alekhin, et al., The PDF4LHC working group interim report, arXiv:1101.0536, 2011.
- [41] H.-L. Lai, M. Guzzi, J. Huston, Z. Li, P.M. Nadolsky, J. Pumplin, C.-P. Yuan, New parton distributions for collider physics, Phys. Rev. D 82 (2010) 074024, <http://dx.doi.org/10.1103/PhysRevD.82.074024>, arXiv:1007.2241.
- [42] R.D. Ball, V. Bertone, F. Cerutti, L.D. Debbio, S. Forte, A. Guffanti, J.I. Latorre, J. Rojo, M. Ubiali, NNPDF Collaboration, Impact of heavy quark masses on parton distributions and LHC Phenomenology, Nucl. Phys. B 849 (2011) 296, <http://dx.doi.org/10.1016/j.nuclphysb.2011.03.021>, arXiv:1101.1300.
- [43] J.S. Gainer, J. Lykken, K.T. Matchev, S. Mrenna, M. Park, Beyond geolocating: constraining higher dimensional operators in  $H \rightarrow 4\ell$  with off-shell production and more, arXiv:1403.4951, 2014.
- [44] C. Englert, M. Spannowsky, Limitations and opportunities of off-shell coupling measurements, arXiv:1405.0285, 2014.
- [45] M. Ghezzi, G. Passarino, S. Uccirati, Bounding the Higgs width using effective field theory, arXiv:1405.1925, 2014.
- [46] ATLAS, CMS Collaborations, LHC Higgs Combination Group, Procedure for the LHC Higgs boson search combination in Summer 2011, Technical Report ATL-PHYS-PUB 2011-11, CMS NOTE 2011/005, 2011, <http://cdsweb.cern.ch/record/1379837>.
- [47] G.J. Feldman, R.D. Cousins, A unified approach to the classical statistical analysis of small signals, Phys. Rev. D 57 (1998) 3873, <http://dx.doi.org/10.1103/PhysRevD.57.3873>, arXiv:physics/9711021.

## CMS Collaboration

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

*Yerevan Physics Institute, Yerevan, Armenia*

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>

*Institut für Hochenergiephysik der OeAW, Wien, Austria*

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

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

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

*Universiteit Antwerpen, Antwerpen, 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. Villella

*Vrije Universiteit Brussel, Brussel, 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

*Université Libre de Bruxelles, Bruxelles, 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

*Ghent University, Ghent, 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 Catholique de Louvain, Louvain-la-Neuve, Belgium*

N. Beliy, T. Caebegs, E. Daubie, G.H. Hammad

*Université de Mons, Mons, Belgium*

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

*Centro Brasileiro de Pesquisas Físicas, 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 do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*

C.A. Bernardes<sup>b</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>

<sup>a</sup> *Universidade Estadual Paulista, São Paulo, Brazil*

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

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

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

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

*University of Sofia, Sofia, Bulgaria*

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

*Institute of High Energy Physics, 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

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

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

*Universidad de Los Andes, Bogota, Colombia*

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

*Technical University of Split, Split, Croatia*



Z. Antunovic, M. Kovac

*University of Split, Split, Croatia*

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

*Institute Rudjer Boskovic, Zagreb, Croatia*

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

*University of Cyprus, Nicosia, Cyprus*

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

*Charles University, Prague, Czech Republic*

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

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

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

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

P. Eerola, G. Fedi, M. Voutilainen

*Department of Physics, University of Helsinki, 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

*Helsinki Institute of Physics, Helsinki, Finland*

T. Tuuva

*Lappeenranta University of Technology, Lappeenranta, Finland*

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

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

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

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

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

S. Gadrat

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

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

Z. Tsamalaidze<sup>8</sup>

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

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, I. Physikalisches Institut, 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. Teysier, S. Thüer, M. Weber

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

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

*RWTH Aachen University, III. Physikalisches Institut B, Aachen, 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, G. Hellwig, 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, 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

*Deutsches Elektronen-Synchrotron, 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, T. Pöhlsen, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Seidel, J. Sibille<sup>16</sup>, V. Sola, H. Stadie, G. Steinbrück, D. Troendle, E. Usai, L. Vanelderren

*University of Hamburg, Hamburg, 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

