Search for new light gauge bosons in Higgs boson decays to four-lepton final states in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector at the LHC

G. Aad et al.*
(Atlas Collaboration)

(Received 29 May 2015; published 3 November 2015)

I. INTRODUCTION

Hidden sector or dark sector states appear in many extensions to the Standard Model (SM) [1–10], to provide a candidate for the dark matter in the Universe [11] or to explain astrophysical observations of positron excesses [12–14]. A hidden or dark sector can be introduced with an additional $U(1)_d$ dark gauge symmetry [5–10].

In this paper, we present model-independent searches for dark sector states. We then interpret the results in benchmark models where the dark gauge symmetry is mediated by a dark vector boson $Z_d$. The dark sector could couple to the SM through kinetic mixing with the hypercharge gauge boson [15–17]. In this hypercharge portal scenario, the kinetic mixing parameter $\epsilon$ controls the coupling strength of the dark vector boson and SM particles. If, in addition, the $U(1)_d$ symmetry is broken by the introduction of a dark Higgs boson, then there could also be a mixing between the SM $Z$ boson and the dark sector Higgs boson [5–10]. In this scenario, the Higgs portal coupling $\kappa$ controls the strength of the Higgs coupling to dark vector bosons. The observed Higgs boson would then be the lighter partner of the new Higgs doublet, and could also decay via the dark sector. There is an additional Higgs portal scenario where there could be a mass-mixing between the SM $Z$ boson and $Z_d$ [7,8]. In this scenario, the dark vector boson $Z_d$ may couple to the SM $Z$ boson with a coupling proportional to the mass mixing parameter $\delta$.

The presence of the dark sector could be inferred either from deviations from the SM-predicted rates of Drell-Yan (DY) events or from Higgs boson decays through exotic intermediate states. Model-independent upper bounds, from electroweak constraints, on the kinetic mixing parameter of $\epsilon \leq 0.03$ are reported in Refs. [5,18,19] for dark vector boson masses between 1 and 200 GeV. Upper bounds on the kinetic mixing parameter based on searches for dilepton resonances, $pp \to Z_d \to \ell^+\ell^–$, below the $Z$-boson mass are found to be in the range of 0.005–0.020 for dark vector boson masses between 20 and 80 GeV [20]. The discovery of the Higgs boson [21–23] during Run 1 of the Large Hadron Collider (LHC) [24,25] opens a new and rich experimental program that includes the search for exotic decays $H \to ZZ_d \to 4\ell$ and $H \to Z_dZ_d \to 4\ell$. This scenario is not entirely excluded by electroweak constraints [5–10,18,20]. The $H \to ZZ_d$ process probes the parameter space of $\epsilon$ and $m_{Z_d}$, or $\delta$ and $m_{Z_d}$, where $m_{Z_d}$ is the mass of the dark vector boson, and the $H \to Z_dZ_d$ process covers the parameter space of $\kappa$ and $m_{Z_d}$ [5,6]. DY production, $pp \to Z_d \to \ell^+\ell^–$, offers the most promising discovery potential for dark vector bosons in the event of no mixing between the dark Higgs boson and the SM Higgs boson. The $H \to ZZ_d \to 4\ell$ process offers a discovery potential complementary to the DY process for $m_{Z_d} < m_Z$ [5,20]. Both of these would be needed to understand the properties of the dark sector.
of the dark vector boson [5]. If the dark Higgs boson mixes with the SM Higgs boson, the $H \rightarrow Z_dZ_d \rightarrow 4\ell'$ process would be important, probing the dark sector through the Higgs portal coupling [5,6].

This paper presents a search for Higgs bosons decaying to four leptons via one or two $Z_d$ bosons using $pp$ collision data at $\sqrt{s} = 8$ TeV collected at the CERN LHC with the ATLAS experiment. The search uses a data set corresponding to an integrated luminosity of 20.7 fb$^{-1}$ with an uncertainty of 3.6% for $H \rightarrow ZZ_d \rightarrow 4\ell'$ based on the luminosity calibration used in Refs. [26,27], and 20.3 fb$^{-1}$ with an uncertainty of 2.8% for $H \rightarrow Z_dZ_d \rightarrow 4\ell'$ based on a more recent calibration [28]. Same-flavor decays of the $Z$ and $Z_d$ bosons to electron and muon pairs are considered, giving the $4\ell_e$, $2\ell_e\ell_\mu$, and $4\ell_\mu$ final states. Final states including $\tau$ leptons are not considered in the $H \rightarrow ZZ_d \rightarrow 4\ell'$ and $H \rightarrow Z_dZ_d \rightarrow 4\ell'$ decays. In the absence of a significant signal, upper bounds are set on the relative branching ratios $\text{BR}(H \rightarrow ZZ_d \rightarrow 4\ell')/\text{BR}(H \rightarrow 4\ell')$ and $\text{BR}(H \rightarrow Z_dZ_d \rightarrow 4\ell')/\text{BR}(H \rightarrow ZZ \rightarrow 4\ell')$ as functions of the mass of the dark vector boson $m_{Z_d}$. The branching ratio limits are used to set upper bounds on the kinetic mixing, mass mixing, and Higgs boson mixing parameters [5,6]. The search is restricted to the mass range where the $Z_d$ from the decay of the Higgs boson is on-shell, i.e. 15 GeV < $m_{Z_d}$ < $m_H$/2, where $m_H = 125$ GeV. Dark vector boson bosons below 15 GeV are not considered in the present search. Although the low-mass region is theoretically well motivated [7,8], the high $p_T$ of the $Z_d$ boson relative to its mass leads to signatures that are better studied in dedicated searches [29].

The paper is organized as follows. The ATLAS detector is briefly described in Sec. II. The signal and background modeling is summarized in Sec. III. The data set, triggers, and event reconstruction are presented in Sec. IV. Detailed descriptions of the searches are given in Secs. V and VI for $H \rightarrow ZZ_d \rightarrow 4\ell'$ and $H \rightarrow Z_dZ_d \rightarrow 4\ell'$ processes, respectively. Finally, the concluding remarks are presented in Sec. VII.

## II. EXPERIMENTAL SETUP

The ATLAS detector [30] covers almost the whole solid angle around the collision point with layers of tracking detectors, calorimeters and muon chambers. The ATLAS inner detector (ID) has full coverage$^1$ in the azimuthal angle $\phi$ and covers the pseudorapidity range $|\eta| < 2.5$. It consists of a silicon pixel detector, a silicon microstrip detector, and a straw-tube tracker that also measures transition radiation for particle identification, all immersed in a 2 T axial magnetic field produced by a superconducting solenoid.

High-granularity liquid-argon (LAr) electromagnetic sampling calorimeters, with excellent energy and position resolution, cover the pseudorapidity range $|\eta| < 3.2$. The hadronic calorimeter in the range $|\eta| < 1.7$ is provided by a scintillator-tile calorimeter, consisting of a large barrel and two smaller extended barrel cylinders, one on either side of the central barrel. The LAr endcap ($1.5 < |\eta| < 3.2$) and forward sampling calorimeters ($3.1 < |\eta| < 4.9$) provide electromagnetic and hadronic energy measurements.

The muon spectrometer (MS) measures the deflection of muon trajectories with $|\eta| < 2.7$ in a toroidal magnetic field. Over most of the $\eta$-range, precision measurement of the track coordinates in the principal bending direction of the magnetic field is provided by monitored drift tubes. Cathode strip chambers are used in the innermost layer for 2.0 < $|\eta| < 2.7$. The muon spectrometer is also instrumented with dedicated trigger chambers, resistive-plate chambers in the barrel and thin-gap chambers in the end-cap, covering $|\eta| < 2.4$.

The data are collected using an online three-level trigger system [31] that selects events of interest and reduces the event rate from several MHz to about 400 Hz for recording and offline processing.

## III. MONTE CARLO SIMULATION

Samples of Higgs boson production in the gluon fusion (ggF) mode, with $H \rightarrow ZZ_d \rightarrow 4\ell'$ and $H \rightarrow Z_dZ_d \rightarrow 4\ell'$, are generated for $m_H = 125$ GeV and $15 < m_{Z_d} < 60$ GeV (in 5 GeV steps) in MadGraph5 [32] with CTEQ6L1 [33] parton distribution functions (PDF) using the hidden Abelian Higgs model (HAHM) as a benchmark signal model [5,9,10]. Pythia8 [34,35] and Photos [36–38] are used to take into account parton showering, hadronization, and initial- and final-state radiation.

