

CERN-PH-EP/2015-010  
2015/02/18

CMS-EXO-13-007

# Search for narrow high-mass resonances in proton-proton collisions at $\sqrt{s} = 8$ TeV decaying to Z and Higgs bosons

The CMS Collaboration\*

## Abstract

The first search for a narrow, high-mass resonance decaying into Z and Higgs (H) bosons is presented. The final state studied consists of a merged jet pair and a  $\tau$  pair resulting from the decays of Z and H bosons, respectively. The analysis is based on a data sample of proton-proton collisions at a center-of-mass energy of 8 TeV, collected with the CMS experiment in 2012, and corresponding to an integrated luminosity of  $19.7 \text{ fb}^{-1}$ . In the resonance mass range of interest, the Z and H bosons are produced with large momenta, which implies that the final products of the two quarks or the two  $\tau$  leptons must be detected within a small angular interval. From a combination of all possible decay modes of the  $\tau$  leptons, production cross sections in a range between 0.9 and 27.8 fb are excluded at 95% confidence level, depending on the resonance mass.

*Submitted to Physics Letters B*



# 1 Introduction

Very recently, the validity of the standard model (SM) of particle physics has been confirmed by the discovery of a Higgs boson with mass near 125 GeV by the ATLAS and CMS experiments [1, 2]. Though the SM successfully describes a broad range of high energy phenomena, the solution to remaining problems with the structure of the SM, particularly the hierarchy problem, leads naturally to the introduction of physics beyond the standard model (BSM), possibly at the TeV scale [3]. Many of the BSM models predict the existence of heavy resonances with masses of the order of a TeV, which may have sizable couplings to the gauge and Higgs boson fields of the SM [4–7]. We consider here two main families among these models: those that predict an additional neutral gauge boson (generically called a  $Z'$ ) [4, 5] and those that incorporate composite Higgs bosons [6, 7].

Grand unified theories predict that all fundamental interactions can be unified at very high energies using one simple gauge group. If the dimensionality of this group is larger than 5, then the theory includes at least one extra neutral gauge boson, the  $Z'$ . The mass of this new particle is a free parameter of the theory. In composite Higgs models, the Higgs boson is a pseudo-Nambu-Goldstone boson of a broken global symmetry. Other composite bound states beyond the Higgs are expected to exist and could be experimentally observed.

Several searches for massive resonances decaying into pairs of vector bosons or Higgs bosons have been performed by the ATLAS and CMS experiments [8–13]. In this analysis, we search for a resonance with a mass in the range 0.8–2.5 TeV decaying to  $ZH$ , where the  $Z$  boson decays to  $q\bar{q}$  and the Higgs boson decays to  $\tau^+\tau^-$ , with no assumptions on additional particles produced in the final state. It is assumed that the natural width of the resonance is negligible in comparison to the experimental mass resolution which is between 6% and 10% of the mass of the resonance. In the model considered, the spin of the resonance is assumed to be one. However, it has been verified that the analysis is insensitive to the angular distributions of the decay products and therefore applies to other spin hypotheses.

The theoretical model used as benchmark in this work is described in Ref. [14]. In this model a heavy  $SU(2)_L$  vector triplet (HVT) containing neutral and charged spin-1 states is introduced. This scenario is well-motivated in cases where the new physics sector is either weakly coupled [15], or strongly coupled, e.g., in the minimal composite model [16]. The cross sections and branching fractions ( $\mathcal{B}$ ) for the heavy triplet model depend on the new physics scenario under study and can be characterized by three parameters in the phenomenological Lagrangian: the strength of the couplings to fermions  $c_F$ , to the Higgs  $c_H$ , and the self-coupling  $g_V$ . In the case of a strongly coupled sector, the new heavy resonance has larger couplings to the  $W$ ,  $Z$ , and  $H$  bosons, resulting in larger branching fractions for the diboson final states. Our benchmark model characterizes this scenario by choosing the parameters  $g_V = 3$  and  $c_F = -c_H = 1$ , which configure a strongly coupled sector.

In the high-mass case under study, the directions of the particles stemming from  $Z$  and  $H$  boson decays are separated by a small angle. This feature is referred to as the “boosted” regime. For the case of  $Z \rightarrow q\bar{q}$ , this results in the presence of one single reconstructed jet after hadronization called a “ $Z$ -jet”. The novel feature of this analysis is the reconstruction and selection of a  $\tau$  pair in the boosted regime. The presence of missing energy in  $\tau$  decays does not allow a direct determination of the invariant mass. In the following, we label  $\tau$  decays in a simplified way:  $\tau^\pm \rightarrow e^\pm\nu\bar{\nu}$  as “ $\tau_e$ ”,  $\tau^\pm \rightarrow \mu^\pm\nu\bar{\nu}$  as “ $\tau_\mu$ ”, and  $\tau^\pm \rightarrow (n\pi)(mK)\nu$  as “ $\tau_h$ ”, where  $n$  and  $m$  can be 0, 1, 2, or 3, and the pions and kaons can be either charged or neutral. Six channels, depending on the combinations of  $\tau$  decays, are studied separately and labeled as all-leptonic ( $\tau_e\tau_e$ ,  $\tau_e\tau_\mu$ ,  $\tau_\mu\tau_\mu$ ), semileptonic ( $\tau_e\tau_h$ ,  $\tau_\mu\tau_h$ ), and all-hadronic ( $\tau_h\tau_h$ ).

The experimental strategy is to reconstruct and identify the two bosons and to combine their information into a variable that can discriminate between signal and background and on which a statistical study can be performed. This variable is the estimated mass of the  $Z'$  after applying dedicated reconstruction techniques to the boosted  $q\bar{q}$  and  $\tau\tau$  pairs ( $m_{ZH}$ ). The  $m_{ZH}$  distribution would show an excess of events at the assumed  $Z'$  mass if a signal were present.

## 2 CMS detector

A detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [17]. The central feature of the CMS detector is a 3.8 T superconducting solenoid of 6 m internal diameter. Within the field volume are the silicon tracker, the crystal electromagnetic calorimeter (ECAL), and the brass and scintillator hadron calorimeter (HCAL). The muon detectors are located outside the solenoid and are installed between the layers of the steel flux-return yoke of the solenoid. In addition, CMS has extensive forward calorimetry, in particular two steel and quartz-fiber hadron forward calorimeters, which cover the pseudorapidity range  $2.9 < |\eta| < 5.0$ .

## 3 Data sample and simulation

The analysis is based on a data sample collected by the CMS experiment in proton-proton collisions at a center-of-mass energy of 8 TeV in 2012, corresponding to an integrated luminosity of  $19.7 \text{ fb}^{-1}$ . Events are selected online by a trigger that requires the presence of a hadronic jet with a transverse momentum  $p_T$  larger than 320 GeV or a total hadronic transverse energy in the event,  $H_T$ , defined as the sum of the transverse energy of all the jets of the event, larger than 650 GeV. The transverse energy of a particle is defined as the energy multiplied by the sine of the polar angle. Using events selected by less restrictive, pre-scaled triggers, it has been verified that the efficiency of this trigger after applying the offline event selection is above 99%. The difference from 100% is considered as a systematic uncertainty.

The process  $q\bar{q} \rightarrow Z' \rightarrow ZH \rightarrow q\bar{q}\tau^+\tau^-$  is simulated at parton level using a MADGRAPH 5 [18] implementation of the model described in Ref. [19]. Seven signal samples are generated with masses between 0.8 and 2.5 TeV. Showering and hadronization are performed with PYTHIA 6.426 [20].

Although the main sources of background are estimated using observed events, Monte Carlo (MC) simulations are used to develop and validate the methods used in the analysis. Background samples are generated using MADGRAPH (Z+jets, W+jets), POWHEG 1.0 r1380 ( $t\bar{t}$  and single top quark production) [21–24], and PYTHIA (SM diboson production and QCD multijet events with large  $H_T$ ). GEANT4 [25] is used for the simulation of the CMS detector.

## 4 Event reconstruction

A particle-flow (PF) algorithm [26, 27] is used to identify and to reconstruct candidate charged hadrons, neutral hadrons, photons, muons, and electrons produced in proton-proton collisions. Jets and  $\tau_h$  candidates are then reconstructed using the PF candidates. The jet energy scale is calibrated through correction factors that depend on the  $p_T$  and  $\eta$  of the jet [28]. All particles reconstructed with the PF algorithm are used to determine the missing transverse momentum,  $\vec{p}_T^{\text{miss}}$ . In first approximation,  $\vec{p}_T^{\text{miss}}$  is defined as the negative vector sum of transverse momenta of all reconstructed particles [29].

Jets are reconstructed using the Cambridge–Aachen (CA) algorithm [30], with a distance parameter of 0.8, chosen so that it contains the hadronization products of the two quarks from the Z boson. Jet pruning and subjet-searching algorithms are applied to these jets as in Ref. [11]. In these algorithms the original jets are re-clustered by removing pileup and underlying-event particles at low- $p_T$  and large-angle. The term pileup refers to additional interactions occurring in the same LHC bunch crossing. We define  $m_{\text{jet}}^p$  as the invariant mass of the jet constituents after the pruning procedure. This invariant mass provides good discrimination between Z-jets and quark/gluon-jets since it tends to be shifted towards the energy scale at which the jet was produced. We also define a quantity called “N-subjettiness”,  $\tau_N$ , that is sensitive to the different jet substructure characteristics of QCD and Z-jets, as [31]:

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min(\Delta R_{1,k}, \Delta R_{2,k}, \dots, \Delta R_{N,k}), \quad (1)$$

where  $N$  is the number of subjets in which the original jet can be reclustered with the  $k_T$  algorithm [32, 33]; the index  $k$  runs over the PF constituents of the jet;  $p_{T,k}$  is the transverse momentum of the  $k$ th constituent;  $\Delta R_{n,k}$  is a distance defined as  $\sqrt{(\Delta\eta_{n,k})^2 + (\Delta\phi_{n,k})^2}$  where  $\Delta\eta_{n,k}$  and  $\Delta\phi_{n,k}$  are the differences in pseudorapidity and azimuthal angle between the  $k$ th constituent and the  $n$ th subjet axis; and  $d_0 = \sum_k p_{T,k} R_0$  is a normalization factor with  $R_0$  equal to the original jet distance parameter. The variable  $\tau_N$  quantifies the tendency of a jet to be composed of  $N$  subjets, having smaller values for jets with a  $N$ -subjets-like configuration. We define  $\tau_{21}$  as the ratio between the 2-subjettiness and the 1-subjettiness,  $\tau_{21} = \tau_2/\tau_1$ . The variables  $m_{\text{jet}}^p$  and  $\tau_{21}$  have been shown to have a good discrimination power between signal and background [34], therefore in the following they are used to define signal and background enriched regions of the analysis.