*Institut für Experimentelle Kernphysik, Karlsruhe, Germany*

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

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

A. Panagiotou, N. Saoulidou, E. Stiliaris

*University of Athens, Athens, Greece*

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

*University of Ioánnina, Ioánnina, Greece*

G. Bencze, C. Hajdu, P. Hidas, D. Horvath<sup>17</sup>, F. Sikler, V. Veszpremi, G. Vesztergombi<sup>18</sup>, A.J. Zsigmond

*Wigner Research Centre for Physics, Budapest, Hungary*

N. Beni, S. Czellar, J. Karancsi<sup>19</sup>, J. Molnar, J. Palinkas, Z. Szillasi

*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*

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

*University of Debrecen, Debrecen, Hungary*

S.K. Swain

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

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

*Panjab University, Chandigarh, India*

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

*University of Delhi, Delhi, 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

*Saha Institute of Nuclear Physics, Kolkata, India*

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

*Bhabha Atomic Research Centre, Mumbai, India*

T. Aziz, S. Bhowmik<sup>20</sup>, R.M. Chatterjee, S. Ganguly, S. Ghosh, M. Guchait<sup>21</sup>, A. Gurtu<sup>22</sup>, G. Kole, S. Kumar, M. Maity<sup>20</sup>, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage<sup>23</sup>

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

S. Banerjee, R.K. Dewanjee, S. Dugad

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

H. Bakhshiansohi, H. Behnamian, S.M. Etesami<sup>24</sup>, A. Fahim<sup>25</sup>, R. Goldouzian, A. Jafari, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, B. Safarzadeh<sup>26</sup>, M. Zeinali

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

M. Felcini, M. Grunewald

*University College Dublin, Dublin, Ireland*

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>

<sup>a</sup> INFN Sezione di Bari, Bari, Italy

<sup>b</sup> Università di Bari, Bari, Italy

<sup>c</sup> Politecnico di Bari, Bari, 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>

<sup>a</sup> INFN Sezione di Bologna, Bologna, Italy

<sup>b</sup> Università di Bologna, Bologna, 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>

<sup>a</sup> INFN Sezione di Catania, Catania, Italy

<sup>b</sup> Università di Catania, Catania, Italy

<sup>c</sup> CSFNSM, Catania, 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. Gonzi <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>

<sup>a</sup> INFN Sezione di Firenze, Firenze, Italy

<sup>b</sup> Università di Firenze, Firenze, Italy

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

INFN Laboratori Nazionali di Frascati, Frascati, Italy

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

<sup>a</sup> INFN Sezione di Genova, Genova, Italy

<sup>b</sup> Università di Genova, Genova, Italy

M.E. Dinardo <sup>a,b</sup>, S. Fiorendi <sup>a,b,2</sup>, S. Gennai <sup>a,2</sup>, R. Gerosa <sup>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, 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>

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

<sup>b</sup> Università di Milano-Bicocca, Milano, 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>

<sup>a</sup> INFN Sezione di Napoli, Napoli, Italy

<sup>b</sup> Università di Napoli 'Federico II', Napoli, Italy

<sup>c</sup> Università della Basilicata (Potenza), Napoli, Italy

<sup>d</sup> Università G. Marconi (Roma), Napoli, 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>, U. Dosselli <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>, 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>

<sup>a</sup> INFN Sezione di Padova, Padova, Italy

<sup>b</sup> Università di Padova, Padova, Italy

<sup>c</sup> Università di Trento (Trento), Padova, 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>

<sup>a</sup> INFN Sezione di Pavia, Pavia, Italy

<sup>b</sup> Università di Pavia, Pavia, 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>

<sup>a</sup> INFN Sezione di Perugia, Perugia, Italy

<sup>b</sup> Università di Perugia, Perugia, Italy

K. Androsov <sup>a,27</sup>, P. Azzurri <sup>a</sup>, G. Bagliesi <sup>a</sup>, J. Bernardini <sup>a</sup>, T. Boccali <sup>a</sup>, G. Broccolo <sup>a,c</sup>, R. Castaldi <sup>a</sup>, M.A. Ciocci <sup>a,27</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,27</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,28</sup>, F. Palla<sup>a,2</sup>, A. Rizzi<sup>a,b</sup>, A. Savoy-Navarro<sup>a,29</sup>, A.T. Serban<sup>a</sup>, P. Spagnolo<sup>a</sup>, P. Squillacioti<sup>a,27</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>