The background processes considered in the $H \rightarrow ZZ_d \rightarrow 4\ell'$ and $H \rightarrow Z_dZ_d \rightarrow 4\ell'$ searches follow those used in the $H \rightarrow ZZ' \rightarrow 4\ell'$ measurements [39], and consist of the following:

1. Higgs boson production via the SM ggF, VBF (vector boson fusion), $WH$, $ZH$, and $ttH$ processes with $H \rightarrow ZZ' \rightarrow 4\ell'$ final states. In the $H \rightarrow Z_dZ_d \rightarrow 4\ell'$ search, these background processes are normalized with the theoretical cross sections, where the Higgs boson production cross sections and decay branching ratios, as well as their uncertainties, are taken from Refs. [40,41]. In the $H \rightarrow ZZ_d \rightarrow 4\ell'$ search, the normalization of $H \rightarrow 4\ell'$ is determined from data. The cross section for the ggF process has been calculated to next-to-leading order (NLO) [42–44] and next-to-next-to-leading order (NNLO) [45–47] in QCD. In addition, QCD
soft-gluon resummations calculated in the next-to-next-to-leading-logarithmic (NNLL) approximation are applied for the ggF process [48]. NLO electroweak (EW) radiative corrections are also applied [49,50]. These results are compiled in Refs. [51–53] assuming factorization between QCD and EW corrections. For the VBF process, full QCD and EW corrections up to NLO [54–56] and approximate NNLO QCD [57] corrections are used to calculate the cross section. The cross sections for the associated WH and ZH production processes are calculated at NLO [58] and at NNLO [59] in QCD, and NLO EW radiative corrections are applied [60]. The cross section for associated Higgs boson production with a $t\bar{t}$ pair is calculated at NLO in QCD [61–64].

The SM ggF and VBF processes producing $H \rightarrow ZZ \rightarrow 4\ell$ backgrounds are modeled with POWHEG, PYTHIA8 and CT10 PDFs [33]. The SM WH, ZH, and $t\bar{t}H$ processes producing $H \rightarrow ZZ \rightarrow 4\ell$ backgrounds are modeled with PYTHIA8 with CT6L1 PDFs.

(ii) SM ZZ$^*$ production. The rate of this background is estimated using simulation normalized to the SM cross section at NLO. The $ZZ^* \rightarrow 4\ell$ background is modeled using simulated samples generated with POWHEG [65] and PYTHIA8 [35] for $gg \rightarrow ZZ^*$, and $gg2ZZ$ [66] and JIMMY [67] for $gg \rightarrow ZZ^*$, and CT10 PDFs for both.

(iii) $Z + \text{jets}$ and $t\bar{t}$. The rates of these background processes are estimated using data-driven methods. However Monte Carlo (MC) simulation is used to understand the systematic uncertainty on the data-driven techniques. The $Z + \text{jets}$ production is modeled with up to five partons using ALPGEN [68] and is divided into two sources: $Z + \text{light-jets}$, which includes $Zc\bar{c}$ in the massless $c$-quark approximation and $Zb\bar{b}$ with $b\bar{b}$ from parton showers; and $Zb\bar{b}$ using matrix-element calculations that take into account the $b$-quark mass. The matching scheme of matrix elements and parton shower evolution (see Ref. [69] and the references therein) is used to remove any double counting of identical jets produced via the matrix-element calculation and the parton shower, but this scheme is not implemented for $b$-jets. Therefore, $b\bar{b}$ pairs with separation $\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} > 0.4$ between the $b$-quarks are taken from the matrix-element calculation, whereas for $\Delta R < 0.4$ the parton-shower $b\bar{b}$ pairs are used. For comparison between data and simulation, the NNLO QCD FEWZ [70,71] and NLO QCD MCFM [72,73] cross-section calculations are used to normalize the simulations for inclusive $Z$ boson and $Zb\bar{b}$ production, respectively. The $t\bar{t}$ background is simulated with MC@NLO-4.06 [74] with parton showers and underlying-event modeling as implemented in HERWIG 6.5.20 [75] and JIMMY. The AUET2C [76] tune for the underlying events is used for $t\bar{t}$ with CT10 PDFs.

(iv) SM WZ and WW production. The rates of these backgrounds are normalized to theoretical calculations at NLO in perturbative QCD [77]. The simulated event samples are produced with SHERPA [78] and CT10 PDFs.

(v) Backgrounds containing $J/\psi$ and $Y$, namely $ZJ/\psi$ and $ZY$. These backgrounds are normalized using the ATLAS measurements described in Ref. [79]. These processes are modeled with PYTHIA8 [35] and CTEQ6L1 PDFs.

Differing pileup conditions (multiple proton-proton interactions in the same or neighboring bunch crossings) as a function of the instantaneous luminosity are taken into account by overlaying simulated minimum-bias events generated with PYTHIA8 onto the hard-scattering process and reweighting them according to the distribution of the mean number of interactions observed in data. The MC generated samples are processed either with a full ATLAS detector simulation [80] based on the GEANT4 program [81] or a fast simulation based on the parametrization of the response to the electromagnetic and hadronic showers in the ATLAS calorimeters [82] and a detailed simulation of other parts of the detector and the trigger system. The results based on the fast simulation are validated against fully simulated samples and the difference is found to be negligible. The simulated events are reconstructed and analyzed with the same procedure as the data, using the same trigger and event selection criteria.

IV. EVENT RECONSTRUCTION

A combination of single-lepton and dilepton triggers is used to select the data samples. The single-electron trigger has a transverse energy ($E_T$) threshold of 25 GeV while the single-muon trigger has a transverse momentum ($p_T$) threshold of 24 GeV. The dielectron trigger has a threshold of $E_T = 12$ GeV for both electrons. In the case of muons, triggers with symmetric thresholds at $p_T = 13$ GeV and asymmetric thresholds at 18 and 8 GeV are used. Finally, electron-muon triggers are used with electron $E_T$ thresholds of 12 or 24 GeV depending on the electron identification requirement, and a muon $p_T$ threshold of 8 GeV. The trigger efficiency for events passing the final selection is above 97% [39] in each of the final states considered.

Data events recorded during periods when significant portions of the relevant detector subsystems were not fully functional are rejected. These requirements are applied independently of the lepton final state. Events in a time window around a noise burst in the calorimeter are removed [83]. Further, all triggered events are required to contain a reconstructed primary vertex formed from at least three tracks, each with $p_T > 0.4$ GeV.
Electron candidates consist of clusters of energy deposited in the electromagnetic calorimeter and associated with ID tracks [84]. The clusters matched to tracks are required to satisfy a set of identification criteria such that the longitudinal and transverse shower profiles are consistent with those expected from electromagnetic showers. The electron transverse momentum is computed from the cluster energy and the track direction at the interaction point. Selected electrons must satisfy $E_T > 7$ GeV and $|\eta| < 2.47$. Each electron must have a longitudinal impact parameter ($z_0$) of less than 10 mm with respect to the reconstructed primary vertex, defined as the vertex with at least three associated tracks with either complete or partial tracks reconstructed in the muon spectrometer [85]. If a complete track is present, the two independent momentum measurements are combined; otherwise the momentum is measured using the ID. The muon reconstruction and identification coverage is extended by using tracks reconstructed in the forward region ($2.5 < |\eta| < 2.7$) of the MS, which is outside the ID coverage. In the center of the barrel region ($|\eta| < 0.1$), where there is no coverage from muon chambers, ID tracks with $p_T > 15$ GeV are identified as muons if their calorimetric energy deposits are consistent with a minimum ionizing particle. Only one muon per event is allowed to be reconstructed in the MS only or identified with the calorimeter. Selected muons must satisfy $p_T > 6$ GeV and $|\eta| < 2.7$. The requirement on the longitudinal impact parameter is the same as for electrons except for the muons reconstructed in the forward region without an ID track. To reject cosmic-ray muons, the impact parameter in the bending plane ($d_0$) is required to be within 1 mm of the primary vertex.

In order to avoid double-counting of leptons, an overlap removal procedure is applied. If two reconstructed electron candidates share the same ID track or are too close to each other in $\eta$ and $\phi$ ($\Delta R < 0.1$), the one with the highest transverse energy deposit in the calorimeter is kept. An electron within $\Delta R = 0.2$ of a muon candidate is removed, and a calorimeter-based reconstructed muon within $\Delta R = 0.2$ of an electron is removed.

Once the leptons have been selected with the aforementioned basic identification and kinematic requirements, events with at least four selected leptons are kept. All possible combinations of four leptons (quadruplets) containing two same-flavor, opposite-charge sign (SFOS) leptons, are made. The selected leptons are ordered by decreasing transverse momentum and the three highest-$p_T$ leptons should have, respectively, $p_T > 20$ GeV, $p_T > 15$ GeV and $p_T > 10$ GeV. It is then required that one (two) leptons match the single-lepton (dilepton) trigger objects. The leptons within each quadruplet are then ordered in SFOS pairs, and denoted 1 to 4, indices 1 and 2 being for the first pair, 3 and 4 for the second pair.

