

Search for a Higgs boson in the decay channel $H \rightarrow ZZ^{(*)} \rightarrow q\bar{q}\ell^{-}\ell^{+}$ in pp collisions at $\sqrt{s} = 7$ TeV

The CMS collaboration

ABSTRACT: A search for the standard model Higgs boson decaying into two Z bosons with subsequent decay into a final state containing two quark jets and two leptons, $H \rightarrow ZZ^{(*)} \rightarrow q\bar{q}\ell^{-}\ell^{+}$ is presented. Results are based on data corresponding to an integrated luminosity of 4.6 fb^{-1} of proton-proton collisions at $\sqrt{s} = 7$ TeV, collected with the CMS detector at the LHC. In order to discriminate between signal and background events, kinematic and topological quantities, including the angular spin correlations of the decay products, are employed. Events are further classified according to the probability of the jets to originate from quarks of light or heavy flavor or from gluons. No evidence for the Higgs boson is found, and upper limits on its production cross section are determined for a Higgs boson of mass between 130 and 600 GeV .

KEYWORDS: Hadron-Hadron Scattering

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1 Introduction

An important goal of experiments at the Large Hadron Collider (LHC) [1] is to study the mechanism of electroweak symmetry breaking through which the weak W and Z bosons acquire mass while the photon, γ , remains massless. Within the standard model (SM) [2–4] of particle physics it is postulated that the Higgs field provides the mechanism of electroweak symmetry breaking [5–10]. This model also predicts that the Higgs field would give rise to a spin-zero Higgs boson (H) with quantum numbers of the vacuum, $J^{PC} = 0^{++}$. Limits set by the experiments at LEP [11] and the Tevatron [12] leave a wide range of allowed Higgs boson masses $m_H > 114.4 \text{ GeV}$ and $m_H \notin [162, 166] \text{ GeV}$ at 95% confidence level (CL). Recently, further limits were set by the ATLAS experiment [13–15] at the LHC: $m_H \notin [145, 206], [214, 224], \text{ and } [340, 450] \text{ GeV}$. Indirect measurements [16] suggest that the mass of a SM Higgs boson would most likely fall below 158 GeV at 95% CL.

At the LHC, within the SM, Higgs bosons are primarily produced by gluon fusion (gg) [17–26] with an additional small contribution due to weak vector boson fusion (VBF) [27–32] and smaller contributions from other processes. The decay of a Higgs boson to two light fermions is highly suppressed [33–36]. Decay channels of the SM Higgs boson with two gauge bosons in the final state provide the greatest discovery potential at the LHC. For a Higgs boson mass $m_H < 2m_W$ those final states contain two photons or two weak bosons, ZZ^* or WW^* , where in each case one of the gauge bosons is off mass shell. For $m_H \geq 2m_W$, the main final states are those with two on-mass-shell weak bosons: W^+W^- for $2m_W \leq m_H < 2m_Z$, and additionally ZZ for $m_H \geq 2m_Z$.

In this Letter we present a search for a SM-like Higgs boson decaying via two Z bosons, one of which could be off mass shell, with a subsequent decay into two quark jets and two leptons, $H \rightarrow ZZ^{(*)} \rightarrow q\bar{q} \ell^- \ell^+$. Constraints on the rate of the Higgs boson production and decay are presented as a function of mass and interpretations are given in two scenarios: SM and a model with four generations of fermions [37–41]. The branching fraction of this

decay channel is about 20 times higher than that of $H \rightarrow ZZ^{(*)} \rightarrow \ell^- \ell^+ \ell^- \ell^+$. Inclusion of this semileptonic final state in the search for the Higgs boson leads to improved sensitivity at higher masses, where kinematic requirements can effectively suppress background. In the low mass region with leptonically decaying off-mass-shell Z bosons, we can achieve effective background suppression by constraining the two jets to the known Z boson mass m_Z [42]. The search is performed with a sample of proton-proton collisions at a center-of-mass energy $\sqrt{s} = 7$ TeV corresponding to an integrated luminosity $\mathcal{L} = (4.6 \pm 0.2) \text{ fb}^{-1}$ recorded by the Compact Muon Solenoid (CMS) experiment [43] at the LHC during 2011.

2 Event Reconstruction

We search for a fully reconstructed decay chain of the Higgs boson $H \rightarrow ZZ^{(*)} \rightarrow q\bar{q} \ell^- \ell^+$, see figure 1, where the charged leptons ℓ^\pm are either muons or electrons and the quarks are identified as jets in the CMS detector. The search is optimized separately for two ranges of the reconstructed mass, $125 < m_{ZZ} < 170$ GeV (low-mass) and $183 < m_{ZZ} < 800$ GeV (high-mass), corresponding to the $H \rightarrow ZZ^*$ and $H \rightarrow ZZ$ analyses, respectively. The intermediate mass range between $2m_W < m_H < 2m_Z$ has reduced sensitivity because of the small branching fraction for $H \rightarrow ZZ$ and is not included in the analysis.

A detailed description of the CMS detector can be found in ref. [43]. In the cylindrical coordinate system of CMS, ϕ is the azimuthal angle and the pseudorapidity (η) is defined as $\eta = -\ln[\tan(\theta/2)]$, where θ is the polar angle with respect to the counterclockwise beam direction. 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-scintillator hadron calorimeter (HCAL). The muon system is installed outside the solenoid and embedded in the steel return yoke. The CMS tracker consists of silicon pixel and silicon strip detector modules, covering the pseudorapidity range $|\eta| < 2.5$. The ECAL consists of lead tungstate crystals, which provide coverage for pseudorapidity $|\eta| < 1.5$ in the central barrel region and $1.5 < |\eta| < 3.0$ in the two forward endcap regions. The HCAL consists of a set of sampling calorimeters which utilize alternating layers of brass as absorber and plastic scintillator as active material. The muon system includes barrel drift tubes covering the pseudorapidity range $|\eta| < 1.2$, endcap cathode strip chambers ($0.9 < |\eta| < 2.5$), and resistive plate chambers ($|\eta| < 1.6$).