In order to match trigger requirements and avoid inefficiencies close to the threshold, at least one jet in the event is required to have  $p_T > 400 \text{ GeV}$  and  $|\eta| < 2.4$ . In addition, this jet is required to pass minimal consistency requirements on the fraction of charged and neutral particles contributing to it, to avoid fake jets from isolated noise patterns in the calorimeters or the tracker systems. While the CA jet selection is common to all the channels considered, the reconstruction of the  $\tau\tau$  system is performed differently depending on the  $\tau$  decay channel.

The all-leptonic channels are identified by combinations of electrons, muons, and  $\vec{p}_T^{\text{miss}}$ , which are products of the decay of a pair of  $\tau$  leptons from the Higgs boson. Electrons are reconstructed by combining the information from an ECAL energy cluster with that of a matching track in the silicon tracker [35]. Electrons are selected if they have  $p_T > 10 \text{ GeV}$ ,  $|\eta| < 2.5$ , and satisfy requirements on the ECAL shower shape, the ratio of energies measured in HCAL and ECAL around the electron candidate, the compatibility with the primary vertex of the event, and the track-cluster matching parameters. Muon candidates [36] are reconstructed by performing a global track fit in which the silicon tracker and the muon system information is combined. For the  $\tau_\mu\tau_\mu$  channel, to avoid identification inefficiencies caused by the small angular separation of the two muon trajectories, the second muon candidate is reconstructed with a different algorithm in which tracks in the silicon tracker are matched in space to signals in the muon detectors [11]. Muons are required to have  $p_T > 10 \text{ GeV}$ ,  $|\eta| < 2.4$  and to pass additional requirements on the quality of the track reconstruction, on the impact parameter of the track, and on the number of measurements in the tracker and the muon systems. Electron and muon candidates are required to satisfy particle-flow based isolation criteria that require low activity in a cone around the lepton, the isolation cone, after the removal of particles due to additional interactions. Because the lepton from the other signal  $\tau$  decay in the boosted pair can fall in the isolation cone, other electrons and muons are not considered in the computation

of the isolation criteria.

In the semileptonic channels, a lepton selected with all the criteria above is combined with a  $\tau_h$  candidate. The reconstruction of  $\tau_h$  starts from the clustering of jets using the anti- $k_T$  algorithm [37] with a distance parameter of 0.5. Electrons and muons, identified by looser criteria than the nominal ones used in the analysis, are removed from the list of particles used in the clustering if they fall within the jet distance parameter. The  $\tau_h$  is reconstructed and identified using the “hadron-plus-strips” technique [38], which searches for the most common decay modes of the  $\tau_h$  starting from charged hadrons and photons forming  $\pi^0$  candidates. We select  $\tau_h$  candidates with  $p_T > 20$  GeV and  $|\eta| < 2.3$ . Electrons and muons misidentified as  $\tau_h$  are suppressed using dedicated criteria based on the consistency between the measurements in the tracker, the calorimeters, and the muon detectors [38]. Finally, loose PF-based isolation criteria are applied to the  $\tau_h$  candidates, not counting electrons and muons in the cone.

In the all-hadronic  $\tau\tau$  channel two narrow jets (distance parameter in a range of 0.01–0.1) are merged into a single jet (CA-jet with  $R = 0.8$ ). A subjet-searching technique [39] is applied to all of the CA-jets in each event to identify the  $\tau_h$  candidates. At the next-to-last step of the clustering algorithm, there are two subjets, which are ordered by mass. If both have  $p_T > 10$  GeV and the mass of the leading subjet is smaller than  $2/3$ , the mass of the original merged jet, the two objects are used as seeding jets for  $\tau$  lepton reconstruction via the “hadron-plus-strips” technique. If any of the criteria above fail, the procedure for one of the subjets is performed again for a maximum of four iterations. The efficiency for finding subjets with this method in signal events is 92%, independent of  $p_T$ , for  $\tau_h$  with  $p_T > 40$  GeV. In the lowest bin investigated ( $p_T$  between 20 and 40 GeV) the efficiency is around 80%.

The visible mass,  $m_{\text{vis}}$ , of the  $\tau\tau$  system is defined as the invariant mass of all detectable products of the two decays. Because the unobserved neutrinos can carry a significant fraction of the  $\tau\tau$  energy/momenta, this variable is not suited for reconstructing resonances that include the  $\tau\tau$  system among its decay products. Instead, the Secondary Vertex fit (SVFIT) algorithm described in [40], which combines the  $\vec{p}_T^{\text{miss}}$  with the visible momenta to calculate a more precise estimator of the kinematics of the parent boson, is used to reconstruct the  $\tau\tau$  system in all search channels.

## 5 Event selection

In the all-leptonic and semileptonic channels, the  $\tau\tau$  four-momentum estimated from SVFIT is combined with that of the CA-jet to obtain the resonance mass  $m_{ZH}$ . Several preselection requirements are applied to remove backgrounds from low-mass resonances and from overlaps of lepton and  $\tau$  lepton reconstruction in the detector:  $m_{\text{vis}} > 10$  GeV,  $\Delta R_{\ell\ell} > 0.1$  (where  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$  and  $\ell$  denotes both hadronic or leptonic  $\tau$  decay),  $|\vec{p}_T^{\text{miss}}| > 20$  GeV, and  $p_{T,\tau\tau} > 100$  GeV, as estimated from the SVFIT procedure.

Because of its different background composition, a different preselection is applied for the all-hadronic channel. Only events that have not been included in the all-leptonic or semileptonic categories are considered in this category. The event is then separated into two hemispheres containing the decay products of the two bosons by requiring the following preselection:  $|\vec{p}_T^{\text{miss}}| > 40$  GeV,  $|\Delta\phi(\text{CA-jet}, \tau)| > 2.0$  and  $|\Delta\phi(\vec{p}_T^{\text{miss}}, \tau)| < 1.5$ , for each of the two  $\tau$  candidates.

Further criteria for signal selection include tighter requirements on variables including the  $p_T$  of the highest- $p_T$  (leading) lepton or  $\tau_h$  and  $m_{\tau\tau}$  as estimated from the SVFIT procedure. An

upper limit is placed on  $\Delta R_{\ell\ell}$  in order to reject  $W$ +jets events, where a jet misidentified as a  $\tau$  lepton is usually well-separated in space from the isolated lepton. The number of  $b$  jets in the event also provides a useful criterion to reduce the  $t\bar{t}$  contribution. Jets may be identified as  $b$  jets, using the combined secondary vertex algorithm [41] which exploits observables related to the long lifetime of  $b$  hadrons, and are considered if not overlapping with  $\tau$  candidates and CA-jets. Those  $b$  jets are clustered with the anti- $k_T$  jet algorithm, with a distance parameter  $R = 0.5$ . Optimization of the selection on these variables is based on the Punzi factor of merit ( $\mathcal{P}$ ) [42], defined as:  $\mathcal{P} = \varepsilon_{\text{sig}} / (1 + \sqrt{B})$ , where  $\varepsilon_{\text{sig}}$  is the signal efficiency and  $B$  is the background yield after applying the selection. The results of the optimization are listed in Table 1. It has been verified that the optimized values of the selections are not sensitive to the choice of  $m_{ZH}$  window used to evaluate  $\varepsilon_{\text{sig}}$  and  $B$ .

Table 1: Summary of the optimized event selection for the six  $\tau\tau$  channels. The selection variables are explained in the text. The label  $\ell$  refers to electrons, muons, and  $\tau$  leptons decaying hadronically.

Selection	$\tau_e\tau_e, \tau_e\tau_\mu, \tau_\mu\tau_\mu$	$\tau_e\tau_h, \tau_\mu\tau_h$	$\tau_h\tau_h$
$ \vec{p}_T^{\text{miss}} $	$>100$ GeV	$>50$ GeV	$>80$ GeV
$p_{T,\ell}^{\text{leading}}$	—	$>35$ GeV	$>50$ GeV
$N_{b\text{-tagged jet}}$	$=0$	$=0$	—
$\Delta R_{\ell\ell}$	$<1.0$	$<1.0$	$<1.0$
$m_{\tau\tau}$	—	—	105–180 GeV

## 6 Background estimation

After the full selection, different background estimation techniques based on control samples in observed events are used for each channel.

In the  $\tau_e\tau_e$ ,  $\tau_e\tau_\mu$ , and  $\tau_\mu\tau_\mu$  channels, the background is almost entirely composed of  $Z^{(*)}$ +jets events. This background source lacks events with a genuine massive boson decaying to quarks, therefore a technique based on sidebands of the  $m_{\text{jet}}^p$  and  $\tau_{21}$  variables is used for background estimation. In an enlarged search region defined by  $m_{\text{jet}}^p > 20$  GeV, we define a ZH “signal region” by the conditions  $70 < m_{\text{jet}}^p < 110$  GeV and  $\tau_{21} < 0.75$ , while the rest of the parameter space is referred to as the “sideband region”.