The $H \rightarrow ZZ_d \rightarrow 4\ell$ search is conducted with the same sample of selected 4$\ell$ events as used in Refs. [26,27] with the four-lepton invariant mass requirement of $115 < m_{4\ell} < 130$ GeV. This collection of events is referred to as the 4$\ell$ sample. The invariant mass of the opposite-sign, same-flavor pair closest to the $Z$-boson pole mass of 91.2 GeV [86] is denoted $m_{12}$. The invariant mass of the remaining dilepton pair is defined as $m_{34}$. The $H \rightarrow 4\ell$ yield, denoted $n(H \rightarrow 4\ell)$, is determined by subtracting the relevant backgrounds from the 4$\ell$ sample as shown in Eq. (1):

$$n(H \rightarrow 4\ell) = n(4\ell) - n(ZZ^*) - n(tt) - n(Z + jets). \quad (1)$$

The other backgrounds from $WW$, $WZ$, $ZJ/\psi$ and ZY are negligible and not considered.

The search is performed by inspecting the $m_{34}$ mass spectrum and testing for a local excess consistent with the decay of a narrow $Z_d$ resonance. This is accomplished through a template fit of the $m_{34}$ distribution, using histogram-based templates of the $H \rightarrow ZZ_d \rightarrow 4\ell$ signal and backgrounds. The signal template is obtained from simulation and is described in Sec. V B. The $m_{34}$ distributions and the expected normalizations of the $tt$ and $Z + jets$ backgrounds, along with the $m_{34}$ distributions of the $H \rightarrow ZZ^* \rightarrow 4\ell$ background, as shown in Fig. 1, are determined as described in Sec. V D. The prefit signal and $H \rightarrow ZZ^* \rightarrow 4\ell$ background event yields are set equal to the $H \rightarrow 4\ell$ observed yield given by Eq. (1). The expected yields for the 4$\ell$ sample are shown in Table I.
TABLE I. The estimated prefit background yields of (MC) ZZ\(^*\), (data-driven) \(\bar{t} + Z +\) jets, their sum, the observed 4\(\ell\) event yield and the estimated prefit \(H \rightarrow 4\ell\) contribution in the 4\(\ell\) sample. The \(H \rightarrow 4\ell\) estimate in the last column is obtained as the difference between the observed event yield and the sum of the ZZ\(^*\) and \(\bar{t} + Z +\) jets backgrounds. The prefit \(H \rightarrow ZZ^* \rightarrow 4\ell\) background and \(H \rightarrow ZZ_d \rightarrow 4\ell\) signal events are normalized to the \(H \rightarrow 4\ell\) observed events. The uncertainties are statistical and systematic, respectively. The systematic uncertainties are discussed in Sec. V E. Uncertainties on the \(H \rightarrow 4\ell\) rates do not include the statistical uncertainty from the observed number.

<table>
<thead>
<tr>
<th>Channel</th>
<th>ZZ(^*)</th>
<th>(\bar{t} + Z +) jets</th>
<th>Sum</th>
<th>Observed</th>
<th>(H \rightarrow 4\ell)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4(\mu)</td>
<td>3.1 \pm 0.2 \pm 0.4</td>
<td>0.6 \pm 0.04 \pm 0.2</td>
<td>3.7 \pm 0.04 \pm 0.6</td>
<td>12</td>
<td>8.3 \pm 0.04 \pm 0.6</td>
</tr>
<tr>
<td>4(e)</td>
<td>1.3 \pm 0.2 \pm 0.5</td>
<td>0.8 \pm 0.07 \pm 0.4</td>
<td>2.1 \pm 0.07 \pm 0.9</td>
<td>9</td>
<td>6.9 \pm 0.07 \pm 0.9</td>
</tr>
<tr>
<td>2(\mu)2(e)</td>
<td>1.4 \pm 0.01 \pm 0.3</td>
<td>1.2 \pm 0.10 \pm 0.4</td>
<td>2.6 \pm 0.10 \pm 0.6</td>
<td>7</td>
<td>4.4 \pm 0.10 \pm 0.6</td>
</tr>
<tr>
<td>2(e)2(\mu)</td>
<td>2.1 \pm 0.02 \pm 0.3</td>
<td>0.6 \pm 0.04 \pm 0.2</td>
<td>2.7 \pm 0.10 \pm 0.5</td>
<td>8</td>
<td>5.3 \pm 0.04 \pm 0.5</td>
</tr>
<tr>
<td>all</td>
<td>7.8 \pm 0.04 \pm 1.2</td>
<td>3.2 \pm 0.1 \pm 1.0</td>
<td>11.1 \pm 0.1 \pm 1.8</td>
<td>36</td>
<td>24.9 \pm 0.1 \pm 1.8</td>
</tr>
</tbody>
</table>

In the absence of any significant local excess, the search can be used to constrain a relative branching ratio \(R_B\), defined as

\[
R_B = \frac{\text{BR}(H \rightarrow ZZ_d \rightarrow 4\ell)}{\text{BR}(H \rightarrow 4\ell)} = \frac{\text{BR}(H \rightarrow ZZ_d \rightarrow 4\ell)}{\text{BR}(H \rightarrow ZZ_d \rightarrow 4\ell) + \text{BR}(H \rightarrow ZZ^* \rightarrow 4\ell)}, \tag{2}
\]

where \(R_B\) is zero in the Standard Model. A likelihood function \(\mathcal{L}\) is defined as a product of Poisson probability densities \(\mathcal{P}\) in each bin \(i\) of the \(m_{34}\) distribution, and is used to obtain a measurement of \(R_B\):

\[
\mathcal{L}(\rho, \mu_H, \nu) = \prod_{i=1}^{N_{\text{bins}}} \mathcal{P}(n_i^{\text{obs}} | n_i^{\text{exp}}) = \prod_{i=1}^{N_{\text{bins}}} \mathcal{P}(n_i^{\text{obs}} | \mu_H \times (n_i^{Z^*} + \rho \times n_i^{Z_d}) + b_i(\nu)), \tag{3}
\]

where \(\mu_H\) is the normalization of the \(H \rightarrow ZZ^* \rightarrow 4\ell\) background (and allowed to float in the fit), \(\rho\) the parameter of interest related to the \(H \rightarrow ZZ_d \rightarrow 4\ell\) normalization and \(\rho \times \mu_H\) the normalization of the \(H \rightarrow ZZ_d \rightarrow 4\ell\) signal. The symbol \(\nu\) represents the systematic uncertainties on the background estimates that are treated as nuisance parameters, and \(N_{\text{bins}}\) the total number of bins of the \(m_{34}\) distribution. The likelihood to observe the yield in some bin, \(n_i^{\text{obs}}\), given the expected yield \(n_i^{\text{exp}}\) is then a function of the expected yields \(n(H \rightarrow 4\ell)\) of \(H \rightarrow ZZ_d \rightarrow 4\ell\) (\(\mu_H \times \rho \times n_i^{Z_d}\)) and \(H \rightarrow ZZ^* \rightarrow 4\ell\) (\(\mu_H \times n_i^{Z^*}\)), and the contribution of backgrounds \(b_i(\nu)\).

An upper bound on \(\rho\) is obtained from the binned likelihood fit to the data, and used in Eq. (2) to obtain a measurement of \(R_B\), taking into account the detector acceptance (\(A\)) and reconstruction efficiency (\(\epsilon\)):

\[
R_B = \frac{\rho \times \mu_H \times n(H \rightarrow 4\ell)}{\rho \times \mu_H \times n(H \rightarrow 4\ell) + C \times \mu_H \times n(H \rightarrow 4\ell) + \mu_H \times \rho \times n(Z_d) + \rho \times \mu_H \times n(Z^*) + b(\nu)} = \frac{\rho}{\rho + C}, \tag{4}
\]

where \(C\) is the ratio of the products of the acceptances and reconstruction efficiencies in \(H \rightarrow ZZ_d \rightarrow 4\ell\) and \(H \rightarrow ZZ^* \rightarrow 4\ell\) events:

\[
C = \frac{A_{ZZ_d} \times \epsilon_{ZZ_d}}{A_{ZZ^*} \times \epsilon_{ZZ}}. \tag{5}
\]

The acceptance is defined as the fraction of generated events that are within a fiducial region. The reconstruction efficiency is defined as the fraction of events within the fiducial region that are reconstructed and selected as part of the 4\(\ell\) signal sample.