Although the main sources of background are estimated from data, Monte Carlo (MC) simulations are used to develop and validate the methods used in the analysis. Background samples are generated using either MADGRAPH 4.4.12 [45] (inclusive Z and top-quark production), ALPGEN 2.13 [46] (inclusive Z production), POWHEG [47–49] (top-quark production), or PYTHIA 6.4.22 [50] (ZZ, WZ, WW, QCD production). Signal events are generated using POWHEG and a dedicated generator from ref. [44]. Parton distribution functions (PDF) are modeled using the parametrization CTEQ6 [51] at leading order (LO) and CT10 [52] at next-to-leading order (NLO). For both signal and background MC, events are simulated using a GEANT4 [53] based model of the CMS detector and processed using the same reconstruction algorithms as used for data.

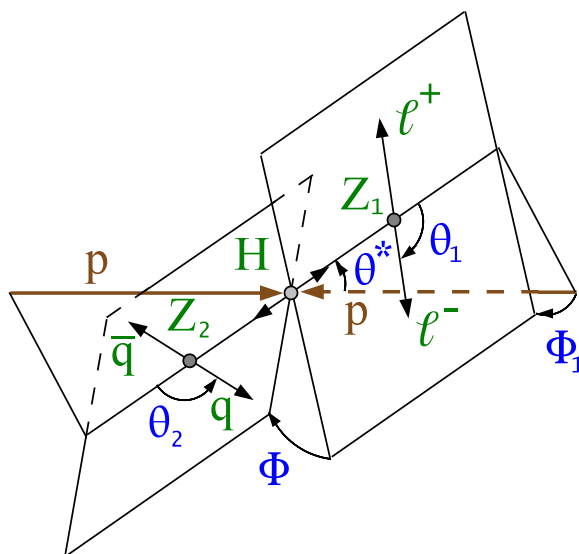


Figure 1. Diagram describing the process $pp \rightarrow H + X \rightarrow ZZ^{(*)} + X \rightarrow q\bar{q}\ell^-\ell^+ + X$ in terms of the angles $(\theta^*, \Phi_1, \theta_1, \theta_2, \Phi)$ defined in the parent particle rest frames (H or Z), where X indicates other products of the pp collision not shown on the diagram [44].

Muons are measured with the tracker and the muon system. Electrons are detected as tracks in the tracker pointing to energy clusters in the ECAL. Both muons and electrons are required to have a momentum transverse to the pp beam direction, p_T , greater than 20 GeV and 10 GeV, for the leading and subleading p_T lepton, respectively. These requirements are tightened to 40 GeV and 20 GeV in the analysis of the H candidates at higher masses. Leptons are measured in the pseudorapidity range $|\eta| < 2.4$ for muons, and $|\eta| < 2.5$ for electrons, although for electrons the transition range between the barrel and endcap, $1.44 < |\eta| < 1.57$, is excluded. Both the p_T and η requirements are consistent with those in the online trigger selection requiring two charged leptons, either electrons or muons. In the high-mass analysis, we also accept events selected with a single-muon trigger. The details of electron and muon identification criteria are described elsewhere [54]. Muons are required to be isolated from hadronic activity in the detector by restricting the sum of transverse momentum or energy in the tracker, ECAL, and HCAL, within a surrounding cone of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$, to be less than 15% of the measured p_T of the muon, where $\Delta\eta$ and $\Delta\phi$ are the differences in pseudorapidity and in azimuthal angle measured from the trajectory of the muon. Electron isolation requirements are similar but vary depending on the shape of the electron shower. In both cases the energy associated with the lepton is excluded from the isolation sum.

Jets are reconstructed with the particle-flow (PF) algorithm [55], which is an event reconstruction technique with the aim of reconstructing all particles produced in a given collision event through the combination of information from all sub-detectors. Reconstructed particle candidates are clustered to form PF jets with the anti- k_T algorithm [56, 57] with the distance parameter $R = 0.5$. The HCAL, ECAL, and tracker data are combined in the

PF algorithm to measure jets. Jets that overlap with isolated leptons within $\Delta R = 0.5$ are removed from consideration.

Jets are required to be inside the tracker acceptance, thus allowing high reconstruction efficiency and precise energy measurements using the PF algorithm. Jet-energy corrections are applied to account for the non-linear response of the calorimeters to the particle energies and other instrumental effects. These corrections are based on in-situ measurements using dijet and γ +jet data samples [58]. Overlapping minimum bias events (pile-up) coming from different proton-proton collisions and the underlying event have an effect on jet reconstruction by contributing additional energy to the reconstructed jets. The median energy density resulting from pile-up is evaluated in each event, and the corresponding energy is subtracted from each jet [59]. A jet requirement, primarily based on the energy balance between charged and neutral hadrons in a jet, is applied to remove misidentified jets. All jets are required to have $p_T > 30$ GeV.

Each pair of oppositely charged leptons and each pair of jets are considered as Z candidates. Background suppression is primarily based on the dilepton and dijet invariant masses, $m_{\ell\ell}$ and m_{jj} . The requirement $75 < m_{jj} < 105$ GeV is applied in order to reduce the Z+jets background and $70 < m_{\ell\ell} < 110$ GeV to reduce background without a Z in the final state, such as $t\bar{t}$. Figure 2(a) shows the dijet invariant mass m_{jj} distribution for signal and background. In the search for the Higgs boson in the final state ZZ^* , we require the invariant mass of the $Z^* \rightarrow \ell^-\ell^+$ candidate to be less than 80 GeV instead of the previous requirement. Below threshold for on-shell production of ZZ, the signal cross section is much smaller but also the Z^*/γ^* +jets background is strongly reduced.

The statistical analysis is based on the invariant mass of the Higgs boson candidate, m_{ZZ} , which is calculated using a fit of the final state four momenta and applying the constraint that the dijet invariant mass is consistent with the mass of the Z boson. The experimental resolutions are taken into account in this fit.

