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Searches for production of two Higgs bosons using the CMS detector

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Abstract

Four searches for the production of two Higgs bosons using the CMS detector are presented. The analyses are performed on pp collision data collected during the Run I of the LHC at $\sqrt{s} = 7 - 8$ TeV corresponding to an integrated luminosity of 5.1 – 17.9-19.7 fb^{-1}. The analyses are covering the resonant production of Higgs boson pairs in the $b\bar{b}\gamma\gamma$ and $b\bar{b}b\bar{b}$ final states for masses between 260 and 1100 GeV, the resonant production of Higgs boson pairs in multilepton and diphoton final states for masses between 260 and 360 GeV, as well as additional Higgs boson-like states in the diphoton spectrum for masses between 110 and 150 GeV. The observations are compatible with expectations from standard model processes, and upper limits at 95% confidence-level are extracted on the production cross section of new particles.

Keywords: CMS, Higgs boson, Higgs boson pair production, Warped Extra Dimension, Two Higgs Doublet Model

1. Introduction

The recent observation of a Higgs boson particle at $m_h = 125.03 \pm 0.3$ GeV by the ATLAS and CMS collaborations [1, 2] - which properties (spin-parity, couplings) appear to be very standard model (SM)-like from the LHC-Run I data ($\sqrt{s} = 7 - 8$ TeV, $L \approx 25$ fb^{-1}) [3, 4] - solves the mass generation problem in the SM. However, given the absence (so far) of new Beyond the standard model (BSM) physics signals, many fundamental questions remain open such as the hierarchy, dark matter, and matter-antimatter asymmetry questions. The possibility that this Higgs boson would be a portal to BSM physics has to be explored.

In this context, there is a strong interest to study final states with several Higgs bosons :

- There could be a connection in between the Higgs boson and BSM physics, as for example in Warped Extra Dimension (WED) models, this will be discussed in section 2;
- The Higgs sector could be non-minimal and part of a broader ensemble. The Two Higgs Doublet Model (2HDM), as predicted for example by the Minimal Supersymmetric standard model (MSSM), would be such an ensemble and will be discussed in sections 3 and 4;
- Final states with several Higgs bosons are the handle to measure directly the last couplings predicted by the SM, namely the Higgs self-coupling λ (related to its mass $m_h^2 = \sqrt{2}\lambda/G_F$) and the $VVhh$ coupling.

The searches that are described in this document are performed on the pp collision data collected by the CMS experiment during the LHC Run I at $\sqrt{s} = 8$ TeV corresponding to an integrated luminosity of 17.9-19.7 fb^{-1}. A detailed description of the CMS detector can be found elsewhere [5].

2. Beyond the standard model: Warped Extra Dimensions

Warped Extra Dimension (WED) models [6] are aiming to explain the hierarchy problem of the SM. Such models predict the existence of particles X that can decay to a pair of Higgs bosons if $m_X > 2 \cdot m_h$, with

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m_h = 125 GeV. These particles can be for example the radion (spin-0) or the first Kaluza-Klein (KK) excitation of the graviton (spin-2), which are both related to the description of gravity. Their production cross section by gluon fusion is depending on the scale Λ_R. The mass of the particles depends on the ED stabilization mechanism in the case of the radion and on the geometry of the ED in case of the graviton: the mass can be for practical search purposes considered a free parameter. The following analyses will focus on studying only the non-boosted regime $m_X \in [260, 1100]$ GeV, for which a non-negligible fraction of signal events exhibits fully resolved final state objects. First a search in the $b\bar{b}\gamma\gamma$ final state will be described in section 2.1, then a search in the $b\bar{b}b\bar{b}$ final state will be presented in section 2.2.

2.1. Search in the final state with two photons and two bottom quarks

This analysis, described in detail in [7], looks for resonant pair production of Higgs bosons in the $b\bar{b}\gamma\gamma$ final state, which allow a full reconstruction of the four-body system. The branching ratio to this final state is 0.26% assuming SM couplings.