**B. Signal modeling**

A signal would produce a narrow peak in the \(m_{34}\) mass spectrum. The width of the \(m_{34}\) peak for the \(Z_d\) signal is dominated by detector resolution for all \(Z_d\) masses considered. For the individual decay channels and their combination, the resolutions of the \(m_{34}\) distributions are determined from Gaussian fits. The \(m_{34}\) resolutions show a linear trend between \(m_{Z_d} = 15\) GeV and \(m_{Z_d} = 55\) GeV and vary from 0.3 to 1.5 GeV, respectively, for the combination of all the final states. The resolutions of the \(m_{34}\) distributions are smaller than the mass spacing between the generated signal samples (5 GeV), requiring an interpolation to probe intermediate values of \(m_{Z_d}\). Histogram-based templates are used to model the \(Z_d\) signal where no simulation is available; these templates are obtained from morphed signals produced with the procedure defined in Ref. [87]. The morphed signal templates are generated with a mass spacing of 1 GeV.

The acceptances and reconstruction efficiencies of the \(H \rightarrow ZZ_d \rightarrow 4\ell\) signal and \(H \rightarrow ZZ^* \rightarrow 4\ell\) background are used in Eqs. (4) and (5) to obtain the measurement of the relative branching ratio \(R_B\). The acceptances and
efficiencies are derived with $H \rightarrow ZZ_d \rightarrow 4\ell$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ MC samples where the Higgs boson is produced via ggF. The product of acceptance and reconstruction efficiency for VBF differs from ggF by only 1.2% and the contribution of $VH$ and $t\bar{t}H$ production modes is negligible: the products of acceptance and reconstruction efficiency obtained using the ggF production mode are used also for VBF, VH and $t\bar{t}H$.

C. Event selection

The Higgs boson candidate is formed by selecting two pairs of SFOS leptons. The value of $m_{12}$ is required to be between 50 and 106 GeV. The value of $m_{34}$ is required to be in the range 12 GeV $\leq m_{34} \leq 115$ GeV. The four-lepton invariant mass $m_{4\ell}$ is required to be in the range $115 < m_{4\ell} < 130$ GeV. After applying the selection to the 8 TeV data sample, 36 events are left as shown in Table I. The events are grouped into four channels based on the flavor of the reconstructed leptons. Events with four electrons are in the $4e$ channel. Events in which the Z boson is reconstructed with electrons, and $m_{34}$ is from muons, are in the $2e2\mu$ channel. Similarly, events in which the Z is reconstructed from muons and $m_{34}$ is from electrons are in the $2\mu2e$ channel. Events with four muons are in the $4\mu$ channel.

D. Background estimation

The search is performed using the same background estimation strategy as the $H \rightarrow ZZ^* \rightarrow 4\ell$ measurements. The expected rates of the $t\bar{t}$ and $Z + \text{jets}$ backgrounds are estimated using data-driven methods as described in detail in Refs. [26,27]. The results of the expected $t\bar{t}$ and $Z + \text{jets}$ background estimations from data control regions are summarized in Table II. In the “$m_{12}$ fit method,” the $m_{12}$ distribution of $t\bar{t}$ is fitted with a second-order Chebychev polynomial, and the $Z + \text{jets}$ component is fitted with a Breit-Wigner line shape convolved with a Crystal Ball resolution function [26]. In the “$e^+e^-\rightarrow e^+e^-$ relaxed requirements” method, a background control region is formed by relaxing the electron selection criteria for electrons of the subleading pairs [26]. Since a fit to the data using $m_{34}$ background templates is carried out in the search, both the distribution in $m_{34}$ and normalization of the backgrounds are relevant. For all relevant backgrounds ($H \rightarrow ZZ^* \rightarrow 4\ell, ZZ^*, t\bar{t}$ and $Z + \text{jets}$) the $m_{34}$ distribution is obtained from simulation.

E. Systematic uncertainties

The sources of the systematic uncertainties in the $H \rightarrow ZZ_d \rightarrow 4\ell$ search are the same as in the $H \rightarrow ZZ^* \rightarrow 4\ell$ measurements. Uncertainties on the lepton reconstruction and identification efficiencies, as well as on the energy and momentum reconstruction and scale are described in detail in Refs. [26,27], and shown in Table III. The lepton identification is the dominant contribution to the systematic uncertainties on the ZZ$^*$ background. The largest uncertainty in the $H \rightarrow ZZ_d \rightarrow 4\ell$ search is the normalization of the $t\bar{t}$ and $Z + \text{jets}$ backgrounds. Systematic uncertainties related to the determination of selection efficiencies of isolation and impact parameters requirements are shown to be negligible in comparison with other systematic uncertainties. The uncertainty in luminosity [28] is applied to the ZZ$^*$ background normalization. The electron energy scale uncertainty is determined from $Z \rightarrow ee$ samples and for energies below 15 GeV from $J/\psi \rightarrow ee$ decays [26,27]. Final-state QED radiation modeling and background contamination affect the mass scale uncertainty negligibly. The muon momentum scale systematic uncertainty is determined from $Z \rightarrow \mu\mu$ samples and from $J/\psi \rightarrow \mu\mu$ as well as $Y \rightarrow \mu\mu$ decays [26,27]. Theory related systematic uncertainties on the Higgs production cross section and branching ratios are discussed in Refs. [39–41], but do not apply in this search since the

<table>
<thead>
<tr>
<th>Method</th>
<th>Estimated background</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{12}$ fit: $Z + \text{jets}$ contribution</td>
<td>$2.4 \pm 0.5 \pm 0.6$</td>
</tr>
<tr>
<td>$m_{12}$ fit: $t\bar{t}$ contribution</td>
<td>$0.14 \pm 0.03 \pm 0.03$</td>
</tr>
<tr>
<td>$m_{12}$ fit: $Z + \text{jets}$ contribution</td>
<td>$2.5 \pm 0.5 \pm 0.6$</td>
</tr>
<tr>
<td>$m_{12}$ fit: $t\bar{t}$ contribution</td>
<td>$0.10 \pm 0.02 \pm 0.02$</td>
</tr>
<tr>
<td>$e^+e^-\rightarrow e^+e^-$ relaxed requirements:</td>
<td>$5.2 \pm 0.4 \pm 0.5$</td>
</tr>
<tr>
<td>sum of $Z + \text{jets}$ and $t\bar{t}$ contributions</td>
<td>$4\ell$</td>
</tr>
<tr>
<td>$e^+e^-\rightarrow e^+e^-$ relaxed requirements:</td>
<td>$3.2 \pm 0.5 \pm 0.4$</td>
</tr>
<tr>
<td>sum of $Z + \text{jets}$ and $t\bar{t}$ contributions</td>
<td>$4\ell$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>$4\mu$</th>
<th>$4\ell$</th>
<th>$2\mu2e$</th>
<th>$2e2\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron identification</td>
<td>$\cdots$</td>
<td>$9.4$</td>
<td>$8.7$</td>
<td>$2.4$</td>
</tr>
<tr>
<td>Electron energy scale</td>
<td>$\cdots$</td>
<td>$0.4$</td>
<td>$\cdots$</td>
<td>$0.2$</td>
</tr>
<tr>
<td>Muon identification</td>
<td>$0.8$</td>
<td>$\cdots$</td>
<td>$0.4$</td>
<td>$0.7$</td>
</tr>
<tr>
<td>Muon momentum scale</td>
<td>$0.2$</td>
<td>$\cdots$</td>
<td>$0.1$</td>
<td>$\cdots$</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$3.6$</td>
<td>$3.6$</td>
<td>$3.6$</td>
<td>$3.6$</td>
</tr>
<tr>
<td>$t\bar{t}$ and $Z + \text{jets}$ normalization</td>
<td>$25.0$</td>
<td>$25.0$</td>
<td>$25.0$</td>
<td>$25.0$</td>
</tr>
<tr>
<td>$ZZ^*$ (QCD scale)</td>
<td>$5.0$</td>
<td>$5.0$</td>
<td>$5.0$</td>
<td>$5.0$</td>
</tr>
<tr>
<td>$ZZ^*$ ($q\bar{q}/PDF$ and $\alpha_s$)</td>
<td>$4.0$</td>
<td>$4.0$</td>
<td>$4.0$</td>
<td>$4.0$</td>
</tr>
<tr>
<td>$ZZ^*$ (ggPDF and $\alpha_s$)</td>
<td>$8.0$</td>
<td>$8.0$</td>
<td>$8.0$</td>
<td>$8.0$</td>
</tr>
</tbody>
</table>

PHYSICAL REVIEW D 92, 092001 (2015)
$H \rightarrow 4\ell$ normalization is obtained from data. Uncertainties on the $m_{\ell\ell}$ shapes arising from theory uncertainties on the PDFs and renormalization and factorization scales are found to be negligible. Theory cross-section uncertainties are applied to the ZZ background. Normalization uncertainties are taken into account for the $Z + \text{jets}$ and $t\bar{t}$ backgrounds based on the data-driven determination of these backgrounds.