Since the Higgs boson is spinless, the angular distribution of its decay products is independent of the production mechanism. Five angles (θ^* , Φ_1 , θ_1 , θ_2 , Φ) defined in ref. [44] and in figure 1 fully describe the kinematics of the $gg \rightarrow H \rightarrow ZZ^{(*)} \rightarrow q\bar{q}\ell^-\ell^+$ process. Further kinematic selection exploits these five angular observables, which are only weakly correlated with the invariant masses of the H and the two Z bosons and with the longitudinal and transverse momenta of the Higgs boson candidate. The five angles along with the invariant masses provide most of the discriminating power between signal and background. We construct an angular likelihood discriminant (LD) based on the probability ratio of the signal and background hypotheses $\mathcal{P}_{\text{sig}}/(\mathcal{P}_{\text{sig}}+\mathcal{P}_{\text{bkg}})$, as described in ref. [44]. The likelihood ratio is defined for each value of m_{ZZ} and its dependence on m_{ZZ} is parameterized with smooth functions. Distributions of the angular LD for signal and background are shown in figure 2(b). The signal probability distribution is a correlated five-dimensional angular parameterization multiplied by empirically determined polynomial acceptance functions from simulation that describe non-uniform reconstruction efficiencies in the detector. The background distribution is an empirical parameterization taken as a product of independent distributions for each observable using simulation. Both are parameterized as functions of m_{ZZ} . Cuts on the angular LD are chosen to optimize the expected sensitivity to the

production of a SM Higgs boson and depend on m_{ZZ} . The angular LD was found to have marginal separation power for $m_{ZZ} < 170$ GeV and therefore is not used in selection requirements for this low-mass range.

The parton type of the jets provides a powerful tool for background discrimination. In signal events, the jets originate from Z bosons decaying to quarks that subsequently hadronize. The flavor of quarks in Z decays is almost equally distributed among the five types d, u, s, c, b, with some preference given to the down-type quarks. The dominant background is a leptonically decaying Z boson produced in association with high- p_T jets, a process in which gluon radiation plays a major role. Beside gluons, the u and d quarks from the protons dominate the jet production associated with the Z. Therefore, the main features that discriminate signal from background are the relatively large contribution of heavy-flavor quarks (b and c) and the absence of gluons. We take advantage of both features in the analysis by tagging the b flavor and introducing a likelihood discriminant that separates gluon and light-quark jets on a statistical basis, as described below.

To identify jets originating from the hadronization of bottom quarks, we use the CMS track counting high-efficiency (TCHE) b-tagging algorithm [60, 61], which relies on tracks with large impact parameters. A jet is b-tagged if there are at least two tracks each with a three-dimensional impact-parameter significance larger than a given threshold which has been optimized. The distributions of the resulting b-tagging discriminant is shown in figure 2 (c). The data are split into three b-tag categories: a 2 b-tag category is required to have one jet identified with medium ($\sim 65\%$ efficiency) and the other jet with loose ($\sim 80\%$ efficiency) TCHE requirements; events not selected in the 2 b-tag category are categorized as 1 b-tag if they have at least one jet satisfying the loose-tag requirements; the 0 b-tag category contains all the remaining events. The composition of the expected signal and background events varies significantly among the three categories, see figure 2 (d).

The 0 b-tag category is dominated by the Z+jets background, and from these events we further select a “gluon-tagged” category, which is excluded from further analysis if the two leading jets are consistent with being initiated by gluons, based on three measured quantities. These are the number of charged hadronic particle tracks, the number of photons and neutral hadrons, and the variable $PTD = \sqrt{\sum p_T^2 / (\sum p_T)^2}$, where the sum is extended over all jet constituents. The variable PTD is related to the fragmentation variable $z = p_T(\text{constituent})/p_T(\text{jet})$ and is approximately equal to $\sqrt{\sum z^2}$. Gluon hadronization favors the production of a larger number of stable particles. This translates into the observation of softer (low PTD), high-multiplicity jets when compared to those generated by final-state quarks. We construct a quark-gluon LD from the above three observables. The corresponding LD distributions for signal and background are shown in figure 2 (e). The relative number of gluon- and quark-jets for the main background, Z+jets, is not well known and it is not expected to be well reproduced by the simulation. The quark-gluon LD is instead verified using data samples of γ +jets enriched in quark-jets.

In order to suppress the substantial $t\bar{t}$ background in the 2 b-tag category, we apply a selection on the missing transverse energy (E_T^{miss}) which is defined as the modulus of the negative vector sum of all reconstructed PF particles in the event. We construct a

discriminant, λ , which is the ratio of the likelihoods of the hypothesis with E_T^{miss} equal to the value measured with the PF algorithm and the null hypothesis ($E_T^{\text{miss}} = 0$) [62]. This discriminant provides a measure that the event contains genuine missing transverse energy. The distribution of $2 \ln \lambda(E_T^{\text{miss}})$ is shown in figure 2(f). We apply a loose requirement, $2 \ln \lambda(E_T^{\text{miss}}) < 10$, in the 2 b-tag category only. In the low-mass analysis, we instead apply the selection requirement $E_T^{\text{miss}} < 50 \text{ GeV}$ in the 2 b-tag category.

Data and MC predictions of background distributions after the preselection requirements are shown in figure 2, where the additional contribution of a Higgs boson signal would be indistinguishable above the overwhelming background. The overall agreement between background simulation and data is good except for systematic differences related to the quark-gluon composition in Z+jets events, as shown in figure 2(e). We do not rely directly on simulation for background estimates. Instead, the background is determined directly using sidebands in data (see section 3).

The main selection requirements are summarized in table 1. When an event contains multiple candidates passing the selection requirements, we retain the one with jets in the highest b-tag category for the analysis. Further ambiguity between multiple candidates is resolved selecting the candidate with m_{jj} and $m_{\ell\ell}$ values closest to the Z boson mass m_Z . The distribution of the m_{ZZ} invariant mass for background and data are displayed for the three b-tag categories in figure 3. No significant deviation is observed between the data and the expectation for background. The main backgrounds include inclusive Z production with either light-flavor or heavy-flavor jets, top-quark production, and diboson production such as WZ and ZZ. The expected and observed event yields are listed in table 2. The expected background is quoted from the m_{jj} sideband procedure described below and from simulation. In the low-mass range, the background distribution is obtained from the m_{jj} sideband while its size is estimated from the m_{ZZ} sideband chosen for each m_H hypothesis, as discussed below.