The total background is estimated in intervals of  $m_{ZH}$ , using the formula:

$$N_{\text{bkg}}(x) = \mathcal{N} N_{\text{sb}}(x) \alpha(x), \quad (2)$$

where  $x = m_{ZH}$ ,  $\mathcal{N}$  is a normalization factor,  $N_{\text{sb}}(x)$  is the number of events observed in the sideband region, in bins of  $m_{ZH}$ , and  $\alpha(x)$  is a binned ratio between the shapes of the  $m_{ZH}$  distributions in the signal and sideband region, taken from the sum of MC components. The normalization factor is found through a fit of the observed pruned jet mass distribution, following the procedure used in Ref. [11]. The pruned jet mass distribution in the region  $20 < m_{\text{jet}}^p < 200$  GeV,  $\tau_{21} < 0.75$  is fit in MC samples with the following function:

$$F(x) = \mathcal{N} e^{ax} (1 + \text{erf}[(x - b)/c]), \quad (3)$$

where “erf” is the error function and the parameters  $a$ ,  $b$  and  $c$  are estimated from the MC simulation. A fit to the observed distribution, excluding the signal region, is then used to determine  $\mathcal{N}$ . Figure 1 shows the observed distributions of  $m_{ZH}$  in all-leptonic channels, along

with the corresponding MC expectations for signal and background, as well as the background estimation derived with the above procedure.

In the  $\tau_e \tau_h$  and  $\tau_\mu \tau_h$  channels, additional significant contributions to the total background come from  $W$ +jets and  $t\bar{t}$  events, where a hadronic jet is misidentified as a  $\tau$ . Events from  $t\bar{t}$  production with one  $W$  boson decaying leptonically and one decaying to quarks can potentially produce a signal-like structure in  $m_{\text{jet}}^p$  and  $\tau_{21}$ . Two scale factors (SFs) relating the ratio of the observed to simulated event rates, one for the  $t\bar{t}$  peaking contribution and the other for the  $t\bar{t}$  combinatorial background, are estimated from a control sample defined by the preselection described before, but requiring at least one  $b$ -tagged jet. It has been established with simulation that more than 95% of this sample is composed of  $t\bar{t}$  events. The pruned jet mass distribution is fit with the sum of two functions:

$$F_{t\bar{t}}(x) = N(\text{non-peaking}) e^{Ax} (1 + \text{erf}[(x - B)/C]) + N(\text{peaking}) \mathcal{G}(D, E) \quad (4)$$

where  $A$ ,  $B$ , and  $C$  define the shape of the non-peaking component, analogous to Eq. (3), and  $\mathcal{G}(D, E)$  is a Gaussian function of mean  $D$  and standard deviation  $E$ . The values of these two parameters are fixed to those found in the analysis searching for vector boson pair resonances [11]. From this fit, the two scale factors between data and MC are found, one for each contribution:  $r_1^{\text{SF}} = N(\text{peaking})_{\text{data}} / N(\text{peaking})_{\text{MC}}$  and  $r_2^{\text{SF}} = N(\text{non-peaking})_{\text{data}} / N(\text{non-peaking})_{\text{MC}}$ . The same procedure as for the all-leptonic channels is then applied, fitting the observed sideband distribution but using a modified function, given by the sum of the  $t\bar{t}$  contribution plus the function of Eq. (3), where the  $t\bar{t}$  normalization is fixed at the MC expectation, scaled by the two SFs. Figure 2 shows the distributions of  $m_{\text{ZH}}$  in semileptonic channels, along with the corresponding MC expectations and the background estimation derived with the above procedure. For each of the methods used, consistency checks comparing data and background predictions are performed using samples of events at the preselection level, which are expected to have small contributions from any signal resonances.

The background in the  $\tau_h \tau_h$  channel is dominated by  $Z$ +jets,  $W$ +jets, and  $t\bar{t}$  production. In addition, there is a small but non-negligible contribution from QCD multijets production. For all these processes, it is possible that at least one extra jet or lepton is misidentified as  $\tau_h$ , allowing the event to pass the full selection. In this channel, for events where the leading jet satisfies the requirement  $\tau_{21} < 0.75$ , a plane is defined using the  $m_{\text{jet}}^p$  and  $m_{\tau\tau}$  variables and four regions are considered: “region A” ( $70 < m_{\text{jet}}^p < 110$  GeV and  $105 < m_{\tau\tau} < 180$  GeV), “region B” ( $20 < m_{\text{jet}}^p < 70$  GeV and  $105 < m_{\tau\tau} < 180$  GeV), “region C” ( $20 < m_{\text{jet}}^p < 70$  GeV and  $60 < m_{\tau\tau} < 105$  GeV), and “region D” ( $70 < m_{\text{jet}}^p < 110$  GeV and  $60 < m_{\tau\tau} < 105$  GeV). Most of the signal events are expected in region A, while regions B, C, D are dominated by background events. Studies of the correlation factors for simulated events and in regions orthogonal to the signal region show that the variables  $m_{\text{jet}}^p$  and  $m_{\tau\tau}$  are essentially uncorrelated. In this case, the total number of background events in the region A can be estimated as:

$$N_{\text{bkg}} = (N_B N_D) / N_C. \quad (5)$$

The method described by Eq. (5), called “ABCD method”, gives a background prediction in the signal region that has been checked to be insensitive to possible signal contamination in the regions B, C, D.

Figure 3 shows the observed distributions of  $m_{\text{ZH}}$  in the  $\tau_h \tau_h$  channel, along with the corresponding MC expectations for signal and background. The background prediction from the ABCD method is not shown, because the low number of events in regions B, C, D is not sufficient to derive the shape of the distribution in the signal region. The ABCD method is checked



using an alternative background estimation technique, where  $t\bar{t}$ ,  $W$ +jets and  $Z$ +jets background contributions are given by Eq. (2), while the QCD multijet background is estimated from a control sample of events where at least one  $\tau$  candidate fails the isolation requirement. The same control sample is used to obtain the shape of the QCD distribution in the signal region presented in Fig. 3.

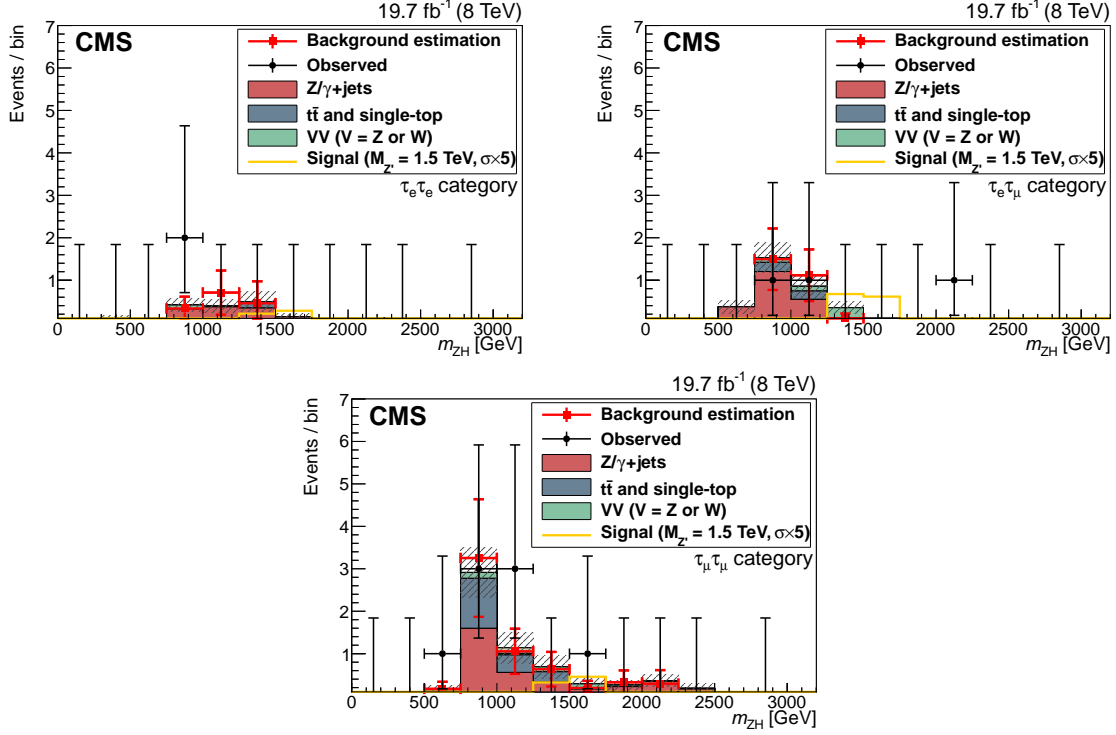


Figure 1: Observed distributions of  $m_{ZH}$  for the all-leptonic channels along with the corresponding MC expectations for signal and background, as well as background estimation derived from data: (top left)  $\tau_e\tau_e$  category; (top right)  $\tau_e\tau_\mu$  category; (bottom)  $\tau_\mu\tau_\mu$  category. The shaded bands indicate the statistical uncertainty from MC background. The signal cross section is scaled by a factor of 5.

## 7 Systematic uncertainties

The sources of systematic uncertainty in this analysis, which affect either the background estimation or the signal efficiencies, are described below.