**F. Results and interpretation**

A profile-likelihood test statistic is used with the $CL_s$ modified frequentist formalism [88–91] implemented in the RooStats framework [92] to test whether the data are compatible with the signal-plus-background and background-only hypotheses. Separate fits are performed for different $m_{Zd}$ hypotheses from 15 to 55 GeV, with 1 GeV spacing. After scanning the $m_{Zd}$ mass spectrum for an excess consistent with the presence of an $H \rightarrow ZZ_d \rightarrow 4\ell$ signal, no significant deviation from SM expectations is observed. Theory cross-section uncertainties are taken into account for the $Z + \text{jets}$ and $t\bar{t}$ backgrounds. Normalization uncertainties are taken into account for the $Z + \text{jets}$ and $t\bar{t}$ backgrounds based on the data-driven determination of these backgrounds.

The asymptotic approximation [90] is used to estimate the expected and observed exclusion limits on $\rho$ for the combination of all the final states, and the result is shown in Fig. 2. The relative branching ratio $R_B$ as a function of $m_{Z_d}$ is extracted using Eqs. (2) and (4) where the value of $C$ as a function of $m_{Z_d}$ is shown in Fig. 3, for the combination of all four final states. This is then used with $\rho$ to constrain the value of $R_B$, and the result is shown in Fig. 4 for the combination of all four final states.

The simplest benchmark model adds to the SM Lagrangian [6–8,10] a $U(1)_{\rho}$ gauge symmetry that introduces the dark vector boson $Z_d$. The dark vector boson may mix kinetically with the SM hypercharge gauge boson with kinetic mixing parameter $\epsilon$ [6,10]. This enables the decay $H \rightarrow ZZ_d$ through the hypercharge portal. The $Z_d$ is assumed to be narrow and on shell. Furthermore, the present search assumes prompt $Z_d$ decays consistent with current bounds on $\epsilon$ from electroweak constraints [18,19]. The coupling of the $Z_d$ to SM fermions is given in Eq. (47) of Ref. [6] to be linear in $\epsilon$, so that $\text{BR}(Z_d \rightarrow 4\ell)$ is independent of $\epsilon$ due to cancellations [6]. In this model, the $H \rightarrow ZZ_d \rightarrow 4\ell$ search can be used to constrain the hypercharge kinetic mixing parameter $\epsilon$ as follows: the upper limit on $R_B$ shown in Fig. 4 leads to an upper limit on $\text{BR}(H \rightarrow ZZ_d \rightarrow 4\ell)$ assuming the SM branching ratio of $H \rightarrow ZZ^* \rightarrow 4\ell$ of $1.25 \times 10^{-4}$ [40,41] as shown in Fig. 5. The limit on $\epsilon$ can be obtained directly from the $\text{BR}(H \rightarrow ZZ_d \rightarrow 4\ell)$ upper bounds and by using Table 2.
The model also assumes that the sector may manifest itself in the decays of the Higgs boson. The measurement of the relative branching ratio \( R_B \) as shown in Fig. 4 can also be used to constrain the mass-mixing parameter of the model described in Refs. [7,8] where the SM is extended with a dark vector boson and another Higgs doublet, and a mass mixing between the dark vector boson and the SM Z boson is introduced. This model explores how a \( U(1)_d \) gauge interaction in the hidden sector may manifest itself in the decays of the Higgs boson. The model also assumes that the \( Z_d \) being in the hidden sector, does not couple directly to any SM particles including the Higgs boson (i.e. the SM particles do not carry dark charges). However, particles in the extensions to the SM, such as a second Higgs doublet, may carry dark charges allowing for indirect couplings via the \( Z-Z_d \) mass mixing. The possibility of mixing between the SM Higgs boson with other scalars such as the dark sector Higgs boson is not considered for simplicity. The \( Z-Z_d \) mass-mixing scenario also leads to potentially observable \( H \to ZZ_d \to 4\ell \) decays at the LHC even with the total integrated luminosity collected in Run 1. The partial widths of \( H \to ZZ_d \to 4\ell \) and \( H \to ZZ_d \) are given in terms of the \( Z-Z_d \) mass-mixing parameter \( \delta \) and \( m_{Z_d} \) in Eq. (34) of Ref. [8] and Eq. (A.4) of Ref. [7], respectively. As a result, using the measurement of the relative branching ratio \( R_B \) described in this paper, one may set upper bounds on the product \( \delta^2 \times \text{BR}(Z_d \to 2\ell) \) as a function of \( m_{Z_d} \) as follows. From Eq. (2) and for \( m_{Z_d} < (m_\text{H} - m_Z) \)

\[
\frac{BR(H \to ZZ_d \to 4\ell)}{BR(H \to ZZ^* \to 4\ell)} = \frac{R_B}{1 - R_B} \frac{\Gamma(H \to ZZ_d)}{\Gamma_{SM}} \frac{\text{BR}(Z^* \to 2\ell) \times \text{BR}(Z_d \to 2\ell)}{\text{BR}(H \to ZZ^* \to 4\ell)},
\]

where \( \Gamma_{SM} \) is the total width of the SM Higgs boson and \( \Gamma(H \to ZZ_d) \ll \Gamma_{SM} \). From Eqs. (4), (A.3) and (A.4) of Ref. [7], \( \Gamma(H \to ZZ_d) \sim \delta^2 \). It therefore follows from Eq. (6), with the further assumption \( m_{Z_d}^2 < (m_\text{H}^2 - m_Z^2) \) that

\[
\frac{R_B}{1 - R_B} = \delta^2 \times \text{BR}(Z_d \to 2\ell) \times \frac{\text{BR}(Z^* \to 2\ell)}{\text{BR}(H \to ZZ^* \to 4\ell)} \times \frac{f(m_{Z_d})}{\Gamma_{SM}},
\]

where \( v \) is the vacuum expectation value of the SM Higgs field. The limit is set on the product \( \delta^2 \times \text{BR}(Z_d \to 2\ell) \) since both \( \delta \) and \( \text{BR}(Z_d \to 2\ell) \) are model dependent: in the case where kinetic mixing dominates, \( \text{BR}(Z_d \to 2\ell) \sim 30\% \) for the model presented in Ref. [6] but it could be smaller when \( Z-Z_d \) mass mixing dominates [8]. In the \( m_{Z_d} \) mass range of 15 GeV to \( (m_\text{H} - m_Z) \), the upper bounds on \( \delta^2 \times \text{BR}(Z_d \to 2\ell) \) are in the range \( \sim (1.5-8.7) \times 10^{-5} \) as shown in Fig. 7, assuming the same signal acceptances shown in Fig. 3.

VI. \( H \to Z_dZ_d \to 4\ell \)

A. Search strategy

\( H \to Z_dZ_d \to 4\ell \) candidate events are selected as discussed in Sec. VIB. The Z, J/ψ, Y vetoes are applied as
also discussed in Sec. VI B. Subsequently, the analysis exploits the small mass difference between the two SFOS lepton pairs of the selected quadruplet to perform a counting experiment. After the small mass difference requirements between the SFOS lepton pairs, the estimated background contributions, coming from $H \to ZZ \to 4l$, and $ZZ^* \to 4l$, are small. These backgrounds are normalized with the theoretical calculations of their cross sections. The other backgrounds are found to be negligible. Since there is no significant excess, upper bounds on the signal strength, defined as the ratio of the $H \to Z_dZ_d \to 4l$ rate normalized to the SM $H \to ZZ^* \to 4l$ expectation are set as a function of $m_{Z_d}$, using the combined upper limit on the relative branching ratio of $H \to ZZ_d \to 4l$ and the partial width of $H \to ZZ_d$ computed in Refs. [7,8].

B. Event selection

For the $H \to Z_dZ_d \to 4l$ search, unlike in the $H \to ZZ^* \to 4l$ study [93], there is no distinction between a primary pair (on-shell $Z$) and a secondary pair (off-shell $Z$), since both $Z_d$ bosons are considered to be on shell. Among all the different quadruplets, only one is selected by minimizing the mass difference $\Delta m = |m_{12} - m_{34}|$, where $m_{12}$ and $m_{34}$ are the invariant masses of the first and second pairs, respectively. The mass difference $\Delta m$ is expected to be minimal for the signal since the two dilepton systems should have invariant masses consistent with the same $m_{Z_d}$. No requirement is made on $\Delta m$; it is used only to select a unique quadruplet with the smallest $\Delta m$. Subsequently, isolation and impact parameter significance requirements are imposed on the leptons of the selected quadruplet as described in Ref. [39]. Figure 8 shows the minimal value of $\Delta m$ for the $2e2\mu$ final state after the impact parameter significance requirements. Similar distributions are found for the $4e$ and $4\mu$ final states. The dilepton and four-lepton invariant mass distributions are shown in Figs. 9 and 10, respectively, for $m_{12}$ and $m_{34}$ combined.