3 Event Analysis

Data containing a Higgs boson signal would have a distinct resonance peak in addition to the continuum background distribution. The estimates from simulation shown in figure 3 provide a good illustration of the expected background but require further validation of both theoretical predictions, such as production cross section, and detector effects, e.g. b-tagging efficiency. These effects can explain the discrepancies between data and background simulation, which are sizable near the ZZ threshold around $m_{ZZ} = 200 \text{ GeV}$. However, the analysis technique relies on sidebands measured in data and is largely insensitive to the modeling of the m_{ZZ} distributions.

In order to minimize the systematic uncertainty from the background models, we estimate the background distribution from the m_{jj} sidebands, defined as $60 < m_{jj} < 75 \text{ GeV}$ and $105 < m_{jj} < 130 \text{ GeV}$. In simulation, the composition and distribution of the dominant backgrounds in the sidebands is similar to that in the signal region, $75 < m_{jj} < 105 \text{ GeV}$. The expected number of background events, $N_{\text{bkg}}(m_{ZZ})$, is obtained from the

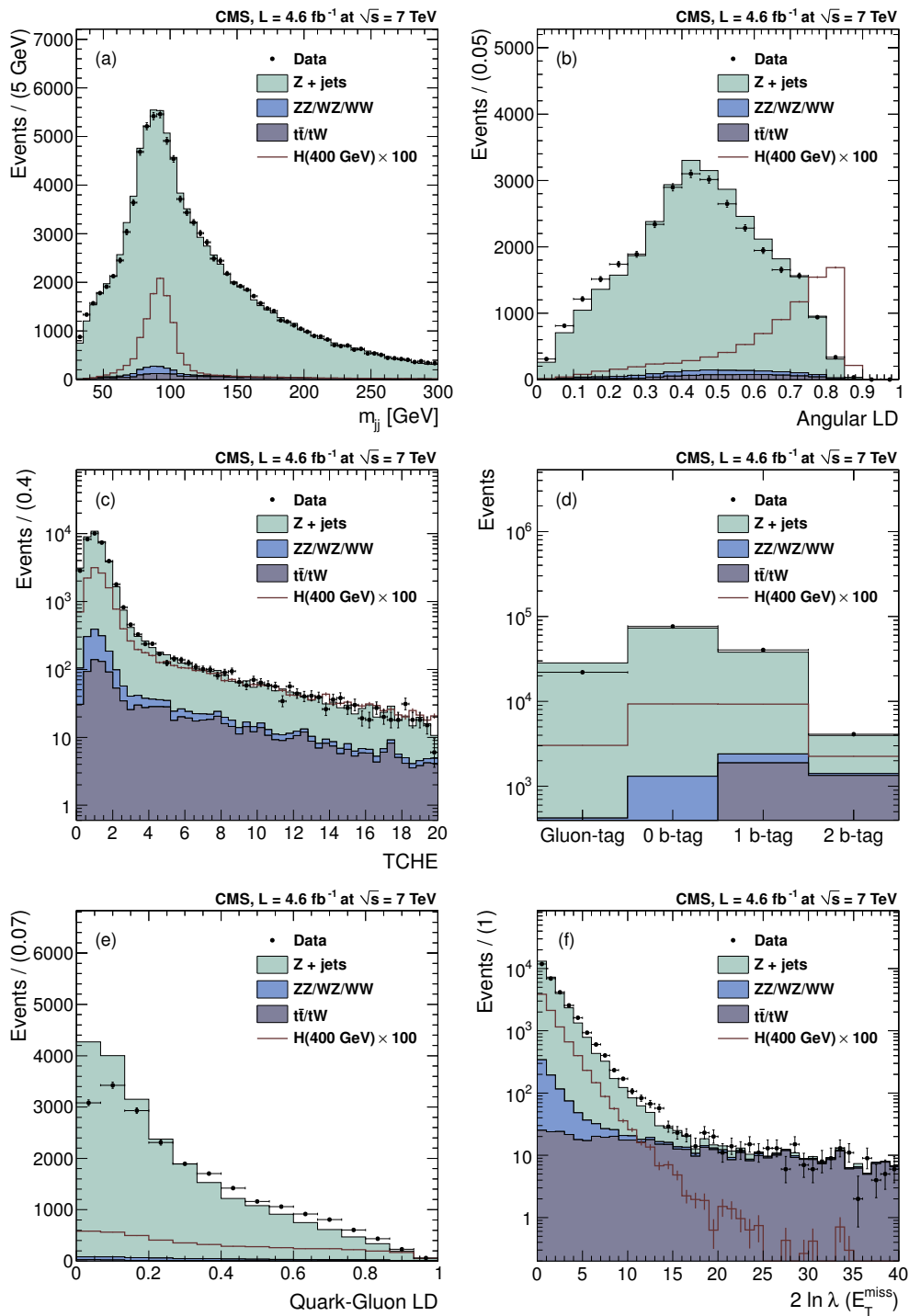


Figure 2. Distribution of the dijet invariant mass m_{jj} (a), angular likelihood discriminant (b), b-tagging discriminant (c), flavor tagging category (d), including the gluon-tagged category, quark-gluon likelihood discriminant (e), and $2 \ln \lambda (E_T^{\text{miss}})$ (f). Points with error bars show distributions of data after preselection requirements defined in table 1 with an additional requirement $70 < m_{\ell\ell} < 110$ GeV. Solid histograms depict the background expectation from simulated events with the different components illustrated. Open histograms indicate the expected distribution for a Higgs boson with a 400 GeV mass, multiplied by a factor of 100.