This analysis features many common points with the analysis observing the Higgs boson in the diphoton final state [8]. In particular the diphoton trigger paths, the kinematic selection of the photons ($p_{T\gamma1}/m_{\gamma\gamma} > 1/3$, $p_{T\gamma2}/m_{\gamma\gamma} > 1/4$, $|\eta_\gamma| < 2.5$, $m_{\gamma\gamma} \in [100, 180]$ GeV) as well as the cut-based tight photon identification criteria are the same. The selected primary vertex however is chosen as the one having the maximum sum of the square p_T of its associated tracks. This choice is more efficient due to the presence of jets in the final state. The considered jets are built from particle-flow candidates using the anti-k_T clustering algorithm with a distance parameter of 0.5. They are further required to satisfy loose jet identification criteria to remove detector noise as well as random pileup energy deposits. The jets are required to satisfy $p_{T\mathrm{j}} > 25$ GeV and $|\eta_\mathrm{j}| < 2.5$. The signal jets are coming from the hadronization of b-quarks and the Combined Secondary Vertex (CSV) b-tagger algorithm allows to identify such jets with an efficiency of order 60 − 70% for the medium working point used here, with an efficiency of about 1 − 2% to identify instead jets coming from light quarks or gluons. At least one b-tagged jet is required. It is of interest to classify the events in two categories: one high-purity category, containing 36 − 49% of the signal where at least two b-tagged jets are required, and one medium purity category, containing 36 − 56% of the signal, where exactly one b-tagged jet is required. Events in the low purity category, containing 10 − 16% of the signal where no b-tagged jet is required, are rejected because of their poor discriminating power.

The diphoton Higgs boson candidate is taken as the pair of the two photons with the largest p_T, and the dijet Higgs boson candidate is taken as the jet pair with the maximum $p_{T\mathrm{jj}}$, while always giving preference to b-tagged jets.

The dominant non-resonant background contribution is the Quantum Chromo-Dynamics (QCD) production of two photons and two jets, the second leading non-resonant background being the QCD production of one photon and three jets where one jet is misidentified as a photon. The contribution from the production of a single SM Higgs boson is negligible and taken into account in the search.

The search is separated into two regimes for the signal extraction:

- a low mass regime ($m_X \leq 400$ GeV) where the m_jj invariant mass is required to be compatible with m_h = 125 GeV and $m_{\gamma\gamma\mathrm{jj}}$ is required to be compatible with the m_X hypothesis. The signal is extracted from a fit to the $m_{\gamma\gamma}$ spectrum in data;

- a high mass regime ($m_X \geq 400$ GeV) where both the m_jj and $m_{\gamma\gamma}$ invariant masses are required to be compatible with m_h = 125 GeV. To further improve the resolution on the invariant mass of the resonance, the dijet invariant mass is constrained to be consistent with the mass of a Higgs boson (m_h = 125 GeV). This constraint takes into account the experimental jet resolutions and is known as *kinematic fit*. The signal is extracted from a fit to the $m^{\mathrm{kin}}_{\gamma\gamma\mathrm{jj}}$ spectrum in data.

The signal shape is modeled from the simulation by the sum of a Gaussian and a Crystal-Ball functions. The background is modeled from data by a power-law function for each regime in each category. In this data-driven procedure, it has been verified that the chosen background model does not bias in a non-negligible way the estimate of the signal strength obtained from the limit procedure, by testing the function against a variety of 'truth' functional shapes. An example of signal and background fits for the high-mass search are presented in figure 1.

The expected number of signal events is estimated using simulation. Discrepancies in photon and (b-tagged-)jet identification and reconstruction are corrected for with data-to-simulation scale factors and the associated uncertainties are taken into account. Photon and jet en-