For the $H \to Z_dZ_d \to 4l$ search with hypothesized $m_{Z_d}$, after the impact parameter significance requirements on the selected leptons, four final requirements are applied:

1. $115 < m_{4l} < 130$ GeV where $m_{4l}$ is the invariant mass of the four leptons in the quadruplet, consistent with the mass of the discovered Higgs boson of about 125 GeV [94].

2. $Z$, $J/\psi$, and $Y$ vetoes on all SFOS pairs in the selected quadruplet. The $Z$ veto discards the event if either of the dilepton invariant masses is consistent with the $Z$-boson pole mass: $|m_{12} - m_{Z}| < 10$ GeV or $|m_{34} - m_{Z}| < 10$ GeV. For the $J/\psi$ and $Y$ veto, the dilepton invariant masses are required to be above 12 GeV. This requirement suppresses backgrounds with $Z$ bosons, $J/\psi$, and $Y$.

3. The loose signal region requirement: $m_{12} < m_H/2$ and $m_{34} < m_H/2$, where $m_H = 125$ GeV. In the $H \to Z_dZ_d \to 4l$ search, the kinematic limit for on-shell $Z_d$ is $m_{Z_d} < m_H/2$.

4. The tight signal region requirement: $|m_{Z_d} - m_{12}| < \delta m$ and $|m_{Z_d} - m_{34}| < \delta m$. The optimized values of the $\delta m$ requirements are 5/3/4.5 GeV for the $4e/4\mu/2e2\mu$ final states, respectively (the $\delta m$
FIG. 9 (color online). Dilepton invariant mass, \( m_{ll} \equiv m_{12} \) or \( m_{34} \), in the combined \( 4e + 2e2\mu + 4\mu \) final state, for \( m_H = 125 \text{ GeV} \). The shaded area shows both the statistical and systematic uncertainties. The bottom plots show the significance of the observed number of events in the data compared to the expected number of events from the backgrounds. These distributions are obtained after the impact parameter significance requirement.

These requirements (1)–(4) define the signal region (SR) of \( H \rightarrow Z_dZ_d \rightarrow 4\ell \) that is dependent on the hypothesized \( m_{Z_d} \), and is essentially background-free, but contains small estimated background contributions from \( H \rightarrow ZZ' \rightarrow 4\ell \) and \( ZZ' \rightarrow 4\ell \) processes as shown in Sec. VI E.

C. Background estimation

For the \( H \rightarrow Z_dZ_d \rightarrow 4\ell \) search, the main background contributions in the signal region come from the \( H \rightarrow ZZ' \rightarrow 4\ell \) and \( ZZ' \rightarrow 4\ell \) processes. These backgrounds are suppressed by the requirements of the tight signal region, as explained in Sec. VI B. Other backgrounds with smaller contributions come from the \( Z + \text{jets}, \ell \bar{\ell} \) and diboson backgrounds are negligible. In the case where the Monte Carlo calculation yields zero expected background events in the tight signal region, an upper bound at 68% C.L. on the expected events is estimated using 1.14 events [86], scaled to the data luminosity and normalized to the background cross section:

\[
N_{\text{background}} < L \times \sigma \times \left( \frac{1.14}{N_{\text{tot}}} \right),
\]

where \( L \) is the total integrated luminosity, \( \sigma \) the cross section of the background process, and \( N_{\text{tot}} \) the total 

FIG. 10 (color online). Four-lepton invariant mass, in the combined \( 4e + 2e2\mu + 4\mu \) final state, for \( m_H = 125 \text{ GeV} \). The shaded area shows both the statistical and systematic uncertainties. The bottom plots show the significance of the observed number of events in the data compared to the expected number of events from the backgrounds. These distributions are obtained after the impact parameter significance requirement.

FIG. 11 (color online). Dilepton invariant mass, \( m_{ll} \equiv m_{12} \) or \( m_{34} \), after the loose signal region requirements described in Sec. VI B for the \( 4e, 4\mu \) and, \( 2e2\mu \) final states combined, for \( m_H = 125 \text{ GeV} \). The data is represented by the black dots, and the backgrounds are represented by the filled histograms. The shaded area shows both the statistical and systematic uncertainties. The bottom plots show the significance of the observed data events compared to the expected number of events from the backgrounds. The dashed vertical line is the kinematic limit \((m_{12} \text{ or } m_{34} < 63 \text{ GeV})\) of the loose signal region requirements as discussed in Sec. VI B.
number of weighted events simulated for the background process.

To validate the background estimation, a signal depleted control region is defined by reversing the four-lepton invariant mass requirement with an $m_{4\ell} < 115$ GeV or $m_{4\ell} > 130$ GeV requirement. Good agreement between expectation and observation is found in this validation control region as shown in Fig. 12.

D. Systematic uncertainties

The systematic uncertainties on the theoretical calculations of the cross sections used in the event selection and identification efficiencies are taken into account. The effects of PDFs, $\alpha_S$, and renormalization and factorization scale uncertainties on the total inclusive cross sections for the Higgs production by ggF, VBF, VH and $t\bar{t}H$ are obtained from Refs. [40,41]. The renormalization, factorization scales and PDFs and $\alpha_S$ uncertainties are applied to the $ZZ^*$ background estimates. The uncertainties due to the limited number of MC events in the $t\bar{t}$, $Z +$ jets, $ZJ/\gamma$, $Z\gamma$ and $WW/WZ$ background simulations are estimated as described in Sec. VI C. The luminosity uncertainty [28] is applied to all signal yields, as well as to the background yields that are normalized with their theory cross sections. The detector systematic uncertainties due to uncertainties in the electron and muon identification efficiencies are estimated within the acceptance of the signal region requirements. There are several components to these uncertainties. For the muons, uncertainties in the reconstruction and identification efficiency, and in the momentum resolution and scale, are included. For the electrons, uncertainties in the reconstruction and identification efficiency, the

Table IV. The relative systematic uncertainties on the event yields in the $H \rightarrow Z_dZ_d \rightarrow 4\ell$ search.

<table>
<thead>
<tr>
<th>Source</th>
<th>$4\mu$</th>
<th>$4\ell$</th>
<th>$2\ell 2\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron identification</td>
<td>6.7</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>Electron energy scale</td>
<td>0.8</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Muon identification</td>
<td>2.6</td>
<td></td>
<td>1.3</td>
</tr>
<tr>
<td>Muon momentum scale</td>
<td>0.1</td>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.8</td>
<td>2.8</td>
<td></td>
</tr>
<tr>
<td>ggF QCD</td>
<td>7.8</td>
<td>7.8</td>
<td></td>
</tr>
<tr>
<td>ggF PDFs and $\alpha_S$</td>
<td>7.5</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>$ZZ^*$ PDFs and $\alpha_S$</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>

E. Results and interpretation

Figures 11 and 13 show the distributions of the dilepton invariant mass (for $m_{12}$ and $m_{34}$ combined) and the absolute mass difference $\Delta m = |m_{12} - m_{34}|$ after the loose signal region requirements. Four data events pass the loose signal region requirements, one in the $4\ell$ channel, two in the $4\mu$ channel and one in the $2\ell 2\mu$ channel. Two of these four events pass the tight signal region requirements: the event in the $4\ell$ channel and one of the events in the $4\mu$ channel. The event in the $4\ell$ channel has dilepton masses of 21.8 and 28.1 GeV as shown in Fig. 11, and is consistent with a $Z_d$
mass in the range $23.5 \leq m_{Z_d} \leq 26.5$ GeV. For the event in the $4\mu$ channel that passes the tight signal region requirements, the dilepton invariant masses are 23.2 and $18.0$ GeV as shown in Fig. 11, and they are consistent with a $Z_d$ mass in the range $20.5 \leq m_{Z_d} \leq 21.0$ GeV. In the $m_{Z_d}$ range of 15 to 30 GeV where four data events pass the loose signal region requirements, histogram interpolation [87] is used in steps of 0.5 GeV to obtain the signal acceptances and efficiencies at the hypothesized $m_{Z_d}$. The expected numbers of signal, background and data events, after applying the tight signal region requirements, are shown in Table V.