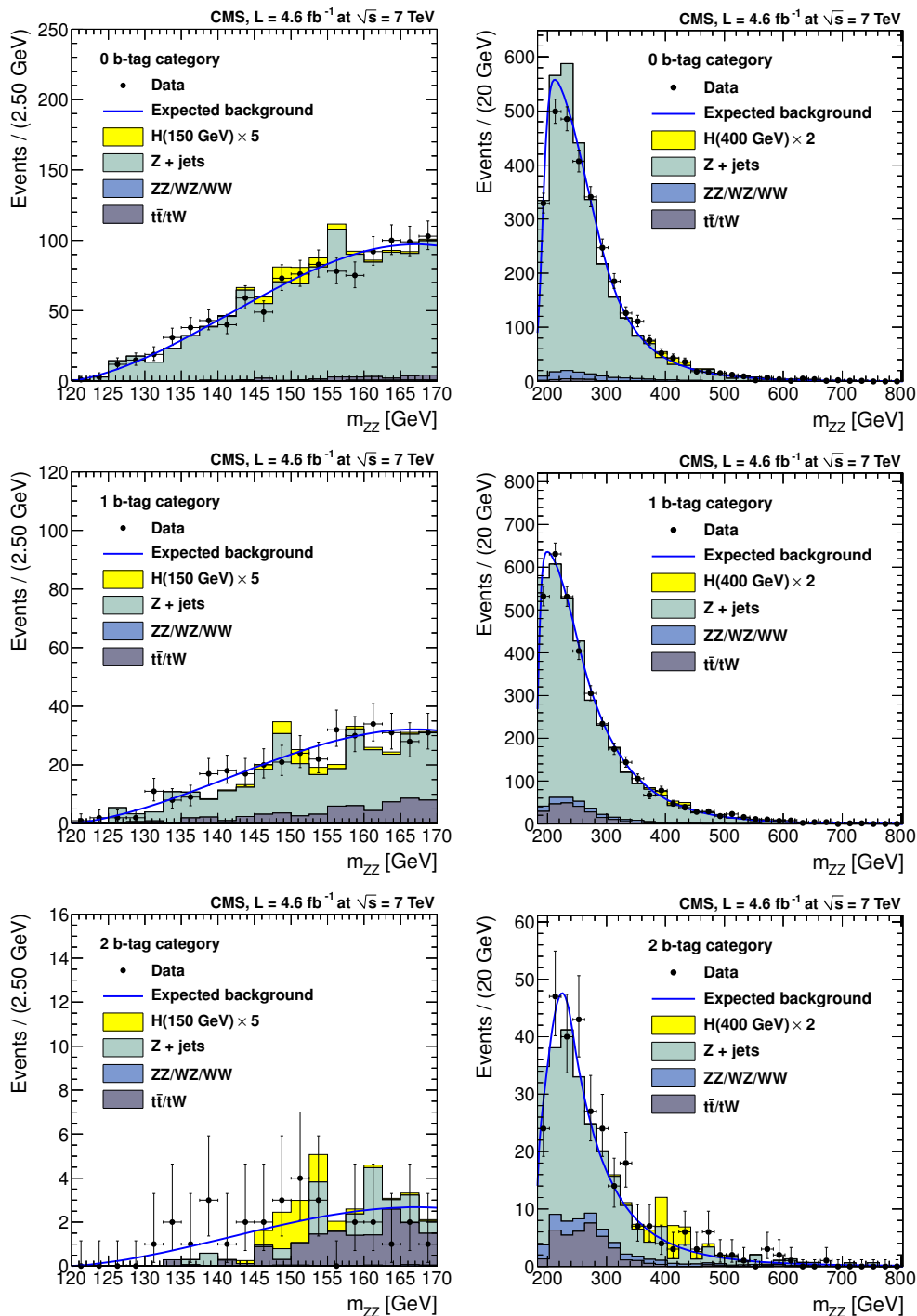


Figure 3. The m_{ZZ} invariant mass distribution after final selection in three categories: 0 b-tag (top), 1 b-tag (middle), and 2 b-tag (bottom). The low-mass range $120 < m_{ZZ} < 170$ GeV is shown on the left and the high-mass range $183 < m_{ZZ} < 800$ GeV is shown on the right. Points with error bars show distributions of data and solid curved lines show the prediction of background from the sideband extrapolation procedure. In the low-mass range, the background is estimated from the m_{ZZ} sideband for each Higgs mass hypothesis and the average expectation is shown. Solid histograms depicting the background expectation from simulated events for the different components are shown. Also shown is the SM Higgs boson signal with the mass of 150 (400) GeV and cross section 5 (2) times that of the SM Higgs boson, which roughly corresponds to expected exclusion limits in each category.

| | | preselection | | |
|----------------------------------|--|---|-----------------------------|--|
| $p_T(\ell^\pm)$ | | leading $p_T > 40(20)$ GeV, subleading $p_T > 20(10)$ GeV | | |
| $p_T(\text{jets})$ | | > 30 GeV | | |
| $ \eta (\ell^\pm)$ | | < 2.5 (e^\pm), < 2.4 (μ^\pm) | | |
| $ \eta (\text{jets})$ | | < 2.4 | | |
| | | final selection | | |
| | | 0 b-tag | 1 b-tag | 2 b-tag |
| b-tag | | none | one loose | medium & loose |
| angular LD | | $> 0.55 + 0.00025 m_{ZZ}$ | $> 0.302 + 0.000656 m_{ZZ}$ | > 0.5 |
| quark-gluon LD | | > 0.10 | none | none |
| E_T^{miss} requirements | | none | none | $2 \ln \lambda(E_T^{\text{miss}}) < 10$ ($E_T^{\text{miss}} < 50$ GeV) |
| m_{jj} | | $\in [75, 105]$ GeV | | |
| $m_{\ell\ell}$ | | $\in [70, 110]$ (< 80) GeV | | |
| m_{ZZ} | | $\in [183, 800]$ ($\in [125, 170]$) GeV | | |

Table 1. Summary of kinematic and topological selection requirements. Numbers in parentheses indicate additional selection requirements in the m_{ZZ} range $[125, 170]$ GeV, where angular and quark-gluon likelihood discriminant requirements are not used.