For the signal efficiency, the main uncertainties come from the limited number of signal MC events (3–10%), the integrated luminosity (2.5%) [43], and the uncertainty on the modeling of pileup (0.2–2.2%). Hereafter, the ranges indicate the different channels and mass regions used in the evaluation of the upper limits. The scale factors for lepton identification are derived from dedicated analyses of observed and simulated  $Z \rightarrow \ell^+\ell^-$  events, using the “tag-and-probe” method [36, 38, 44]. The uncertainties in these factors are taken as systematic uncertainties and amount to 1–4% for electrons, 1–6% for muons and 9–26% for  $\tau$  leptons decaying hadronically. The jet and lepton four-momenta are varied over a range given by the energy scale and resolution uncertainties [28]. In this process, variations in the lepton and jet four-momenta are propagated consistently to  $\vec{p}_T^{\text{miss}}$ . For the all-leptonic and semileptonic channels, additional uncertainties come from the procedure of removing nearby tracks and leptons used in the hadronic  $\tau$  reconstruction, and from the isolation variable computation in the case of boosted topologies.

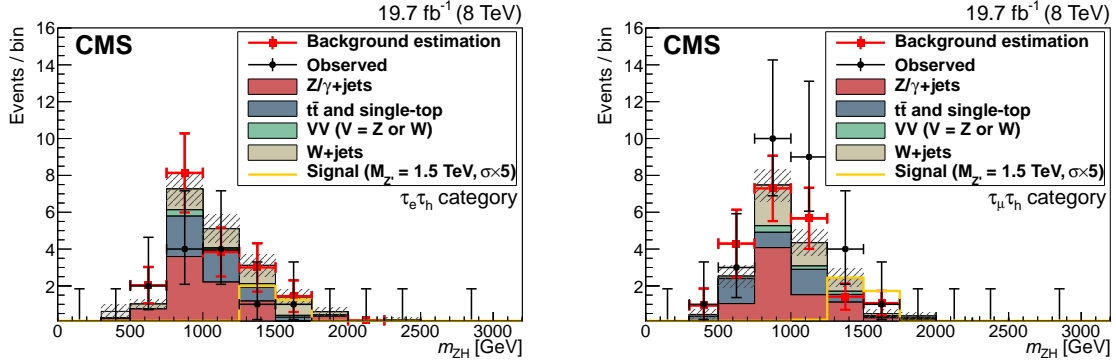


Figure 2: Observed distributions of  $m_{ZH}$  for the semileptonic channels along with the corresponding MC expectations for signal and background, as well as background estimation derived from data: (left)  $\tau_e\tau_h$  category; (right)  $\tau_\mu\tau_h$  category. The shaded bands indicate the statistical uncertainty from MC background. The signal cross section is scaled by a factor of 5.

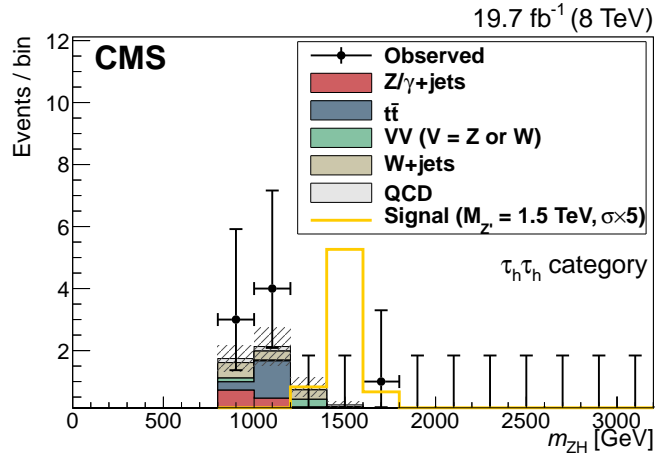


Figure 3: Observed distributions of  $m_{ZH}$  for the  $\tau_h\tau_h$  category along with the corresponding MC expectations for signal and background. The shaded bands indicate the statistical uncertainty from MC background. The signal cross section is scaled by a factor of 5.

The inefficiency resulting from these procedures, as measured in signal simulation, is assigned as a systematic uncertainty, corresponding to 1–16% for  $\tau$  reconstruction and 1–21% for isolation. In the all-hadronic analysis, a constant uncertainty of 10% is assigned for the application of the  $\tau$  reconstruction procedure to collimated subjets, comparing the performance for isolated and non-isolated  $\tau$  leptons in simulation. The jet trigger efficiency has an uncertainty of  $<1\%$ , as determined from a less selective trigger. Following the method derived for vector boson identification in merged jets [45], a scale factor of  $0.94 \pm 0.06$  is used for the efficiency of the pruning and subjet searching techniques applied on the CA jet, where the uncertainty is included in the estimation of the overall systematic uncertainty. For the b tagging, data-to-MC corrections derived from several control samples are applied and the uncertainties on these corrections are propagated as systematic uncertainties in the analysis (2–6%). The procedure used to derive the b-tagging systematic uncertainties is described in Ref. [41].

The uncertainties in the background estimate are dominated by the limited numbers of MC events and sideband data events (4–16 events in all-leptonic channels, 34–37 events in semileptonic channels and 29 in the all-hadronic channels). In the analysis of the all-leptonic and semileptonic channels, additional uncertainties in the background yields of 10–96% originate from the limited number of events of the background MC samples used in the computation of the  $\alpha(x)$  quantity, and 18–47% from the normalization fit.

## 8 Results

Table 2 shows the signal efficiencies (computed using a sample generated with corresponding  $\tau$  decays), the background expectation and the number of observed events for the six analysis channels.

Having observed no significant deviations in the observed number of events from the expected background, we set upper limits on the production cross section of a new resonance in the ZH final state. We use the  $CL_s$  criterion [46, 47] to extract upper bounds on the cross section, combining all six event categories. The test statistic is a profile likelihood ratio [48] and the systematic uncertainties are treated as nuisance parameters with the frequentist approach. The nuisance parameters are described with log-normal prior probability distribution functions, except for those related to the extrapolation from sideband events, which are expected to follow a  $\Gamma$  distribution [48]. In the all-leptonic and semileptonic channels, the numbers of signal and background events are calculated for a region corresponding to  $\pm 2.5$  times the expected resolution around each mass point in  $m_{ZH}$ , while in the all-hadronic channel we consider the number of expected background, signal and observed events in  $m_{ZH} > 800$  GeV for each mass point. The expected and observed upper limits are shown in Fig. 4. Production cross sections times branching fraction in a range between 0.9 and 27.8 fb, depending on the resonance mass (0.8–2.5 TeV), are excluded at a 95% confidence level.

In Fig. 4, the results from this analysis are also compared to the cross section of the theoretical model, used as benchmark in this paper and studied in Ref. [14]. In this model, the parameters are chosen to be  $g_V = 3$  and  $c_F = -c_H = 1$ , corresponding to a strongly coupled sector. In Fig. 5, a scan of the coupling parameters and the corresponding regions of exclusion in the HVT model are shown. The parameters are defined as  $g_V c_H$  and  $g^2 c_F / g_V$ , related to the coupling strength of the new resonance to the Higgs boson and to fermions. Regions of the plane excluded by this search are indicated by hatched areas. Ranges of the scan are limited by the assumption that the new resonance is narrow.

Table 2: Summary of the signal efficiencies, number of expected background events, and number of observed events for the six  $\tau\tau$  channels. Only statistical uncertainties are included. For the all-leptonic and semileptonic channels, numbers of expected background events and observed events are evaluated for each mass point in  $m_{ZH}$  intervals corresponding to  $\pm 2.5$  times the expected resolution. For the all-hadronic channel we consider the number of expected background, signal, and observed events for  $m_{ZH} > 800$  GeV. When the expected background is zero, the 68% confidence level upper limit is listed.

	Mass (TeV)	$\tau_e\tau_e$	$\tau_e\tau_\mu$	$\tau_\mu\tau_\mu$	$\tau_e\tau_h$	$\tau_\mu\tau_h$	$\tau_h\tau_h$
$\mathcal{B}(\tau\tau)$		3.2%	6.2%	3.0%	23.1%	22.6%	41.9%
$\varepsilon_{\text{sig}}(\%)$	0.8	$2.8 \pm 0.7$	$3.4 \pm 0.5$	$4.2 \pm 0.7$	$3.3 \pm 0.3$	$4.4 \pm 0.3$	$2.2 \pm 0.2$
	0.9	$11 \pm 1$	$16 \pm 1$	$20 \pm 2$	$14.3 \pm 0.5$	$18.7 \pm 0.6$	$11.5 \pm 0.4$
	1.0	$17 \pm 2$	$24 \pm 1$	$38 \pm 2$	$21.2 \pm 0.6$	$29.3 \pm 0.7$	$18.0 \pm 0.5$
	1.2	$26 \pm 2$	$30 \pm 1$	$39 \pm 2$	$28.3 \pm 0.7$	$35.8 \pm 0.7$	$23.0 \pm 0.5$
	1.5	$30 \pm 2$	$42 \pm 2$	$53 \pm 2$	$29.2 \pm 0.8$	$38.1 \pm 0.9$	$29.1 \pm 0.7$
	2.0	$28 \pm 2$	$39 \pm 2$	$56 \pm 3$	$31.1 \pm 0.8$	$39.2 \pm 0.9$	$31.9 \pm 0.7$
	2.5	$27 \pm 2$	$37 \pm 2$	$42 \pm 2$	$26.8 \pm 0.8$	$37.0 \pm 0.8$	$30.1 \pm 0.7$
$N_{\text{bkg}}$	0.8	$0.3 \pm 0.5$	$1.1 \pm 0.8$	$1.6 \pm 1.2$	$6.1 \pm 2.0$	$6.7 \pm 2.1$	
	0.9	$0.5 \pm 0.4$	$1.7 \pm 1.2$	$3.8 \pm 2.1$	$9.8 \pm 3.2$	$9.2 \pm 2.9$	
	1.0	$1.4 \pm 1.4$	$1.7 \pm 1.0$	$2.0 \pm 0.9$	$9.5 \pm 3.5$	$7.6 \pm 2.2$	
	1.2	$1.2 \pm 1.2$	$1.2 \pm 0.8$	$1.4 \pm 0.6$	$5.0 \pm 2.0$	$6.6 \pm 2.3$	$6.1^{+3.2}_{-2.5}$
	1.5	$0.4 \pm 0.4$	$0.07 \pm 0.04$	$0.9 \pm 0.4$	$4.3 \pm 1.8$	$2.6 \pm 0.9$	
	2.0	$<0.5$	$<0.4$	$0.7 \pm 0.4$	$0.1 \pm 0.1$	$<0.4$	
	2.5	$<2.1$	$<0.3$	$0.3 \pm 0.1$	$0.18 \pm 0.05$	$<0.5$	
$N_{\text{obs}}$	0.8	1	1	2	3	10	
	0.9	2	2	3	4	13	
	1.0	2	2	5	2	13	
	1.2	0	1	3	5	12	8
	1.5	0	0	1	2	5	
	2.0	0	1	0	0	0	
	2.5	0	0	0	0	0	