For each $m_{Z_d}$, in the absence of any significant excess of events consistent with the signal hypothesis, the upper limits are computed from a maximum-likelihood fit to the ratios of the numbers of data and expected signal and background events in the tight signal regions, following the CLs modified frequentist formalism [88,89] with the profile likelihood test statistic [90,91]. The nuisance parameters associated with the systematic uncertainties described in Sec. VI D are profiled. The parameter of interest in the fit is the signal strength $\mu_d$ defined as the ratio of the $H \rightarrow Z_dZ_d \rightarrow 4\ell$ rate relative to the SM $H \rightarrow ZZ^* \rightarrow 4\ell$ rate:

$$\mu_d = \frac{\sigma \times \text{BR}(H \rightarrow Z_dZ_d \rightarrow 4\ell)}{\sigma \times \text{BR}(H \rightarrow ZZ^* \rightarrow 4\ell)_{\text{SM}}}.$$  \hspace{0.5cm} (9)

The systematic uncertainties in the electron and muon identification efficiencies, renormalization and factorization scales and PDF are 100% correlated between the signal and backgrounds. Pseudoexperiments are used to compute the 95% C.L. upper bound $\mu_d$ in each of the final states and their combination, and for each of the hypothesized $m_{Z_d}$. The 95% confidence level upper bounds on the $H \rightarrow Z_dZ_d \rightarrow 4\ell$ rates are shown in Fig. 14 relative to the SM Higgs boson process $H \rightarrow ZZ^* \rightarrow 4\ell$ as a function of the hypothesized $m_{Z_d}$ for the combination of the three final states $4e, 2e2\mu$ and $4\mu$. Assuming the SM Higgs boson production cross section and using $\text{BR}(H \rightarrow ZZ^* \rightarrow 4\ell)_{\text{SM}} = 1.25 \times 10^{-4}$ [40,41], upper bounds on the branching ratio of $H \rightarrow Z_dZ_d \rightarrow 4\ell$ can be obtained from Eq. (9), as shown in Fig. 15.

The simplest benchmark model is the SM plus a dark vector boson and a dark Higgs boson as discussed in Refs. [6,10], where the branching ratio of $Z_d \rightarrow \ell\ell$ is given as a function of $m_{Z_d}$. This can be used to convert the measurement of the upper bound on the signal strength $\mu_d$ into an upper bound on the branching ratio $\text{BR}(H \rightarrow Z_dZ_d)$ assuming the SM Higgs boson production cross section. Figure 16 shows the 95% C.L. upper limit on the branching ratio of $H \rightarrow Z_dZ_d$ as a function of $m_{Z_d}$ using the combined $\mu_d$ of the three final states. The weaker bound at higher $m_{Z_d}$ is due to the fact that the branching ratio $Z_d \rightarrow \ell\ell$ drops slightly at higher $m_{Z_d}$ [6] as other decay channels become accessible. The $H \rightarrow Z_dZ_d$ decay can be used to obtain an $m_{Z_d}$-dependent limit on an Higgs mixing parameter $\kappa'$ [6]:

$$\kappa' = \kappa \times \frac{m_H^2}{m_{H'}^2 - m_{Z_d}^2}.$$  \hspace{0.5cm} (10)

<table>
<thead>
<tr>
<th>Process</th>
<th>4e</th>
<th>4\mu</th>
<th>2e2\mu</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4\ell$</td>
<td>$1.5 \pm 0.3 \pm 0.2 \times 10^{-2}$</td>
<td>$(1.0 \pm 0.3 \pm 0.3) \times 10^{-2}$</td>
<td>$(2.9 \pm 1.0 \pm 2.0) \times 10^{-3}$</td>
</tr>
<tr>
<td>$ZZ^* \rightarrow 4\ell$</td>
<td>$(7.1 \pm 3.6 \pm 0.5) \times 10^{-4}$</td>
<td>$(8.4 \pm 3.8 \pm 0.5) \times 10^{-3}$</td>
<td>$(9.1 \pm 3.6 \pm 0.6) \times 10^{-3}$</td>
</tr>
<tr>
<td>$WW, WZ$</td>
<td>$&lt;0.7 \times 10^{-2}$</td>
<td>$&lt;0.7 \times 10^{-2}$</td>
<td>$&lt;0.7 \times 10^{-2}$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$&lt;3.0 \times 10^{-2}$</td>
<td>$&lt;3.0 \times 10^{-2}$</td>
<td>$&lt;3.0 \times 10^{-2}$</td>
</tr>
<tr>
<td>$Zbb, Z + jets$</td>
<td>$&lt;0.2 \times 10^{-2}$</td>
<td>$&lt;0.2 \times 10^{-2}$</td>
<td>$&lt;0.2 \times 10^{-2}$</td>
</tr>
<tr>
<td>$ZJ/\psi$ and $Z\gamma$</td>
<td>$&lt;2.3 \times 10^{-3}$</td>
<td>$&lt;2.3 \times 10^{-3}$</td>
<td>$&lt;2.3 \times 10^{-3}$</td>
</tr>
<tr>
<td>Total background</td>
<td>$&lt;5.6 \times 10^{-2}$</td>
<td>$&lt;5.9 \times 10^{-2}$</td>
<td>$&lt;5.3 \times 10^{-2}$</td>
</tr>
<tr>
<td>Data</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4\ell$</td>
<td>$(1.2 \pm 0.3 \pm 0.2) \times 10^{-2}$</td>
<td>$(5.8 \pm 2.0 \pm 2.0) \times 10^{-3}$</td>
<td>$(2.6 \pm 1.0 \pm 2.0) \times 10^{-3}$</td>
</tr>
<tr>
<td>$ZZ^* \rightarrow 4\ell$</td>
<td>$(3.5 \pm 2.0 \pm 0.2) \times 10^{-3}$</td>
<td>$(4.1 \pm 2.7 \pm 0.2) \times 10^{-3}$</td>
<td>$(2.0 \pm 0.6 \pm 0.1) \times 10^{-2}$</td>
</tr>
<tr>
<td>$WW, WZ$</td>
<td>$&lt;0.7 \times 10^{-2}$</td>
<td>$&lt;0.7 \times 10^{-2}$</td>
<td>$&lt;0.7 \times 10^{-2}$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$&lt;3.0 \times 10^{-2}$</td>
<td>$&lt;3.0 \times 10^{-2}$</td>
<td>$&lt;3.0 \times 10^{-2}$</td>
</tr>
<tr>
<td>$Zbb, Z + jets$</td>
<td>$&lt;0.2 \times 10^{-2}$</td>
<td>$&lt;0.2 \times 10^{-2}$</td>
<td>$&lt;0.2 \times 10^{-2}$</td>
</tr>
<tr>
<td>$ZJ/\psi$ and $Z\gamma$</td>
<td>$&lt;2.3 \times 10^{-3}$</td>
<td>$&lt;2.3 \times 10^{-3}$</td>
<td>$&lt;2.3 \times 10^{-3}$</td>
</tr>
<tr>
<td>Total background</td>
<td>$&lt;5.3 \times 10^{-2}$</td>
<td>$&lt;5.1 \times 10^{-2}$</td>
<td>$&lt;6.4 \times 10^{-2}$</td>
</tr>
<tr>
<td>Data</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>
where $\kappa$ is the size of the Higgs portal coupling and $m_S$ is the mass of the dark Higgs boson. The partial width of $H \rightarrow Z_dZ_d$ is given in terms of $\kappa$ [5]. In the regime where the Higgs mixing parameter dominates ($\kappa \gg \epsilon$), $m_S > m_H/2$, $m_Z < m_H/2$ and $H \rightarrow Z_dZ^* \rightarrow 4\epsilon'$ is negligible, the only relevant decay is $H \rightarrow Z_dZ_d$. Therefore the partial width $\Gamma(H \rightarrow Z_dZ_d)$ can be written as

$$\Gamma(H \rightarrow Z_dZ_d) = \Gamma_{SM} \frac{\text{BR}(H \rightarrow Z_dZ_d)}{1 - \text{BR}(H \rightarrow Z_dZ_d)}. \quad (11)$$

The Higgs portal coupling parameter $\kappa$ is obtained using Eq. (53) of Ref. [6] or Table 2 of Ref. [5]:

$$\kappa^2 = \frac{\Gamma_{SM} \text{BR}(H \rightarrow Z_dZ_d)}{f(m_{Z_d}) \frac{1}{1 - \text{BR}(H \rightarrow Z_dZ_d)}}. \quad (12)$$

where

$$f(m_{Z_d}) = \frac{\nu^2}{32\pi m_H} \sqrt{1 - \frac{4m^2_{Z_d}}{m_H^2}} \times \frac{(m_H^2 + 2m_{Z_d}^2)^2 - 8(m_H^2 - m_{Z_d}^2)m_{Z_d}^2}{(m_H^2 - m_{Z_d}^2)^2}. \quad (13)$$

Figure 17 shows the upper bound on the effective Higgs mixing parameter as a function of $m_{Z_d}$: for
$m_H/2 < m_S < 2m_H$, this would correspond to an upper bound on the Higgs portal coupling in the range $\kappa \sim (1-10) \times 10^{-4}$.