<sup>a</sup> INFN Sezione di Pisa, Pisa, Italy

<sup>b</sup> Università di Pisa, Pisa, Italy

<sup>c</sup> Scuola Normale Superiore di Pisa, Pisa, 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>

<sup>a</sup> INFN Sezione di Roma, Roma, Italy

<sup>b</sup> Università di Roma, Roma, 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>

<sup>a</sup> INFN Sezione di Torino, Torino, Italy

<sup>b</sup> Università di Torino, Torino, Italy

<sup>c</sup> Università del Piemonte Orientale (Novara), Torino, 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>

<sup>a</sup> INFN Sezione di Trieste, Trieste, Italy

<sup>b</sup> Università di Trieste, Trieste, Italy

T.J. Kim

Chonbuk National University, Chonju, Korea

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

Kangwon National University, Chunchon, 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

Kyungpook National University, Daegu, Korea

J.Y. Kim, S. Song

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

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

Korea University, Seoul, Korea

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

University of Seoul, Seoul, Korea

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

Sungkyunkwan University, Suwon, Korea

A. Juodagalvis

Vilnius University, Vilnius, Lithuania

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

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

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz<sup>30</sup>, R. Lopez-Fernandez, A. Sanchez-Hernandez

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

S. Carrillo Moreno, F. Vazquez Valencia

*Universidad Iberoamericana, Mexico City, Mexico*

I. Pedraza, H.A. Salazar Ibarguen

*Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*

E. Casimiro Linares, A. Morelos Pineda

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

D. Krofcheck

*University of Auckland, Auckland, New Zealand*

P.H. Butler, S. Reucroft

*University of Canterbury, Christchurch, New Zealand*

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

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

H. Bialkowska, M. Bluj<sup>31</sup>, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, P. Zalewski

*National Centre for Nuclear Research, Swierk, Poland*

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

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

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

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

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, V. Konoplyanikov, A. Lanev, A. Malakhov, V. Matveev<sup>32</sup>, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, N. Skatchkov, V. Smirnov, A. Zarubin

*Joint Institute for Nuclear Research, Dubna, Russia*

V. Golovtsov, Y. Ivanov, V. Kim<sup>33</sup>, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

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

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

*Institute for Nuclear Research, Moscow, Russia*

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

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

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

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

A. Belyaev, E. Boos, V. Bunichev, M. Dubinin<sup>34</sup>, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin

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

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

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

P. Adzic<sup>35</sup>, M. Ekmedzic, J. Milosevic, V. Rekoic

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

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

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

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

*Universidad Autónoma de Madrid, Madrid, Spain*

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

*Universidad de Oviedo, Oviedo, 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

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

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>36</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. Pimiã, D. Piparo, M. Plagge, A. Racz, G. Rolandi<sup>37</sup>, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas<sup>38</sup>, D. Spiga, J. Steggemann, B. Stieger, M. Stoye, D. Treille, A. Tsirou, G.I. Veres<sup>18</sup>, J.R. Vlimant, N. Wardle, H.K. Wöhri, H. Wollny, W.D. Zeuner

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

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

*Paul Scherrer Institut, Villigen, 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. Lustermann, B. Mangano, A.C. Marini, P. Martinez Ruiz del Arbol, D. Meister, N. Mohr, C. Nägeli<sup>39</sup>, F. Nessi-Tedaldi, F. Pandolfi, F. Pauss, M. Peruzzi, M. Quittnat, L. Rebane, M. Rossini, A. Starodumov<sup>40</sup>, M. Takahashi, K. Theofilatos, R. Wallny, H.A. Weber

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

C. Amsler<sup>41</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

*Universität Zürich, Zurich, Switzerland*

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

*National Central University, Chung-Li, 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

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

B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

*Chulalongkorn University, Bangkok, Thailand*

A. Adiguzel, M.N. Bakirci<sup>42</sup>, S. Cerci<sup>43</sup>, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, A. Kayis Topaksu, G. Onengut<sup>44</sup>, K. Ozdemir, S. Ozturk<sup>42</sup>, A. Polatoz, K. Sogut<sup>45</sup>, D. Sunar Cerci<sup>43</sup>, B. Tali<sup>43</sup>, H. Topakli<sup>42</sup>, M. Vergili