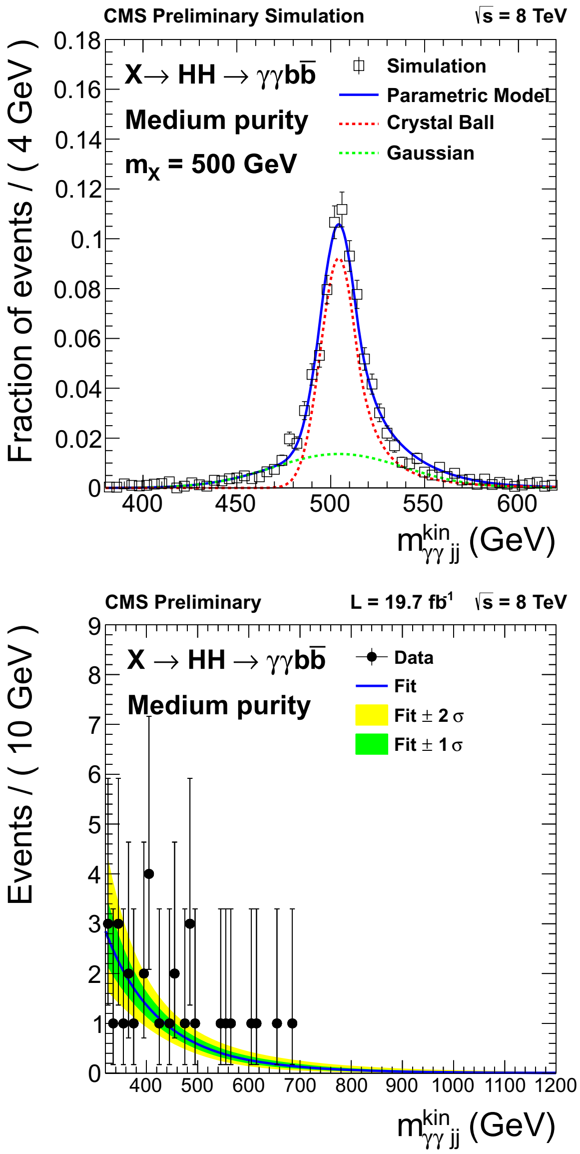

Figure 1: Simulated signal shape (top, open squares) in $m^{\text{kin}}_{\gamma\gamma\text{jj}}$ for a mass hypothesis of $m_X = 500$ GeV. The plain blue line represents the model fitted to the simulation. Data events (bottom, data points) in $m^{\text{kin}}_{\gamma\gamma\text{jj}}$ for the high-mass regime. The black line represents the fitted non-resonant component of the background. Both figures present the medium purity category [7].

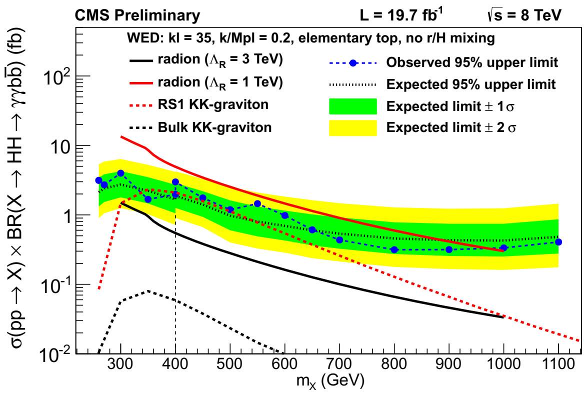

Figure 2: Expected and observed 95% upper limits on the cross section times branching ration $\sigma(pp \to X) \times \text{BR}(\text{X} \to \text{hh} \to \text{b}\bar{\text{b}}\gamma\gamma)$ [7]. Theory lines corresponding to WED models with radion, RS1 KK-graviton and bulk KK-graviton are also shown.

ergy scale and resolution uncertainties are also propagated to the final result.

The analysis is observed to be statistics-limited and no significant deviation from the expectations is observed. The upper limit is computed with the modified frequentist approach CL_s taking the profile likelihood as a test statistics used with an asymptotic approximation. The 95% confidence level expected and observed median upper limits are presented in figure 2. The analysis observes (expects) to exclude the presence of a radion with masses below 970 GeV (880 GeV) for the radion scale $\Lambda_R = 1$ TeV.

2.2. Search in the final state with four bottom quarks

This analysis, described in detail in [9], looks for resonant pair production of Higgs bosons in the $b\bar{b}b\bar{b}$ final state. The branching ratio to this final state is 33.3% if one assumes the SM couplings.

The trigger path used to record the data requires four jets with $p_T > 30$ GeV, two of which are required to have $p_T > 80$ GeV. The path requires also the presence of two jets b-tagged with the CSV algorithm described above. The pp collision data collected at $\sqrt{s} = 8$ TeV with this trigger correspond to an integrated luminosity of 17.9 fb^{-1}.