An interpretation for $H \to Z_dZ_d$ is not done in the $Z$–$Z_d$ mass mixing scenario described in Refs. [7,8] since in this model the rate of $H \to Z_dZ_d$ is highly suppressed relative to that of $H \to ZZ_d$.

VII. CONCLUSIONS

Two searches for an exotic gauge boson $Z_d$ that couples to the discovered SM Higgs boson at a mass around 125 GeV in four-lepton events are presented, using the ATLAS detector at the LHC.

The $H \to ZZ_d \to 4\ell$ analysis uses the events resulting from Higgs boson decays to four leptons to search for an exotic gauge boson $Z_d$, by examining the $m_{34}$ mass distribution. The results obtained in this search cover the exotic gauge boson mass range of $15 < m_{Z_d} < 55$ GeV, and are based on proton-proton collisions data at $\sqrt{s} = 8$ TeV with an integrated luminosity of 20.7 fb$^{-1}$. Observed and expected exclusion limits on the branching ratio of $H \to ZZ_d \to 4\ell$ relative to $H \to 4\ell$ are estimated for the combination of all the final states. For relative branching ratios above 0.4 (observed) and 0.2 (expected), the entire mass range of $15 < m_{Z_d} < 55$ GeV is excluded at 95% C.L. Upper bounds at 95% C.L. on the branching ratio of $H \to ZZ_d \to 4\ell$ are set in the range $(2-3) \times 10^{-5}$ and $(1-10) \times 10^{-4}$, respectively, at 95% C.L., for $15 < m_{Z_d} < 60$ GeV.

Upper bounds on the effective mass-mixing parameter $\delta^2 \times \text{BR}(Z_d \to \ell\ell)$, resulting from the $U(1)_d$ gauge symmetry, are also set using the branching ratio measurements in the $H \to ZZ_d \to 4\ell$ search, and are in the range $(1.5-8.7) \times 10^{-5}$ for $15 < m_{Z_d} < 35$ GeV.

ACKNOWLEDGMENTS

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; EPLANET, ERC and NSRF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT and NSRF, Greece; ISF, MINERVA, GIF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW and NCN, Poland; GRICES and FCT, Portugal; MINE/IFA, Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.
SEARCH FOR NEW LIGHT GAUGE BOSONS IN HIGGS …


PHYSICAL REVIEW D 92, 092001 (2015)


[63] S. Dawson, L. H. Orr, L. Reina, and D. Wackeroth, Next-to-leading order QCD corrections to $pp \rightarrow t\bar{t}h$ at the CERN Large Hadron Collider, Phys. Rev. D 67, 071503 (2003).


SEARCH FOR NEW LIGHT GAUGE BOSONS IN HIGGS …

092001-25

PHYSICAL REVIEW D 92, 092001 (2015)
AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland

Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland

Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland

Physics Department, Southern Methodist University, Dallas, Texas, USA

Physics Department, University of Texas at Dallas, Richardson, Texas, USA

DESY, Hamburg and Zeuthen, Germany

SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom

INFN Laboratori Nazionali di Frascati, Frascati, Italy

Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany

Section de Physique, Université de Genève, Geneva, Switzerland

INFN Sezione di Genova, Italy

Dipartimento di Fisica, Università di Genova, Genova, Italy

E. Andronikashvili Institute of Physics, Ivanje Javakhishvili Tbilisi State University, Tbilisi, Georgia

High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia

II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany

II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany

Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France

Department of Physics, Hampton University, Hampton, Virgin, USA

Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA

Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany

Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan

Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China

Department of Physics, The University of Hong Kong, Hong Kong, China

Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China

Department of Physics, Indiana University, Bloomington, Indiana, USA

Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria

University of Iowa, Iowa City, Iowa, USA

Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA

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

KEK, High Energy Accelerator Research Organization, Tsukuba, Japan

Graduate School of Science, Kobe University, Kobe, Japan

Faculty of Science, Kyoto University, Kyoto, Japan

Kyoto University of Education, Kyoto, Japan

Department of Physics, Kyushu University, Fukuoka, Japan

Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina

Physics Department, Lancaster University, Lancaster, United Kingdom

INFN Sezione di Lecce, Italy
[123] National Research Centre “Kurchatov Institute” B. P. Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
[124a] INFN Sezione di Pisa, Italy
[125] Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
[126a] Laboratorio de Instrumentacao e Fisica Experimental de Partículas—LIP, Lisboa, Portugal
[126b] Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
[126c] Department of Physics, University of Coimbra, Coimbra, Portugal
[126d] Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal
[126e] Departamento de Física, Universidade do Minho, Braga, Portugal
[126f] Departamento de Física Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain), Portugal
[126g] Departamento de Física and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
[127] Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
[128] Czech Technical University in Prague, Praha, Czech Republic
[129] Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
[130] State Research Center Institute for High Energy Physics, Protvino, Russia
[131] Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
[132a] INFN Sezione di Roma, Italy
[132b] Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
[133a] INFN Sezione di Roma Tor Vergata, Italy
[133b] Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
[134a] INFN Sezione di Roma Tre, Italy
[134b] Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
[135a] Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies—Université Hassan II, Casablanca, Morocco
[135b] Centre National de l’Energie des Sciences Techniques Nucléaires, Rabat, Morocco
[135c] Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco
[135d] Faculté des Sciences, Université Mohammed Premier and LPTPM, Oujda, Morocco
[135e] Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
[136] DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
[137] Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA
[138] Department of Physics, University of Washington, Seattle, Washington, USA
[139] Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
[140] Department of Physics, Shinshu University, Nagano, Japan
[141] Fachbereich Physik, Universität Siegen, Siegen, Germany
[142] Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada
[143] SLAC National Accelerator Laboratory, Stanford, California, USA
[144] Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic
[145] Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
[146a] Department of Physics, University of Cape Town, Cape Town, South Africa
[146b] Department of Physics, University of Johannesburg, Johannesburg, South Africa
[146c] School of Physics, University of the Witwatersrand, Johannesburg, South Africa
[146d] Department of Physics, Stockholm University, Sweden
[147] The Oskar Klein Centre, Stockholm, Sweden
[148] Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, New York, USA
[149] Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
[150] School of Physics, University of Sydney, Sydney, Australia
[151] Institute of Physics, Academia Sinica, Taipei, Taiwan
[152] Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
[153] Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
[154] Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
[155] International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
SEARCH FOR NEW LIGHT GAUGE BOSONS IN HIGGS …

PHYSICAL REVIEW D 92, 092001 (2015)

Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
Department of Physics, University of Toronto, Toronto, Ontario, Canada
TRIUMF, Vancouver, British Columbia, Canada
Department of Physics and Astronomy, York University, Toronto, Ontario, Canada
Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA
Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA
INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
ICTP, Trieste, Italy

Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
Department of Physics, University of Illinois, Urbana, Illinois, USA
Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada
Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada
Department of Physics, University of Warwick, Coventry, United Kingdom
Waseda University, Tokyo, Japan

Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
Department of Physics, University of Wisconsin, Madison, Wisconsin, USA
Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
Department of Physics, Yale University, New Haven, Connecticut, USA
Yerevan Physics Institute, Yerevan, Armenia

Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

Deceased.
Also at Department of Physics, King’s College London, London, United Kingdom.
Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
Also at Novosibirsk State University, Novosibirsk, Russia.
Also at TRIUMF, Vancouver BC, Canada.
Also at Department of Physics, California State University, Fresno CA, USA.
Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
Also at Departamento de Fisica e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal.
Also at Tomsk State University, Tomsk, Russia.
Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
Also at Universita di Napoli Parthenope, Napoli, Italy.
Also at Institute of Particle Physics (IPP), Canada.
Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
Also at Louisiana Tech University, Ruston LA, USA.
Also at Institucion Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
Also at Department of Physics, National Tsing Hua University, Taiwan.
Also at Department of Physics, The University of Texas at Austin, Austin TX, USA.
Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
Also at CERN, Geneva, Switzerland.
Also at Georgian Technical University (GTU), Tbilisi, Georgia.
Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.
Also at Manhattan College, New York NY, USA.
Also at Hellenic Open University, Patras, Greece.
Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.
Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
Also at School of Physics, Shandong University, Shandong, China.
Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
Also at Section de Physique, Université de Genève, Geneva, Switzerland.
Also at International School for Advanced Studies (SISSA), Trieste, Italy.
Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, USA.
Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia.
Also at National Research Nuclear University MEPhI, Moscow, Russia.
Also at Department of Physics, Stanford University, Stanford CA, USA.
Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
Also at Department of Physics, The University of Michigan, Ann Arbor MI, USA.
Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.
Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.