*Cukurova University, Adana, Turkey*

I.V. Akin, B. Bilin, S. Bilmis, H. Gamsizkan, G. Karapinar<sup>46</sup>, K. Ocalan, S. Sekmen, U.E. Surat, M. Yalvac, M. Zeyrek

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

E. Gülmez, B. Isildak<sup>47</sup>, M. Kaya<sup>48</sup>, O. Kaya<sup>49</sup>

*Bogazici University, Istanbul, Turkey*

H. Bahtiyar<sup>50</sup>, E. Barlas, K. Cankocak, F.I. Vardarli, M. Yücel

*Istanbul Technical University, Istanbul, Turkey*

L. Levchuk, P. Sorokin

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

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>51</sup>, S. Paramesvaran, A. Poll, S. Senkin, V.J. Smith, T. Williams

*University of Bristol, Bristol, United Kingdom*

K.W. Bell, A. Belyaev<sup>52</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

*Rutherford Appleton Laboratory, Didcot, 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>51</sup>, L. Lyons, A.-M. Magnan, S. Malik, B. Mathias,



J. Nash, A. Nikitenko<sup>40</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

*Imperial College, London, 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

*Brunel University, Uxbridge, United Kingdom*

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

*Baylor University, Waco, USA*

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

*The University of Alabama, Tuscaloosa, USA*

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

*Boston University, Boston, 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

*Brown University, Providence, 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, Davis, Davis, USA*

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

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

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

*University of California, San Diego, La Jolla, 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

*University of California, Santa Barbara, Santa Barbara, 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

*California Institute of Technology, Pasadena, USA*

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

*Carnegie Mellon University, Pittsburgh, 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

*University of Colorado at Boulder, Boulder, 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

*Cornell University, Ithaca, USA*

D. Winn

*Fairfield University, Fairfield, 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, 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>32</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

*Fermi National Accelerator Laboratory, Batavia, 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. Milenovic<sup>53</sup>, G. Mitselmakher, L. Muniz, A. Rinkevicius, L. Shchutska, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

*University of Florida, Gainesville, USA*

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

*Florida International University, Miami, 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 State University, Tallahassee, USA*

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

*Florida Institute of Technology, Melbourne, 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

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

E.A. Albayrak<sup>50</sup>, B. Bilki<sup>54</sup>, W. Clarida, K. Dilsiz, F. Duru, M. Haytmyradov, J.-P. Merlo, H. Mermerkaya<sup>55</sup>, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok<sup>50</sup>, A. Penzo, R. Rahmat, S. Sen, P. Tan, E. Tiras, J. Wetzel, T. Yetkin<sup>56</sup>, K. Yi

*The University of Iowa, Iowa City, USA*

I. Anderson, B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, A.V. Gritsan, P. Maksimovic, C. Martin, U. Sarica, M. Swartz, M. Xiao

*Johns Hopkins University, Baltimore, 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

*The University of Kansas, Lawrence, USA*

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

*Kansas State University, Manhattan, USA*

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

*Lawrence Livermore National Laboratory, Livermore, USA*

A. Baden, 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

*University of Maryland, College Park, 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

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

J.G. Acosta, S. Oliveros

*University of Mississippi, Oxford, 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

*University of Nebraska-Lincoln, Lincoln, USA*

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

*State University of New York at Buffalo, Buffalo, 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

*Northeastern University, Boston, USA*

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

*Northwestern University, Evanston, 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

*University of Notre Dame, Notre Dame, 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

*The Ohio State University, Columbus, 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

*Princeton University, Princeton, USA*

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

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

N. Parashar, J. Stupak

*Purdue University Calumet, Hammond, 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

*Rice University, Houston, 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

*University of Rochester, Rochester, USA*

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

*The Rockefeller University, New York, USA*

S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, 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

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

K. Rose, S. Spanier, A. York

*University of Tennessee, Knoxville, USA*

O. Bouhali<sup>57</sup>, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon<sup>58</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 A&M University, College Station, USA*

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

*Texas Tech University, Lubbock, 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

*Vanderbilt University, Nashville, USA*



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

*University of Virginia, Charlottesville, USA*

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

*Wayne State University, Detroit, USA*

D.A. Belknap, D. Carlsmith, M. Cepeda, S. Dasu, 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

*University of Wisconsin, Madison, USA*

<sup>†</sup> Deceased.