The considered jets are built as described in the previous section and required to satisfy $p_{T_\text{j}} > 40$ GeV and $|\eta_\text{j}| < 2.5$. The analysis requires at least four jets tagged by the Combined MultiVAriate (CMVA) b-tagger algorithm. The CMVA b-tagging algorithm yields a 75% efficiency for tagging true b-jets and 3% for tagging instead jets coming from light quarks or gluons. Among the selected jets, two pairs are chosen to be the two Higgs bosons candidates by the means of a dedicated algorithm.

As the kinematic range of angles and momenta change significantly over the range of the search, the analysis is split into two regimes:

- a Low Mass Region (LMR) for $m_X \leq 440$ GeV, for which two jets are required to have $p_T > 90$ GeV.
- a High Mass Region (HMR) for $m_X \geq 450$ GeV, for which the diHiggs candidates are paired such that the jet pair forming a candidate verify $\Delta R(\mathrm{j}_1, \mathrm{j}_2) < 1.5$. For masses from 740 GeV to 1100 GeV, an additional requirement of $p_{T_{\mathrm{jj}}} > 300$ GeV for each Higgs boson candidate.

In case there are more than two Higgs bosons candidates in an event, only the combination that minimizes $|m_{h1} - m_{h2}|$ is considered.

The signal region (SR) is defined as $\sqrt{\Delta m_{h1}^2 + \Delta m_{h2}^2} < 17.5$ GeV where $\Delta m_{h1,2} = m_{h1,2} - 125$ GeV. It is not, for practical reasons, possible to generate a large enough simulation sample with QCD multi-jet to compare with the data. For the purpose of validating the background model in the signal region, a validation region (VR) is defined similarly around 90 GeV. Sideband regions around the signal region and the validation region (SB and VB respectively) are defined as $\sqrt{\Delta m_{h1}^2 + \Delta m_{h2}^2} \in [17.5, 35]$ GeV and $\Delta m_{h1} \cdot \Delta m_{h2} < 0$. The signal and control regions described above are illustrated on figure 3.

In order to improve the resolution on the m_{jjjj} spectrum, a kinematic fit is performed to constrain the dijet mass to be consistent with $m_h = 125$ GeV ($m_Z = 90$ GeV for the validation region and validation sideband) in a similar way as described in the previous section.

For both LMR and HMR searches, the signal is extracted through a fit to the four-body mass spectrum $m_{\mathrm{jjjj}}^{\mathrm{kin}}$. The dominant background is QCD multi-jet production. The amount of $t\bar{t}$ in the final signal region is between 22 and 27%, and is considered as a separated component of the fit estimated from the simulation. Other processes, like Z+jets, ZZ and ZH have been studied in the simulation and their contribution is estimated to be less than 1% and are therefore neglected.

The QCD multi-jet contribution is fitted by a Gaussian core extended on the high side to an exponential tail, in such a way that the first derivative is continuous. This parametric form has been determined in the sideband region SB. The validity of the extrapolation of this

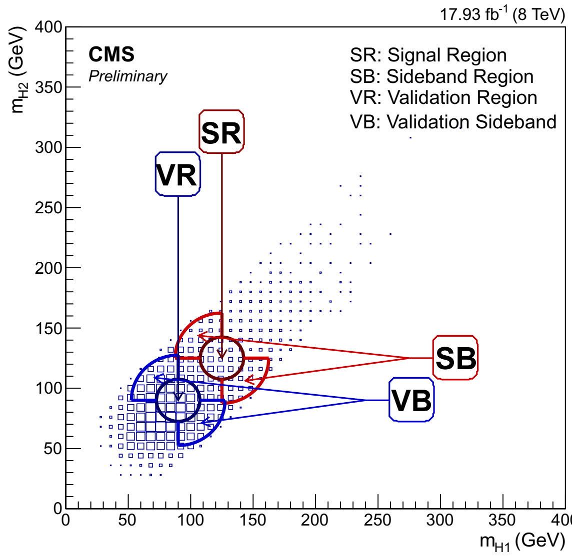

Figure 3: Distribution of data events after b-tagging and kinematic selections as a function of the two reconstructed Higgs boson masses m_{h1} and m_{h2} [9].

choice of shape from SR to SB is demonstrated in the validation region (VR) and validation sidebands (VB). An additional check of this extrapolation in a signal-free control region, defined by reversing the b-tag requirement on one of the jets, has been performed successfully.

The signal is fitted by a Gaussian core extended on both low and high side with exponential tails, in such a way that the first derivative is continuous. The background fit for the LMR in the signal region as well as an example of signal fit are presented in figure 4.