| | 0 b-tag | 1 b-tag | 2 b-tag |
|--|----------------|----------------|----------------|
| $m_{ZZ} \in [125, 170]$ | | | |
| observed yield | 1087 | 360 | 30 |
| expected background (m_{jj} sideband) | 1050 ± 54 | 324 ± 28 | 19 ± 5 |
| expected background (MC) | 1089 ± 39 | 313 ± 20 | 24 ± 4 |
| $m_{ZZ} \in [183, 800]$ | | | |
| observed yield | 3036 | 3454 | 285 |
| expected background (m_{jj} sideband) | 3041 ± 54 | 3470 ± 59 | 258 ± 17 |
| expected background (MC) | 3105 ± 39 | 3420 ± 41 | 255 ± 11 |
| signal expectation (MC) | | | |
| $m_H=150$ GeV | 10.1 ± 1.5 | 4.1 ± 0.6 | 1.6 ± 0.3 |
| $m_H=250$ GeV | 24.5 ± 3.5 | 21.7 ± 3.0 | 8.1 ± 1.7 |
| $m_H=350$ GeV | 29.6 ± 4.3 | 26.0 ± 3.7 | 11.8 ± 2.5 |
| $m_H=450$ GeV | 16.5 ± 2.4 | 15.8 ± 2.2 | 7.9 ± 1.7 |
| $m_H=550$ GeV | 6.5 ± 1.0 | 6.5 ± 0.9 | 3.6 ± 0.8 |

Table 2. Observed and expected event yields for 4.6 fb^{-1} of data. The yields are quoted in the range $125 < m_{ZZ} < 170$ GeV or $183 < m_{ZZ} < 800$ GeV, depending on the Higgs boson mass hypothesis. The expected background is quoted from the m_{jj} sideband procedure and from simulation (MC). In the low-mass range, the background is estimated from the m_{ZZ} sideband for each Higgs mass hypothesis and is not quoted in the table. The errors on the expected background from simulation include only statistical uncertainties.

number of events in the sidebands, $N_{\text{sb}}(m_{ZZ})$, as follows:

$$N_{\text{bkg}}(m_{ZZ}) = N_{\text{sb}}(m_{ZZ}) \times \frac{N_{\text{bkg}}^{\text{sim}}(m_{ZZ})}{N_{\text{sb}}^{\text{sim}}(m_{ZZ})} = N_{\text{sb}}(m_{ZZ}) \times \alpha(m_{ZZ}), \quad (3.1)$$

where $\alpha(m_{ZZ})$ is the ratio of the expected number of background events in the signal and sideband regions obtained from simulation. This factor corrects for acceptance differences between the two regions and also for differences in background composition.

In the high-mass range, the distributions derived from data sidebands are measured for each of the three b-tag requirements and give the normalization of the background and its dependence on m_{ZZ} . The correction $\alpha(m_{ZZ})$ reaches a maximum of about 1.2 near the threshold of $2m_Z$ and falls to nearly a constant value between 0.75 and 1.0 elsewhere, depending on b-tag and kinematic requirements.

In the low-mass range, below the $2m_Z$ threshold, the same kinematic selections are applied to all b-tag categories and a single background spectrum is derived from the m_{jj} sidebands. The correction $\alpha(m_{ZZ})$ is not applied, and instead the normalizations in each category are obtained as a function of m_H , using an m_{ZZ} sideband outside the window $m_H \pm 5 \text{ GeV}$.

The results of the sideband extrapolation procedures are shown as solid curves in figure 3 and are in good agreement with the observed distributions in data. In all cases, the dominant backgrounds include Z+jets with either light- or heavy-flavor jets and top background, both of which populate the m_{jj} signal region and the m_{jj} sidebands. The diboson background amounts to less than 5% of the total in the 0 and 1 b-tag categories and about 10% in the 2 b-tag category. This diboson background is accounted for by $\alpha(m_{ZZ})$ in the high-mass range and by the m_{ZZ} sideband procedure in the low-mass range.

The distribution of m_{ZZ} for the background is parameterized with an empirical function, fitted to the shape and normalization determined from the sidebands. The advantage of this approach is that most of the systematic uncertainties on the background cancel. The dominant normalization uncertainty in the background estimation is due to statistical fluctuations of the number of events in the sidebands. The reconstructed signal distributions are described with a Gaussian function with power-law tails and an empirical function reflecting misreconstruction of the Higgs boson decay products. The signal reconstruction efficiency and the m_{ZZ} distribution are parameterized as a function of m_H and are extrapolated to all mass points. The main uncertainties in the signal m_{ZZ} parameterization are due to resolution which is predominantly affected by the uncertainty on the jet energy scale [58].

The m_{ZZ} distributions of the selected events are split into six categories based on the b-tag type and the lepton flavor. These events are examined for 43 hypothetical Higgs boson masses in a range between 130 GeV and 164 GeV, and 73 hypothetical Higgs boson masses in the range between 200 GeV and 600 GeV, where the mass steps are optimized to account for the expected width, Γ_H , and resolution for measurement of m_H [63]. For each mass hypothesis, we perform a simultaneous likelihood fit of the six m_{ZZ} distributions using the statistical approaches discussed in ref. [63]. As an alternative, we have also studied a cut-based analysis that counts events in regions of the m_{ZZ} distribution and found consistent,

| source | 0 b-tag | 1 b-tag | 2 b-tag |
|------------------------------|---|---------|---------|
| muon reconstruction | 2.7% | | |
| electron reconstruction | 4.5% | | |
| jet reconstruction | 1–8% | | |
| pile-up | 3–4% | | |
| E_T^{miss} | – | – | 3–4% |
| b-tagging | 2–7% | 3–5% | 10–11% |
| gluon-tagging | 4.6% | – | – |
| acceptance (HqT) | 2% | 5% | 3% |
| acceptance (PDF) | 3% | | |
| acceptance (VBF) | 1% | | |
| signal cross section (PDF) | 8–10% | | |
| signal cross section (scale) | 8–11% | | |
| signal shape | $1.5 \times 10^{-7}\% \times m_H^3$ [GeV] | | |
| luminosity | 4.5% | | |

Table 3. Summary of systematic uncertainties on signal normalization. Most sources give multiplicative uncertainties on the cross-section measurement, except for the expected Higgs boson production cross section, which is relevant for the measurement of the ratio to the SM expectation. The ranges indicate dependence on m_H .

but systematically higher median expected limits compared to the likelihood fit approach. We adopt the modified frequentist construction CL_s [63–65] as the primary method for reporting limits. As a complementary method to the frequentist paradigm, we use the Bayesian approach [42] and find consistent results.