<sup>1</sup> Also at Vienna University of Technology, Vienna, Austria.

<sup>2</sup> Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

<sup>3</sup> Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.

<sup>4</sup> Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.

<sup>5</sup> Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

<sup>6</sup> Also at Universidade Estadual de Campinas, Campinas, Brazil.

<sup>7</sup> Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.

<sup>8</sup> Also at Joint Institute for Nuclear Research, Dubna, Russia.

<sup>9</sup> Also at Suez University, Suez, Egypt.

<sup>10</sup> Also at Cairo University, Cairo, Egypt.

<sup>11</sup> Also at Fayoum University, El-Fayoum, Egypt.

<sup>12</sup> Also at British University in Egypt, Cairo, Egypt.

<sup>13</sup> Now at Ain Shams University, Cairo, Egypt.

<sup>14</sup> Also at Université de Haute Alsace, Mulhouse, France.

<sup>15</sup> Also at Brandenburg University of Technology, Cottbus, Germany.

<sup>16</sup> Also at The University of Kansas, Lawrence, USA.

<sup>17</sup> Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

<sup>18</sup> Also at Eötvös Loránd University, Budapest, Hungary.

<sup>19</sup> Also at University of Debrecen, Debrecen, Hungary.

<sup>20</sup> Also at University of Visva-Bharati, Santiniketan, India.

<sup>21</sup> Also at Tata Institute of Fundamental Research – HECR, Mumbai, India.

<sup>22</sup> Now at King Abdulaziz University, Jeddah, Saudi Arabia.

<sup>23</sup> Also at University of Ruhuna, Matara, Sri Lanka.

<sup>24</sup> Also at Isfahan University of Technology, Isfahan, Iran.

<sup>25</sup> Also at Sharif University of Technology, Tehran, Iran.

<sup>26</sup> Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.

<sup>27</sup> Also at Università degli Studi di Siena, Siena, Italy.

<sup>28</sup> Also at Centre National de la Recherche Scientifique (CNRS) – IN2P3, Paris, France.

<sup>29</sup> Also at Purdue University, West Lafayette, USA.

<sup>30</sup> Also at Universidad Michoacana de San Nicolas de Hidalgo, Morelia, Mexico.

<sup>31</sup> Also at National Centre for Nuclear Research, Swierk, Poland.

<sup>32</sup> Also at Institute for Nuclear Research, Moscow, Russia.

<sup>33</sup> Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.

<sup>34</sup> Also at California Institute of Technology, Pasadena, USA.

<sup>35</sup> Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.

<sup>36</sup> Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.

<sup>37</sup> Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.

<sup>38</sup> Also at University of Athens, Athens, Greece.

<sup>39</sup> Also at Paul Scherrer Institut, Villigen, Switzerland.

<sup>40</sup> Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.

<sup>41</sup> Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.

<sup>42</sup> Also at Gaziosmanpasa University, Tokat, Turkey.

<sup>43</sup> Also at Adiyaman University, Adiyaman, Turkey.

<sup>44</sup> Also at Cag University, Mersin, Turkey.

<sup>45</sup> Also at Mersin University, Mersin, Turkey.

<sup>46</sup> Also at Izmir Institute of Technology, Izmir, Turkey.

<sup>47</sup> Also at Ozyegin University, Istanbul, Turkey.

<sup>48</sup> Also at Marmara University, Istanbul, Turkey.

<sup>49</sup> Also at Kafkas University, Kars, Turkey.

<sup>50</sup> Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.

<sup>51</sup> Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.

<sup>52</sup> Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.

- <sup>53</sup> Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
- <sup>54</sup> Also at Argonne National Laboratory, Argonne, USA.
- <sup>55</sup> Also at Erzincan University, Erzincan, Turkey.
- <sup>56</sup> Also at Yildiz Technical University, Istanbul, Turkey.
- <sup>57</sup> Also at Texas A&M University at Qatar, Doha, Qatar.
- <sup>58</sup> Also at Kyungpook National University, Daegu, Korea.