The expected number of signal events and $t\bar{t}$ events are estimated in the simulation. Discrepancies in b-tagged jet identification and reconstruction are corrected for with data-to-simulation scale factors and the associated uncertainties are taken into account. Jet energy scale and resolutions are also propagated to both signal and $t\bar{t}$ modeling for the final result. An additional systematic uncertainty on the $t\bar{t}$ production cross section is taken into account, as well as an additional uncertainty in the background modeling to account for potential bias in the extracted signal strength.

No significant deviation from the SM expectations is observed. The upper limit is computed similarly as described in the previous section, and is presented for the graviton (spin-2) case in figure 5. The analysis observes (expects) to exclude the presence of a RS1 KK-graviton

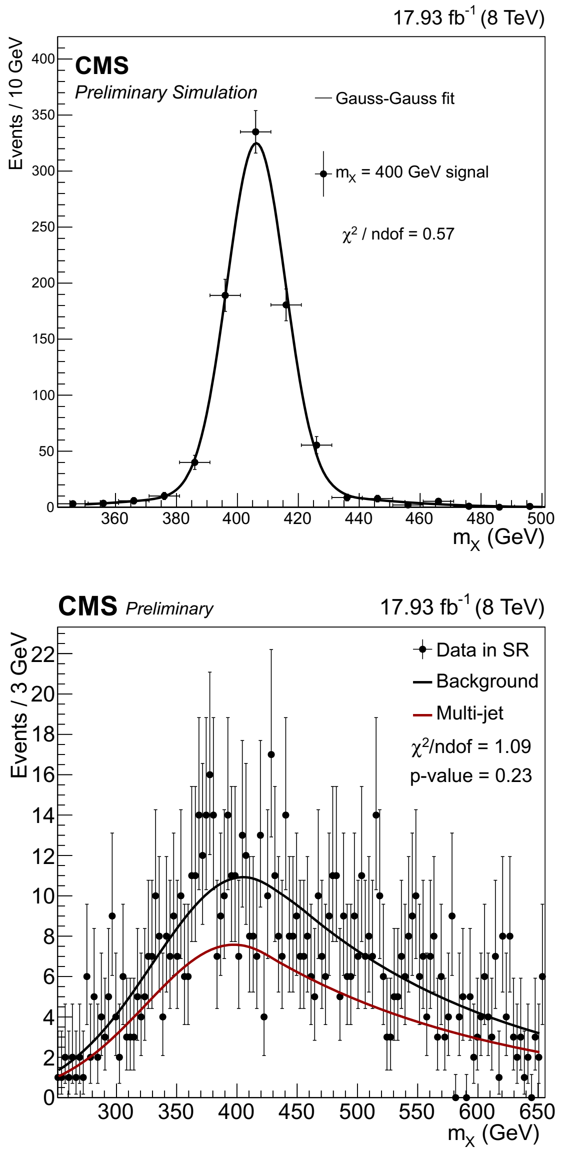

Figure 4: Simulated signal shape (top, dots) in the $m_{\mathrm{jjjj}}^{\mathrm{kin}}$ mass spectrum for a mass hypothesis of m_X = 500 GeV. The plain line represent the model fitted to the simulation. Data events (bottom, dots) in $m_{\mathrm{jjjj}}^{\mathrm{kin}}$ for the LMR. The red line represents the fitted QCD multi-jet contribution, while the black line represent the total fitted background including the $t\bar{t}$ contribution as fitted from the simulation [9].

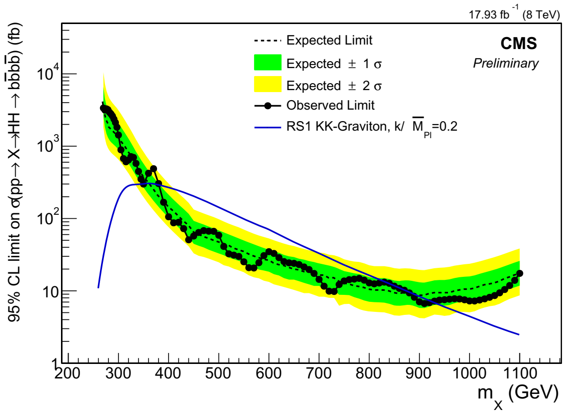

Figure 5: Expected and observed 95% upper limits on the cross section times branching ration $\sigma(pp \to X) \times \mathrm{BR}(X \to hh \to b\bar{b}b\bar{b})$ [9]. Theory line corresponding to WED models RS1 KK-graviton is also shown.

with masses below 380 GeV (360 GeV) for $kL = 35$ and $k/\bar{M}_{\mathrm{Pl}} = 0.2$.