The systematic uncertainties on signal normalization are summarized in table 3. We consider effects from lepton energy scale, resolution, selection, and trigger (electron/muon reconstruction); jet resolution and efficiency (jet reconstruction); pile-up; E_T^{miss} requirements; heavy-quark flavor tagging and quark-gluon discrimination; Higgs boson production mechanism; cross section and branching fractions; resonance mass shape; and LHC luminosity. Reconstruction efficiencies for leptons and their uncertainties are evaluated from data with a “tag-and-probe” [54] approach where one lepton from an inclusive sample of Z decays serves as a tag and the efficiency for the reconstruction of the other lepton is calculated. Contributions from jet reconstruction are evaluated by variation of the jet energy and resolution within calibration uncertainties. The contributions from the uncertainty on pile-up are taken from the simulated difference between the reconstruction and the selection efficiency with pile-up below and above the average expected value, distributed according to the measurement in data. The uncertainty of the E_T^{miss} selection efficiency is computed by examining the E_T^{miss} distributions from Z inclusive production in MC simulation and in data after subtraction of background from top production. Uncertainties due to b tagging have been evaluated with a sample of jet events enriched in heavy flavor by requiring a muon to be spatially close to a jet. The uncertainty on the quark-gluon LD selection efficiency was evaluated using the $\gamma + \text{jet}$ sample in data, which predominantly contains quark jets.

Uncertainties in the production mechanism affect the signal acceptance in the detector. Both the longitudinal momentum of the Higgs boson, because of PDFs, and the transverse momentum of the Higgs boson, because of QCD initial-state radiation effects, are model dependent. We rescale the transverse momentum distribution of the Higgs boson using the HqT [66] code and take the full change in the efficiency as a systematic uncertainty. We follow the PDF4LHC [52, 67–70] recommendation to estimate the uncertainty due to PDF knowledge and to calculate the uncertainty on signal acceptance. Uncertainties on the production cross section for the Higgs boson are taken from ref. [71], which includes uncertainties from the QCD renormalization and factorization scales, PDFs, and α_s . These uncertainties are separated between the gg and VBF production mechanisms, but uncertainties on the gg process dominate in the total production cross section. We also account for a small uncertainty because of a difference in signal acceptance with the gg and VBF production mechanisms, while the selection efficiency was optimized and evaluated for the dominant gg production. A relative uncertainty of 4.5% on luminosity is applied to the signal normalization.

Recent studies [39, 71, 72] show that current Monte Carlo simulations do not describe the correct Higgs boson mass line shape above ≈ 300 GeV. These effects are estimated to lead to an additional uncertainty on the theoretical cross section of 10–30% for m_H of 400–600 GeV and are included in the calculations of the limits.

We also consider the production and decay of the Higgs boson within a model with four generations of fermions (SM4) [37–41], including electroweak radiative corrections. The following scenario has been adopted in the SM4 calculations: $m_{b'}$ = 600 GeV and $m_{t'} - m_{b'} = 50(1 + 0.2 \ln(m_H/115))$ GeV, following recommendation of ref. [71]. The main difference from the SM is a higher production rate and somewhat different branching fractions of the SM4 Higgs boson. We assume that the main uncertainties on the SM4 Higgs production cross section are the same as the gluon-fusion mechanism in the SM [71].

In order to infer the presence or absence of a signal in the data sample, we construct an appropriate test statistic q , a single number encompassing information on the observed data, expected signal, expected background, and all uncertainties associated with these expectations [63]. The definition of q makes use of a likelihood ratio for the signal+background model and the model with the best-fit signal strength plus background. We compare the observed value of the test statistic with its distributions expected under the background-only and signal+background hypotheses. The expected distributions are obtained by generating pseudo-datasets. The signal strength which leads to a 95% CL limit is determined for each Higgs mass hypothesis under study.

4 Results

No evidence for the Higgs boson is found and exclusion limits at 95% CL on the ratio of the production cross section for the Higgs boson to the SM expectation are presented in figure 4. The observed limits are within expectation for the background-only model. The significance of the only local deviation beyond the 95% expectation range around 225 GeV is greatly reduced after taking into account the look-elsewhere effect [73], for

which the estimated trial factor is about 18 in the high-mass range. Results obtained with the Bayesian approach yield very similar limits to those from CL_s .

Limits on the SM production cross section times branching fraction for $H \rightarrow ZZ$ are presented in figure 5. For comparison, expectations are shown for both the SM and for the SM4 model. The ranges 154–161 GeV and 200–470 GeV of SM4 Higgs mass hypotheses are excluded at 95% CL. The exclusion limits in figure 4 are also approaching the cross section for the SM expectation for production of the Higgs boson.

5 Summary

A search for the SM Higgs boson decaying into two Z bosons which subsequently decay to two quark jets and two leptons, $H \rightarrow ZZ^{(*)} \rightarrow q\bar{q}\ell^-\ell^+$, has been presented. Data corresponding to an integrated luminosity of 4.6 fb^{-1} of proton-proton collisions at centre-of-mass energy of 7 TeV have been collected and analyzed by the CMS Collaboration at the LHC. No evidence for a SM-like Higgs boson has been found and upper limits on the production cross section for the SM Higgs boson have been set in the range of masses between 130 and 164 GeV, and between 200 and 600 GeV. In this analysis we have also excluded at 95% CL a large range of Higgs boson mass hypotheses in the model with a fourth generation of fermions having SM-like couplings.