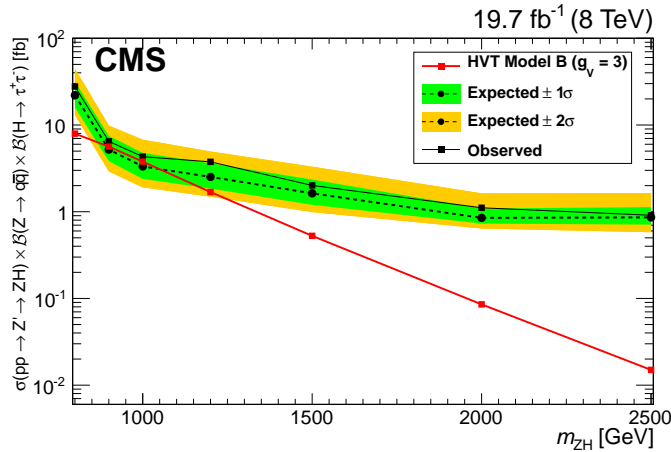


Figure 4: Expected and observed upper limits on the quantity  $\sigma(Z') \mathcal{B}(Z' \rightarrow ZH)$  for the six analysis channels combined. Green and yellow bands correspond to  $\pm 1$  or  $\pm 2\sigma$  variations on the expected upper limit, respectively.

## 9 Summary

The first search for a highly massive ( $\geq 0.8$  TeV) and narrow resonance decaying to Z and H bosons that decay in turn to merged dijet and  $\tau^+\tau^-$  final states has been conducted with data samples collected in 8 TeV proton-proton collisions by the CMS experiment in 2012. For a high-mass resonance decaying to much lighter Z and H bosons, the final state particles must be

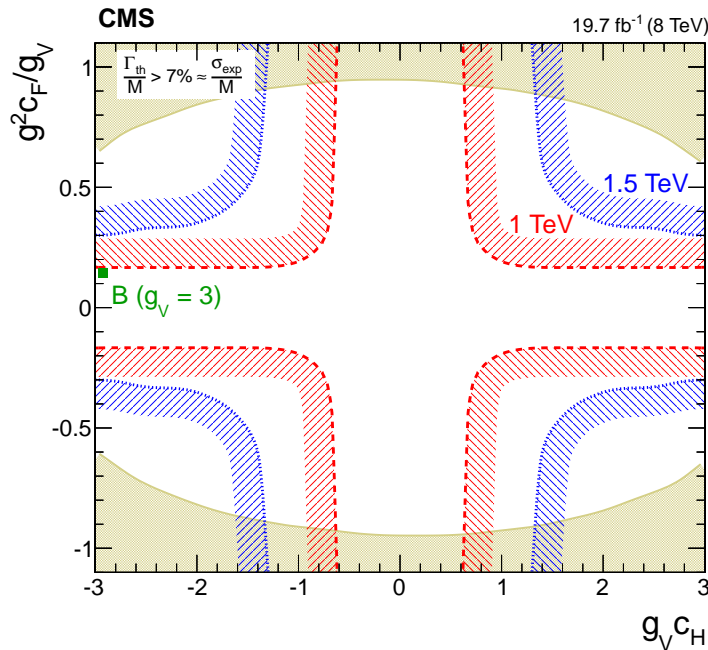


Figure 5: Exclusion regions in the plane of the HVT-model coupling constants ( $g_V c_H$ ,  $g^2 c_F / g_V$ ) for two resonance masses, 1.0 and 1.5 TeV. The point B of the benchmark model used in the analysis is also shown. The boundaries of the regions of the plane excluded by this search are indicated by the dashed and dotted lines, and associated hatching. The areas indicated by the solid line and solid shading correspond to regions where the theoretical width is larger than the experimental resolution of the present search, where the narrow-resonance assumption is not satisfied.

detected and reconstructed in small angular regions. This search was performed by adopting novel and advanced reconstruction techniques to accomplish that end. From a combination of all possible decay modes of the  $\tau$  leptons, production cross sections in a range between 0.9 and 27.8 fb, depending on the resonance mass (0.8–2.5 TeV), are excluded at a 95% confidence level.

## Acknowledgements

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: BMWFW 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, ERC IUT 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); MSIP and NRF (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); MST (Taipei); ThEPCenter, IPST, STAR and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

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

## References

- [1] ATLAS Collaboration, "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC", *Phys. Lett. B* **716** (2012) 1, doi:10.1016/j.physletb.2012.08.020, arXiv:1207.7214.
- [2] CMS Collaboration, "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC", *Phys. Lett. B* **716** (2012) 30, doi:10.1016/j.physletb.2012.08.021, arXiv:1207.7235.
- [3] N. Arkani-Hamed, S. Dimopoulos, and G. Dvali, "The hierarchy problem and new dimensions at a millimeter", *Phys. Lett. B* **429** (1998) 263, doi:10.1016/S0370-2693(98)00466-3, arXiv:hep-ph/9803315.
- [4] A. Leike, "The phenomenology of extra neutral gauge bosons", *Phys. Rept.* **317** (1999) 143, doi:10.1016/S0370-1573(98)00133-1, arXiv:hep-ph/9805494.
- [5] T. G. Rizzo, "Z' phenomenology and the LHC", (2006). arXiv:hep-ph/0610104.
- [6] R. Contino, D. Marzocca, D. Pappadopulo, and R. Rattazzi, "On the effect of resonances in composite Higgs phenomenology", *JHEP* **10** (2011) 081, doi:10.1007/JHEP10(2011)081, arXiv:1109.1570.
- [7] D. Marzocca, M. Serone, and J. Shu, "General composite Higgs models", *JHEP* **08** (2012) 013, doi:10.1007/JHEP08(2012)013, arXiv:1205.0770.
- [8] ATLAS Collaboration, "Search for WZ resonances in the fully leptonic channel using pp collisions at  $\sqrt{s} = 8$  TeV with the ATLAS detector", *Phys. Lett. B* **737** (2014) 223, doi:10.1016/j.physletb.2014.08.039, arXiv:1406.4456.
- [9] ATLAS Collaboration, "Search for resonant diboson production in the  $\ell\ell q\bar{q}$  final state in pp collisions at  $\sqrt{s} = 8$  TeV with the ATLAS detector", (2014). arXiv:1409.6190.
- [10] ATLAS Collaboration, "Search For Higgs Boson Pair Production in the  $\gamma\gamma b\bar{b}$  Final State using pp Collision Data at  $\sqrt{s} = 8$  TeV from the ATLAS Detector", (2014). arXiv:1406.5053.

- [11] CMS Collaboration, “Search for massive resonances decaying into pairs of boosted bosons in semi-leptonic final states at  $\sqrt{s} = 8$  TeV”, *JHEP* **08** (2014) 174, doi:10.1007/JHEP08(2014)174, arXiv:1405.3447.
- [12] CMS Collaboration, “Search for massive resonances in dijet systems containing jets tagged as W or Z boson decays in pp collisions at  $\sqrt{s} = 8$  TeV”, *JHEP* **08** (2014) 173, doi:10.1007/JHEP08(2014)173, arXiv:1405.1994.
- [13] CMS Collaboration, “Search for new resonances decaying via WZ to leptons in proton-proton collisions at  $\sqrt{s} = 8$  TeV”, *Phys. Lett. B* **740** (2014) 83, doi:10.1016/j.physletb.2014.11.026, arXiv:1407.3476.
- [14] D. Pappadopulo, A. Thamm, R. Torre, and A. Wulzer, “Heavy Vector Triplets: Bridging Theory and Data”, (2014). arXiv:1402.4431.
- [15] M. Schmaltz and C. Spethmann, “Two simple W’ models for the early LHC”, *JHEP* **07** (2011) 046, doi:10.1007/JHEP07(2011)046, arXiv:1011.5918.
- [16] B. Bellazzini et al., “Composite Higgs sketch”, *JHEP* **11** (2012) 003, doi:10.1007/JHEP11(2012)003, arXiv:1205.4032.
- [17] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [18] J. Alwall et al., “MadGraph 5: going beyond”, *JHEP* **06** (2011) 128, doi:10.1007/JHEP06(2011)128, arXiv:1106.0522.
- [19] C. Duhr, “Hidden Abelian Higgs Model”, 2011.
- [20] T. Sjöstrand, S. Mrenna, and P. Skands, “PYTHIA 6.4 physics and manual”, *JHEP* **05** (2006) 026, doi:10.1088/1126-6708/2006/05/026, arXiv:hep-ph/0603175.
- [21] P. Nason, “A New method for combining NLO QCD with shower Monte Carlo algorithms”, *JHEP* **11** (2004) 040, doi:10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.
- [22] S. Frixione, P. Nason, and C. Oleari, “Matching NLO QCD computations with parton shower simulations: the POWHEG method”, *JHEP* **11** (2007) 070, doi:10.1088/1126-6708/2007/11/070, arXiv:0709.2092.
- [23] S. Alioli, P. Nason, C. Oleari, and E. Re, “A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX”, *JHEP* **06** (2010) 043, doi:10.1007/JHEP06(2010)043, arXiv:1002.2581.
- [24] S. Alioli, S.-O. Moch, and P. Uwer, “Hadronic top-quark pair-production with one jet and parton showering”, *JHEP* **01** (2012) 137, doi:10.1007/JHEP01(2012)137, arXiv:1110.5251.
- [25] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [26] CMS Collaboration, “Particle-Flow Event Reconstruction in CMS and Performance for Jets, Taus, and  $E_T^{\text{miss}}$ ”, CMS Physics Analysis Summary CMS-PAS-PFT-09-001, CERN, 2009.