3. Extended Higgs sector: two Higgs doublet model

The two Higgs Doublet Model (2HDM) is the simplest extension of the SM with gauge in variance of the minimal Higgs sector. It extends the Higgs sector to two scalar doublets, and predicts the existence of five physical Higgs bosons: two neutral CP-even scalars h and H, one neutral CP-odd pseudo-scalar A and two charged scalars $H^{\pm}$. The scenario of interest here under study is the case when the heavy Higgs boson H is heavy enough to decay into two SM-like Higgs bosons h, which are further assumed to decay according to the SM branching fractions.

A generic search for $H \to hh$ processes has been performed by the CMS collaboration [10], assuming m_h = 126 GeV and $m_H \in [260, 360]$ GeV, considering multilepton and diphoton signatures coming from $WWWW$, $WWZZ$, $WW\tau\tau$, $ZZZZ$, $ZZ\tau\tau$, $ZZbb$, $\tau\tau\tau\tau$, $\gamma\gamma WW$, $\gamma\gamma ZZ$ and $\gamma\gamma\tau\tau$ final states. Here and in the rest of this section, *lepton* refers to the electron, muon, and hadronic decays of tau leptons τ_h. Leptonic decays of tau leptons τ_l are counted as electrons or muons. The analyzed data have been collected in pp collisions at $\sqrt{s}$ = 8 TeV by diphoton and dilepton triggers, corresponding to $L = 19.5\ \mathrm{fb}^{-1}$.

The observed events are classified in multiple exclusive channels:

- Multilepton channels are required to have more than three identified leptons, with at most one τ_h.

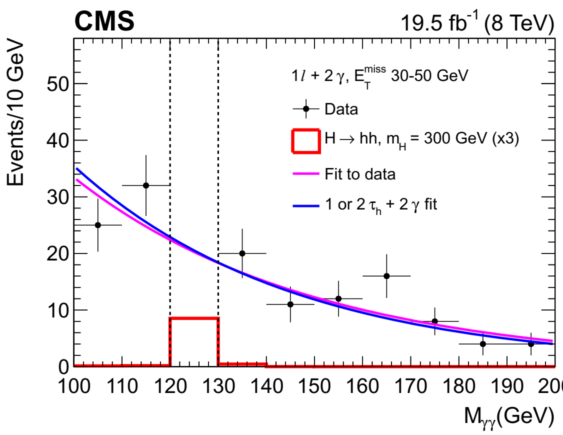

Figure 6: Diphoton invariant mass distribution for $\gamma\gamma l$ events with $\not{E}_T$ in 30 − 50 GeV range with an exponential fit (blue curve) where the exponent is fixed to the value obtained for the control region as defined in the text. A direct fit (magenta curve) is also shown for comparison purposes [10].

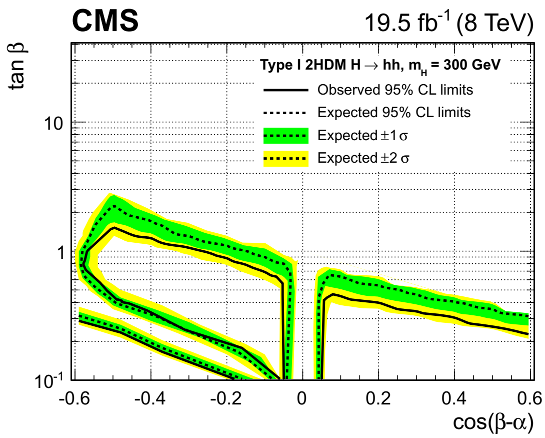

Figure 7: Expected and observed 95% upper limits as a function of parameters $\tan\beta$ and $\cos(\beta-\alpha)$ of Type I 2HDM, for a heavy Higgs boson H with $m_H = 300$ GeV [10].