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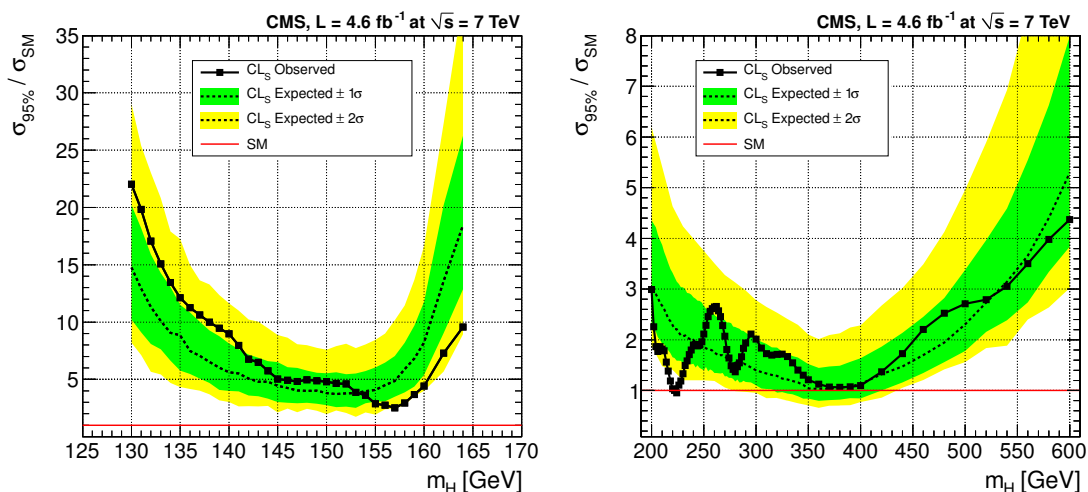


Figure 4. Observed (solid) and expected (dashed) 95% CL upper limit on the ratio of the production cross section to the SM expectation for the Higgs boson obtained using the CL_s technique. The 68% (1σ) and 95% (2σ) ranges of expectation for the background-only model are also shown with green (darker) and yellow (lighter) bands, respectively. The solid line at 1 indicates the SM expectation. Left: low-mass range, right: high-mass range.

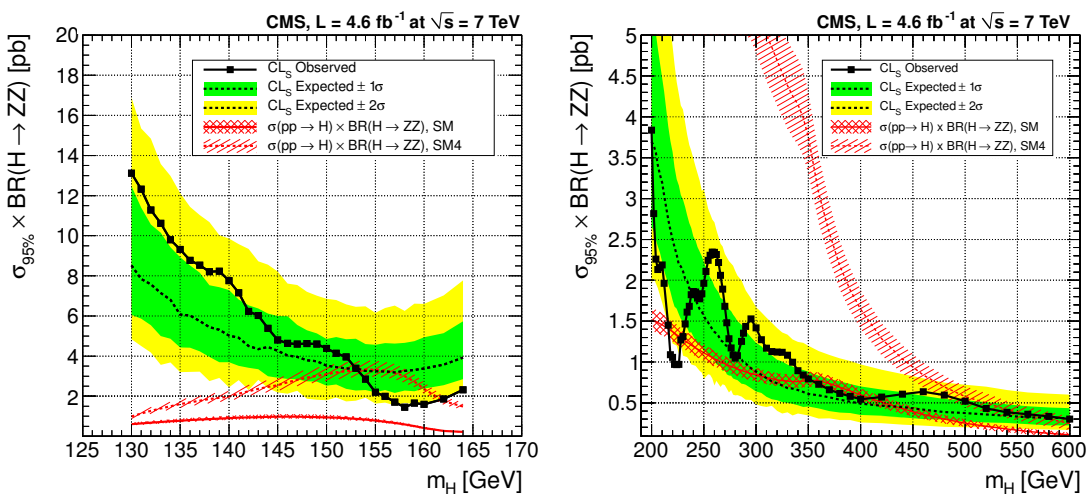


Figure 5. Observed (dashed) and expected (solid) 95% CL upper limit on the product of the production cross section and branching fraction for $H \rightarrow ZZ$ obtained with the CL_s technique. The 68% (1σ) and 95% (2σ) ranges of expectation for the background-only model are also shown with green (darker) and yellow (lighter) bands, respectively. The expected product of the SM Higgs production cross section and the branching fraction is shown as a red solid curve with a band indicating theoretical uncertainties at 68% CL. The same expectation in the fourth-generation model is shown with a red dashed curve with a band indicating theoretical uncertainties. Left: low-mass range, right: high-mass range.

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- 7: Also at Cairo University, Cairo, Egypt
- 8: Also at British University, Cairo, Egypt
- 9: Also at Fayoum University, El-Fayoum, Egypt
- 10: Now at Ain Shams University, Cairo, Egypt
- 11: Also at Soltan Institute for Nuclear Studies, Warsaw, Poland
- 12: Also at Université de Haute-Alsace, Mulhouse, France
- 13: Also at Moscow State University, Moscow, Russia
- 14: Also at Brandenburg University of Technology, Cottbus, Germany
- 15: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 16: Also at Eötvös Loránd University, Budapest, Hungary
- 17: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
- 18: Now at King Abdulaziz University, Jeddah, Saudi Arabia
- 19: Also at University of Visva-Bharati, Santiniketan, India
- 20: Also at Sharif University of Technology, Tehran, Iran
- 21: Also at Isfahan University of Technology, Isfahan, Iran
- 22: Also at Shiraz University, Shiraz, Iran

- 23: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Teheran, Iran
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- 29: Also at University of Florida, Gainesville, U.S.A.
- 30: Also at University of California, Los Angeles, Los Angeles, U.S.A.
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- 33: Also at University of Athens, Athens, Greece
- 34: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 35: Also at The University of Kansas, Lawrence, U.S.A.
- 36: Also at Paul Scherrer Institut, Villigen, Switzerland
- 37: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 38: Also at Gaziosmanpasa University, Tokat, Turkey
- 39: Also at Adiyaman University, Adiyaman, Turkey
- 40: Also at The University of Iowa, Iowa City, U.S.A.
- 41: Also at Mersin University, Mersin, Turkey
- 42: Also at Kafkas University, Kars, Turkey
- 43: Also at Suleyman Demirel University, Isparta, Turkey
- 44: Also at Ege University, Izmir, Turkey
- 45: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
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- 47: Also at Utah Valley University, Orem, U.S.A.
- 48: Also at Institute for Nuclear Research, Moscow, Russia
- 49: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 50: Also at Los Alamos National Laboratory, Los Alamos, U.S.A.
- 51: Also at Argonne National Laboratory, Argonne, U.S.A.
- 52: Also at Erzincan University, Erzincan, Turkey
- 53: Also at Kyungpook National University, Daegu, Korea