- [27] CMS Collaboration, “Commissioning of the Particle-flow Event Reconstruction with the first LHC collisions recorded in the CMS detector”, CMS Physics Analysis Summary CMS-PAS-PFT-10-001, 2010.
- [28] CMS Collaboration, “Determination of jet energy calibration and transverse momentum resolution in CMS”, *JINST* **6** (2011) 11002, doi:10.1088/1748-0221/6/11/P11002, arXiv:1107.4277.
- [29] CMS Collaboration, “Performance of Missing Transverse Momentum Reconstruction Algorithms in Proton-Proton Collisions at  $\sqrt{s} = 8$  TeV with the CMS Detector”, CMS Physics Analysis Summary CMS-PAS-JME-12-002, CERN, 2012.
- [30] M. Wobisch and T. Wengler, “Hadronization corrections to jet cross-sections in deep inelastic scattering”, (1998). arXiv:hep-ph/9907280.
- [31] J. Thaler and K. Van Tilburg, “Identifying boosted objects with N-subjettiness”, *JHEP* **03** (2011) 015, doi:10.1007/JHEP03(2011)015, arXiv:1011.2268.
- [32] S. Catani, Y. L. Dokshitzer, M. H. Seymour, and B. R. Webber, “Longitudinally invariant anti- $k_t$  clustering algorithms for hadron-hadron collisions”, *Nucl. Phys. B* **406** (1993) 187, doi:10.1016/0550-3213(93)90166-M.
- [33] S. D. Ellis and D. E. Soper, “Successive combination jet algorithm for hadron collisions”, *Phys. Rev. D* **48** (1993) 3160, doi:10.1103/PhysRevD.48.3160, arXiv:hep-ph/9305266.
- [34] CMS Collaboration, “Identification techniques for highly boosted W bosons that decay into hadrons”, *JHEP* **12** (2014) 017, doi:10.1007/JHEP12(2014)017, arXiv:1410.4227.
- [35] S. Baffioni et al., “Electron reconstruction in CMS”, *Eur. Phys. J. C* **49** (2007) 1099, doi:10.1140/epjc/s10052-006-0175-5.
- [36] CMS Collaboration, “Performance of CMS muon reconstruction in pp collision events at  $\sqrt{s} = 7$  TeV”, *JINST* **7** (2012) P10002, doi:10.1088/1748-0221/7/10/P10002, arXiv:1206.4071.
- [37] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- $k_t$  jet clustering algorithm”, *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
- [38] CMS Collaboration, “Performance of tau-lepton reconstruction and identification in CMS”, *JINST* **7** (2012) P01001, doi:10.1088/1748-0221/7/01/P01001, arXiv:1109.6034.
- [39] J. M. Butterworth, A. R. Davison, M. Rubin, and G. P. Salam, “Jet substructure as a new Higgs search channel at the LHC”, *Phys. Rev. Lett.* **100** (2008) 242001, doi:10.1103/PhysRevLett.100.242001, arXiv:0802.2470.
- [40] CMS Collaboration, “Evidence for the 125 GeV Higgs boson decaying to a pair of  $\tau$  leptons”, *JHEP* **05** (2014) 104, doi:10.1007/JHEP05(2014)104, arXiv:1401.5041.
- [41] CMS Collaboration, “Identification of b-quark jets with the CMS experiment”, *JINST* **8** (2013) P04013, doi:10.1088/1748-0221/8/04/P04013, arXiv:1211.4462.



- [42] G. Punzi, "Sensitivity of searches for new signals and its optimization", in *PhyStat2003: Statistical Problems in Particle Physics, Astrophysics, and Cosmology*, L. Lyons, R. P. Mount, and R. Reitmeyer, eds. 2003. [arXiv:physics/0308063v2](https://arxiv.org/abs/physics/0308063v2).
- [43] CMS Collaboration, "CMS Luminosity Based on Pixel Cluster Counting - Summer 2013 Update", CMS Physics Analysis Summary CMS-PAS-LUM-13-001, 2013.
- [44] CMS Collaboration, "Electron Reconstruction and Identification at  $\sqrt{s} = 7$  TeV", CMS Physics Analysis Summary CMS-PAS-EGM-10-004, CERN, 2010.
- [45] CMS Collaboration, "Identifying Hadronically Decaying Vector Bosons Merged into a Single Jet", CMS Physics Analysis Summary CMS-PAS-JME-13-006, CERN, 2013.
- [46] A. L. Read, "Presentation of search results: The  $CL_s$  technique", *J. Phys. G* **28** (2002) 2693, [doi:10.1088/0954-3899/28/10/313](https://doi.org/10.1088/0954-3899/28/10/313).
- [47] T. Junk, "Confidence level computation for combining searches with small statistics", *Nucl. Instrum. Meth. A* **434** (1999) 435, [doi:10.1016/S0168-9002\(99\)00498-2](https://doi.org/10.1016/S0168-9002(99)00498-2), [arXiv:hep-ex/9902006](https://arxiv.org/abs/hep-ex/9902006).
- [48] ATLAS and CMS Collaborations, "Procedure for the LHC Higgs boson search combination in summer 2011", Technical Report ATL-PHYS-PUB-2011-011, CMS-NOTE-2011-005, CERN, 2011.



## A The CMS Collaboration

### Yerevan Physics Institute, Yerevan, Armenia

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

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

W. Adam, T. Bergauer, M. Dragicevic, J. Erö, 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. Rabadý<sup>2</sup>, B. Rahbaran, H. Rohringer, R. Schöfbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz<sup>1</sup>

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

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

### Universiteit Antwerpen, Antwerpen, Belgium

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

### Vrije Universiteit Brussel, Brussel, Belgium

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

### Université Libre de Bruxelles, Bruxelles, Belgium

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

### Ghent University, Ghent, Belgium

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

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

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

### Université de Mons, Mons, Belgium

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

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

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

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

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

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

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

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

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

**University of Sofia, Sofia, Bulgaria**

A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

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

J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, T. Cheng, R. Du, C.H. Jiang, R. Plestina<sup>7</sup>, F. Romeo, J. Tao, Z. Wang

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

C. Asawatangtrakuldee, Y. Ban, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu, F. Zhang<sup>8</sup>, L. Zhang, W. Zou

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

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

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

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

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

Z. Antunovic, M. Kovac

**Institute Rudjer Boskovic, Zagreb, Croatia**

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

**University of Cyprus, Nicosia, Cyprus**

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

**Charles University, Prague, Czech Republic**

M. Bodlak, M. Finger, M. Finger Jr.<sup>9</sup>

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

Y. Assran<sup>10</sup>, S. Elgammal<sup>11</sup>, A. Ellithi Kamel<sup>12</sup>, A. Radi<sup>11,13</sup>

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

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

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

P. Eerola, M. Voutilainen

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

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

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

J. Talvitie, T. Tuuva

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

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

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

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

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

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

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

S. Gadrat

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

S. Beauceron, N. Beaupere, C. Bernet<sup>7</sup>, G. Boudoul<sup>2</sup>, E. Bouvier, S. Brochet, C.A. Carrillo Montoya, J. Chasserat, R. Chierici, D. Contardo<sup>2</sup>, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, J.D. Ruiz Alvarez, D. Sabes, L. Sgandurra, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret, H. Xiao

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

Z. Tsamalaidze<sup>9</sup>

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

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

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

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

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

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

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

M. Aldaya Martin, I. Asin, N. Bartosik, J. Behr, U. Behrens, A.J. Bell, A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, S. Choudhury, F. Costanza, C. Diez Pardos, G. Dolinska, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, T. Eichhorn, G. Flucke, J. Garay Garcia, A. Geiser, A. Gizhko, P. Gunnellini, J. Hauk, M. Hempel<sup>15</sup>, H. Jung, A. Kalogeropoulos, O. Karacheban<sup>15</sup>, M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol,

D. Krücker, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann<sup>15</sup>, B. Lutz, R. Mankel, I. Marfin<sup>15</sup>, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, S. Naumann-Emme, A. Nayak, E. Ntomari, H. Perrey, D. Pitzl, R. Placakyte, A. Raspereza, P.M. Ribeiro Cipriano, B. Roland, E. Ron, M.Ö. Sahin, J. Salfeld-Nebgen, P. Saxena, T. Schoerner-Sadenius, M. Schröder, C. Seitz, S. Spannagel, A.D.R. Vargas Trevino, R. Walsh, C. Wissing

**University of Hamburg, Hamburg, Germany**

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

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

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

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

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

**University of Athens, Athens, Greece**

A. Agapitos, S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Stiliaris, E. Tziaferi

**University of Ioánnina, Ioánnina, Greece**

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

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

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

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

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

**University of Debrecen, Debrecen, Hungary**

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

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

S.K. Swain

**Panjab University, Chandigarh, India**

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

**University of Delhi, Delhi, India**

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

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

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

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

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

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

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

**Indian Institute of Science Education and Research (IISER), Pune, India**

S. Sharma

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

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

**University College Dublin, Dublin, Ireland**

M. Felcini, M. Grunewald

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

M. Abbrescia<sup>a,b</sup>, C. Calabria<sup>a,b</sup>, S.S. Chhibra<sup>a,b</sup>, A. Colaleo<sup>a</sup>, D. Creanza<sup>a,c</sup>, L. Cristella<sup>a,b</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>, A. Sharma<sup>a</sup>, L. Silvestris<sup>a,2</sup>, R. Venditti<sup>a,b</sup>, P. Verwilligen<sup>a</sup>

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

G. Abbiendi<sup>a</sup>, A.C. Benvenuti<sup>a</sup>, D. Bonacorsi<sup>a,b</sup>, S. Braibant-Giacomelli<sup>a,b</sup>, L. Brigliadori<sup>a,b</sup>, R. Campanini<sup>a,b</sup>, P. Capiluppi<sup>a,b</sup>, A. Castro<sup>a,b</sup>, F.R. Cavallo<sup>a</sup>, G. Codispoti<sup>a,b</sup>, M. Cuffiani<sup>a,b</sup>, G.M. Dallavalle<sup>a</sup>, F. Fabbri<sup>a</sup>, A. Fanfani<sup>a,b</sup>, D. Fasanella<sup>a,b</sup>, P. Giacomelli<sup>a</sup>, C. Grandi<sup>a</sup>, L. Guiducci<sup>a,b</sup>, S. Marcellini<sup>a</sup>, G. Masetti<sup>a</sup>, A. Montanari<sup>a</sup>, F.L. Navarria<sup>a,b</sup>, A. Perrotta<sup>a</sup>, A.M. Rossi<sup>a,b</sup>, T. Rovelli<sup>a,b</sup>, G.P. Siroli<sup>a,b</sup>, N. Tosi<sup>a,b</sup>, R. Travaglini<sup>a,b</sup>

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

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

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

G. Barbagli<sup>a</sup>, V. Ciulli<sup>a,b</sup>, C. Civinini<sup>a</sup>, R. D'Alessandro<sup>a,b</sup>, E. Focardi<sup>a,b</sup>, E. Gallo<sup>a</sup>, S. Gozzi<sup>a,b</sup>, V. Gori<sup>a,b</sup>, P. Lenzi<sup>a,b</sup>, M. Meschini<sup>a</sup>, S. Paoletti<sup>a</sup>, G. Sguazzoni<sup>a</sup>, A. Tropiano<sup>a,b</sup>

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

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

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

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

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

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

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

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

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

P. Azzi<sup>a</sup>, N. Bacchetta<sup>a</sup>, M. Bellato<sup>a</sup>, D. Bisello<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>, F. Fanzago<sup>a</sup>, F. Gasparini<sup>a,b</sup>, U. Gasparini<sup>a,b</sup>, A. Gozzelino<sup>a</sup>, S. Lacaprara<sup>a</sup>, M. Margoni<sup>a,b</sup>, A.T. Meneguzzo<sup>a,b</sup>, J. Pazzini<sup>a,b</sup>, N. Pozzobon<sup>a,b</sup>, P. Ronchese<sup>a,b</sup>, F. Simonetto<sup>a,b</sup>, E. Torassa<sup>a</sup>, M. Tosi<sup>a,b</sup>, P. Zotto<sup>a,b</sup>, A. Zucchetta<sup>a,b</sup>, G. Zumerle<sup>a,b</sup>

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

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

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

M. Biasini<sup>a,b</sup>, G.M. Bilei<sup>a</sup>, D. Ciangottini<sup>a,b,2</sup>, L. Fanò<sup>a,b</sup>, P. Lariccia<sup>a,b</sup>, G. Mantovani<sup>a,b</sup>, M. Menichelli<sup>a</sup>, A. Saha<sup>a</sup>, A. Santocchia<sup>a,b</sup>, A. Spiezia<sup>a,b,2</sup>

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

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

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

L. Barone<sup>a,b</sup>, F. Cavallari<sup>a</sup>, G. D'imperio<sup>a,b</sup>, D. Del Re<sup>a,b</sup>, M. Diemoz<sup>a</sup>, 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>, 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</sup>, P. Traczyk<sup>a,b,2</sup>

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

N. Amapane<sup>a,b</sup>, R. Arcidiacono<sup>a,c</sup>, S. Argiro<sup>a,b</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>, R. Covarelli, A. Degano<sup>a,b</sup>, N. Demaria<sup>a</sup>, L. Finco<sup>a,b,2</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</sup>, L. Pacher<sup>a,b</sup>, N. Pastrone<sup>a</sup>, M. Pelliccioni<sup>a</sup>, G.L. Pinna Angioni<sup>a,b</sup>, A. Potenza<sup>a,b</sup>, A. Romero<sup>a,b</sup>, M. Ruspa<sup>a,c</sup>, R. Sacchi<sup>a,b</sup>, A. Solano<sup>a,b</sup>, A. Staiano<sup>a</sup>, U. Tamponi<sup>a</sup>

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

S. Belforte<sup>a</sup>, V. Candelise<sup>a,b,2</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>, A. Schizzi<sup>a,b</sup>, T. Umer<sup>a,b</sup>, A. Zanetti<sup>a</sup>

**Kangwon National University, Chunchon, Korea**

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

**Kyungpook National University, Daegu, Korea**

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

**Chonbuk National University, Jeonju, Korea**

T.J. Kim, M.S. Ryu

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

J.Y. Kim, D.H. Moon, S. Song



**Korea University, Seoul, Korea**

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

**Seoul National University, Seoul, Korea**

H.D. Yoo

**University of Seoul, Seoul, Korea**

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

**Sungkyunkwan University, Suwon, Korea**

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

**Vilnius University, Vilnius, Lithuania**

A. Juodagalvis

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

J.R. Komaragiri, M.A.B. Md Ali<sup>28</sup>, W.A.T. Wan Abdullah

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

E. Casimiro Linares, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, A. Hernandez-Almada, R. Lopez-Fernandez, A. Sanchez-Hernandez

**Universidad Iberoamericana, Mexico City, Mexico**

S. Carrillo Moreno, F. Vazquez Valencia

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

I. Pedraza, H.A. Salazar Ibarguen

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

A. Morelos Pineda

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

D. Krofcheck

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

P.H. Butler, S. Reucroft

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

V. Andreev, M. Azarkin<sup>31</sup>, I. Dremin<sup>31</sup>, M. Kirakosyan, A. Leonidov<sup>31</sup>, G. Mesyats, S.V. Rusakov, A. Vinogradov

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

A. Belyaev, E. Boos, M. Dubinin<sup>32</sup>, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

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

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

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

P. Adzic<sup>33</sup>, M. Ekmedzic, J. Milosevic, V. Rekovic

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

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

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

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

**Universidad de Oviedo, Oviedo, Spain**

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

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

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, G. Gomez, A. Graziano, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, R. Vilar Cortabitarte

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

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, A. Benaglia, J. Bendavid, L. Benhabib, J.F. Benitez, P. Bloch, A. Bocci, A. Bonato, O. Bondu, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, S. Colafranceschi<sup>34</sup>, M. D'Alfonso, D. d'Enterria, A. Dabrowski, A. David, F. De Guio, A. De Roeck, S. De Visscher, E. Di Marco, M. Dobson,

M. Dordevic, B. Dorney, N. Dupont-Sagorin, A. Elliott-Peisert, 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, S. Orfanelli, L. Orsini, L. Pape, E. Perez, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pimiä, D. Piparo, M. Plagge, A. Racz, G. Rolandi<sup>35</sup>, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas<sup>36</sup>, D. Spiga, J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Tsirou, G.I. Veres<sup>17</sup>, N. Wardle, H.K. Wöhri, H. Wollny, W.D. Zeuner

**Paul Scherrer Institut, Villigen, Switzerland**

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

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

F. Bachmair, L. Bäni, L. Bianchini, M.A. Buchmann, B. Casal, N. Chanon, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, P. Eller, C. Grab, D. Hits, J. Hoss, G. Kasieczka, W. Lustermann, B. Mangano, A.C. Marini, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, D. Meister, N. Mohr, P. Musella, C. Nägeli<sup>37</sup>, F. Nessi-Tedaldi, F. Pandolfi, F. Pauss, L. Perrozzi, M. Peruzzi, M. Quitnat, L. Rebane, M. Rossini, A. Starodumov<sup>38</sup>, M. Takahashi, K. Theofilatos, R. Wallny, H.A. Weber

**Universität Zürich, Zurich, Switzerland**

C. AMSLER<sup>39</sup>, M.F. Canelli, V. Chiochia, A. De Cosa, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, J. Ngadiuba, D. Pinna, P. Robmann, F.J. Ronga, S. Taroni, Y. Yang

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

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

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

P. Chang, Y.H. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, U. Grundler, W.-S. Hou, Y.F. Liu, R.-S. Lu, M. Miñano Moya, E. Petrakou, J.F. Tsai, Y.M. Tzeng, R. Wilken

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

B. Asavapibhop, G. Singh, N. Srimanobhas, N. Suwonjandee

**Cukurova University, Adana, Turkey**

A. Adiguzel, M.N. Bakirci<sup>40</sup>, S. Cerci<sup>41</sup>, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal<sup>42</sup>, A. Kayis Topaksu, G. Onengut<sup>43</sup>, K. Ozdemir<sup>44</sup>, S. Ozturk<sup>40</sup>, A. Polatoz, D. Sunar Cerci<sup>41</sup>, B. Tali<sup>41</sup>, H. Topakli<sup>40</sup>, M. Vergili, C. Zorbilmez

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

I.V. Akin, B. Bilin, S. Bilmis, H. Gamsizkan<sup>45</sup>, B. Isildak<sup>46</sup>, G. Karapinar<sup>47</sup>, K. Ocalan<sup>48</sup>, S. Sekmen, U.E. Surat, M. Yalvac, M. Zeyrek

**Bogazici University, Istanbul, Turkey**

E.A. Albayrak<sup>49</sup>, E. Gülmez, M. Kaya<sup>50</sup>, O. Kaya<sup>51</sup>, T. Yetkin<sup>52</sup>

**Istanbul Technical University, Istanbul, Turkey**

K. Cankocak, F.I. Vardarli

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

L. Levchuk, P. Sorokin

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

J.J. Brooke, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, Z. Meng, D.M. Newbold<sup>53</sup>, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, S. Senkin, V.J. Smith

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

K.W. Bell, A. Belyaev<sup>54</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, T. Williams, W.J. Womersley, S.D. Worm

**Imperial College, London, United Kingdom**

M. Baber, R. Bainbridge, O. Buchmuller, D. Burton, D. Colling, N. Cripps, P. Dauncey, G. Davies, M. Della Negra, P. Dunne, A. Elwood, W. Ferguson, J. Fulcher, D. Futyan, G. Hall, G. Iles, M. Jarvis, G. Karapostoli, M. Kenzie, R. Lane, R. Lucas<sup>53</sup>, L. Lyons, A.-M. Magnan, S. Malik, B. Mathias, J. Nash, A. Nikitenko<sup>38</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, S.C. Zenz

**Brunel University, Uxbridge, United Kingdom**

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

**Baylor University, Waco, USA**

J. Dittmann, K. Hatakeyama, A. Kasmi, H. Liu, N. Pastika, T. Scarborough, Z. Wu

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

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

**Boston University, Boston, USA**

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

**Brown University, Providence, USA**

J. Alimena, E. Berry, S. Bhattacharya, G. Christopher, D. Cutts, Z. Demiragli, N. Dhingra, A. Ferapontov, A. Garabedian, U. Heintz, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Sagir, T. Sinthuprasith, T. Speer, J. Swanson

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

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

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

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

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

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

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

J.G. Branson, G.B. Cerati, S. Cittolin, R.T. D'Agnolo, A. Holzner, R. Kelley, D. Klein, J. Letts, I. Macneill, D. Olivito, S. Padhi, C. Palmer, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, Y. Tu, A. Vartak, C. Welke, F. Würthwein, A. Yagil, G. Zevi Della Porta

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

D. Barge, J. Bradmiller-Feld, C. Campagnari, T. Danielson, A. Dishaw, V. Dutta, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Incandela, C. Justus, N. Mccoll, S.D. Mullin, J. Richman, D. Stuart, W. To, C. West, J. Yoo

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

A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, J. Duarte, A. Mott, H.B. Newman, C. Pena, M. Pierini, M. Spiropulu, J.R. Vlimant, R. Wilkinson, S. Xie, R.Y. Zhu

**Carnegie Mellon University, Pittsburgh, USA**

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

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

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

**Cornell University, Ithaca, USA**

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

**Fairfield University, Fairfield, USA**

D. Winn

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

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, 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, B. Klima, B. Kreis, S. Kwan<sup>†</sup>, J. Linacre, D. Lincoln, R. Lipton, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, J.M. Marraffino, V.I. Martinez Outschoorn, S. Maruyama, D. Mason, P. McBride, P. Merkel, K. Mishra, S. Mrenna, S. Nahn, C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, A. Whitbeck, J. Whitmore, F. Yang

**University of Florida, Gainesville, USA**

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, M. Carver, 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, H. Mei, P. Milenovic<sup>55</sup>, G. Mitselmakher, L. Muniz, A. Rinkevicius, L. Shchutska, M. Snowball, D. Sperka, J. Yelton, M. Zakaria

**Florida International University, Miami, USA**

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

**Florida State University, Tallahassee, USA**

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

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

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

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

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov,

L. Gauthier, C.E. Gerber, D.J. Hofman, P. Kurt, C. O'Brien, I.D. Sandoval Gonzalez, C. Silkworth, P. Turner, N. Varelas

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

B. Bilki<sup>56</sup>, W. Clarida, K. Dilsiz, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya<sup>57</sup>, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok<sup>49</sup>, A. Penzo, R. Rahmat, S. Sen, P. Tan, E. Tiras, J. Wetzel, K. Yi

**Johns Hopkins University, Baltimore, USA**

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

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

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

**Kansas State University, Manhattan, USA**

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

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

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

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

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

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

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

**University of Minnesota, Minneapolis, USA**

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

**University of Mississippi, Oxford, USA**

J.G. Acosta, S. Oliveros

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

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

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

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

**Northeastern University, Boston, USA**

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

**Northwestern University, Evanston, USA**

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

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

A. Brinkerhoff, K.M. Chan, A. Drozdetskiy, M. Hildreth, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, S. Lynch, N. Marinelli, Y. Musienko<sup>29</sup>, T. Pearson, M. Planer, R. Ruchti, G. Smith, N. Valls, M. Wayne, M. Wolf, A. Woodard

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

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

**Princeton University, Princeton, USA**

O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, 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, A. Zuranski

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

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

**Purdue University, West Lafayette, USA**

V.E. Barnes, D. Benedetti, D. Bortoletto, L. Gutay, Z. Hu, M.K. Jha, M. Jones, K. Jung, M. Kress, N. Leonardo, D.H. Miller, N. Neumeister, F. Primavera, B.C. Radburn-Smith, X. Shi, I. Shipsey, D. Silvers, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu, J. Zablocki

**Purdue University Calumet, Hammond, USA**

N. Parashar, J. Stupak

**Rice University, Houston, USA**

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

**University of Rochester, Rochester, USA**

B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, M. Galanti, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, O. Hindrichs, A. Khukhunaishvili, S. Korjenevski, G. Petrillo, M. Verzetti, D. Vishnevskiy

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

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

**Rutgers, The State University of New Jersey, Piscataway, 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, S. Kaplan, A. Lath, S. Panwalkar, M. Park, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

**University of Tennessee, Knoxville, USA**

K. Rose, S. Spanier, A. York

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

O. Bouhali<sup>58</sup>, A. Castaneda Hernandez, M. Dalchenko, M. De Mattia, S. Dildick, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon<sup>59</sup>, V. Khotilovich, V. Krutelyov, R. Montalvo, I. Osipenkov, Y. Pakhotin, R. Patel, A. Perloff, J. Roe, A. Rose, A. Safonov, I. Suarez, A. Tatarinov, K.A. Ulmer

**Texas Tech University, Lubbock, USA**

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

**Vanderbilt University, Nashville, USA**

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

**University of Virginia, Charlottesville, USA**

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

**Wayne State University, Detroit, USA**

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

**University of Wisconsin, Madison, USA**

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

†: Deceased

1: Also at Vienna University of Technology, Vienna, Austria

2: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

3: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

4: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

5: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

6: Also at Universidade Estadual de Campinas, Campinas, Brazil

7: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

8: Also at Université Libre de Bruxelles, Bruxelles, Belgium

9: Also at Joint Institute for Nuclear Research, Dubna, Russia

10: Also at Suez University, Suez, Egypt

11: Also at British University in Egypt, Cairo, Egypt

12: Also at Cairo University, Cairo, Egypt

13: Now at Ain Shams University, Cairo, Egypt

14: Also at Université de Haute Alsace, Mulhouse, France

15: Also at Brandenburg University of Technology, Cottbus, Germany

16: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary

17: Also at Eötvös Loránd University, Budapest, Hungary

18: Also at University of Debrecen, Debrecen, Hungary

19: Also at University of Visva-Bharati, Santiniketan, India

20: Now at King Abdulaziz University, Jeddah, Saudi Arabia

21: Also at University of Ruhuna, Matara, Sri Lanka

22: Also at Isfahan University of Technology, Isfahan, Iran

23: Also at University of Tehran, Department of Engineering Science, Tehran, Iran

24: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran

25: Also at Università degli Studi di Siena, Siena, Italy

26: Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France

27: Also at Purdue University, West Lafayette, USA

28: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia

29: Also at Institute for Nuclear Research, Moscow, Russia

30: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia



- 
- 31: Also at National Research Nuclear University &quot;Moscow Engineering Physics Institute&quot; (MEPhI), Moscow, Russia
- 32: Also at California Institute of Technology, Pasadena, USA
- 33: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 34: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
- 35: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 36: Also at University of Athens, Athens, Greece
- 37: Also at Paul Scherrer Institut, Villigen, Switzerland
- 38: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 39: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
- 40: Also at Gaziosmanpasa University, Tokat, Turkey
- 41: Also at Adiyaman University, Adiyaman, Turkey
- 42: Also at Mersin University, Mersin, Turkey
- 43: Also at Cag University, Mersin, Turkey
- 44: Also at Piri Reis University, Istanbul, Turkey
- 45: Also at Anadolu University, Eskisehir, Turkey
- 46: Also at Ozyegin University, Istanbul, Turkey
- 47: Also at Izmir Institute of Technology, Izmir, Turkey
- 48: Also at Necmettin Erbakan University, Konya, Turkey
- 49: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 50: Also at Marmara University, Istanbul, Turkey
- 51: Also at Kafkas University, Kars, Turkey
- 52: Also at Yildiz Technical University, Istanbul, Turkey
- 53: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 54: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 55: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 56: Also at Argonne National Laboratory, Argonne, USA
- 57: Also at Erzincan University, Erzincan, Turkey
- 58: Also at Texas A&M University at Qatar, Doha, Qatar
- 59: Also at Kyungpook National University, Daegu, Korea