The classification depends on the number of leptons and their flavors, their relative charge and flavor combinations, the number of b-tagged jets, as well as the missing transverse energy $\not{E}_T$;

- Diphoton channels are required to have at least two identified photons and either one or two identified leptons.

The amount of backgrounds are estimated in different ways depending on the final state:

- For multilepton final states, the backgrounds are coming from Z+ jets , VV+jets, $t\bar{t}$ and QCD processes. Three different control region have been constructed in data in order to:
  - estimate the background coming from a non-prompt third lepton in Z+jets and WW+jets;
  - validate the estimate from simulation of backgrounds coming from diboson and $t\bar{t}$ processes;
  - estimate the background contribution coming from asymmetric photon conversions.
- For diphoton final states, the shape of the background is validated in $m_{\gamma\gamma}$ sidebands, excluding the [120, 130] GeV region, for events containing one or two hadronic τ leptons and having $\not{E}_T < 30$ GeV. An example is presented in figure 6.

The expected number of signal events is estimated using simulation, corrected for data-to-simulation disagreements, and the relevant associated uncertainties are propagated to the final result.

An excess of events in one multilepton channel in three consecutive $\not{E}_T$ bins with a local p-value of 1.5% is observed, the corresponding global p-value considering the sum of these bins is 46%. The deviation from the expectation from SM predictions is not significant. The upper limit, computed in a similar way as described in the previous section is computed for each multilepton and diphoton categories. The most sensitive categories are then added together until 90% of the selected signal is covered.

The obtained model-independent limits can be recast in a 2HDM parameter space, for Type I and Type II scenario: the mixing angle between H and h is defined as α and $\tan\beta$ gives the relative contribution of each Higgs double to the electroweak symmetry breaking. Results for the type I scenario are presented in figure 7.

4. Additional Higgs bosons-like states

A Higgs boson as been observed in the diphoton decay channel with the combination of 7 and 8 TeV datasets collected by the CMS experiment [8]. An ancillary result of the analysis is performed by substracting the observed state, and search for an addition Higgs-boson-like state in the diphoton mass spectrum, applying the the exact same experimental techniques.

A search for additional states within $m_{\gamma\gamma} \in [110, 150]$ [120, 130] GeV is performed, as well as

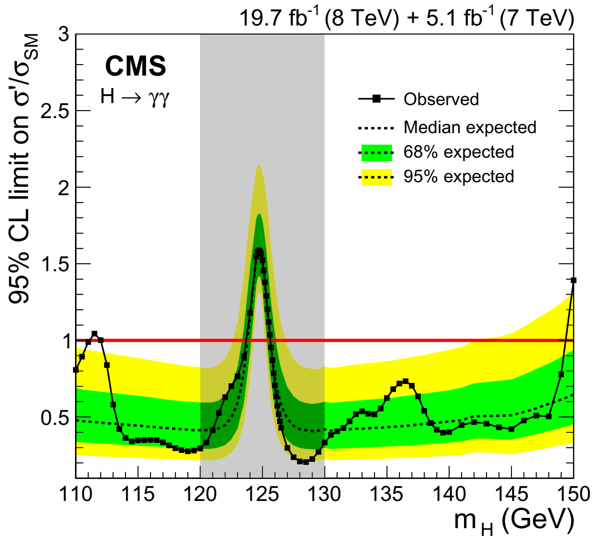

Figure 8: Expected and observed exclusion limits on the signal strength σ'/σ_{SM} for a second Higgs-boson-like state with SM couplings taking the observed state at 125 GeV as part of the background [8].

a search for near and mass degenerate states in [120, 130] GeV, at a masses m_h and $m_h + \Delta m_H$ with respective signal strength of μx and $\mu(1-x)$. No additional deviation from expectations is observed. The result for the first search is presented in figure 8.

5. Conclusion

Four searches for the production of two Higgs bosons using the CMS detector have been presented. The analyses have been performed on pp collision data collected during the Run I of the LHC at $\sqrt{s} = 7 - 8$ TeV corresponding to an integrated luminosity of 5.1 − 17.9-19.7 fb^{-1}. The analyses are covering the resonant production of Higgs boson pairs in the $b\bar{b}\gamma\gamma$ and $b\bar{b}b\bar{b}$ final states for masses between 260 and 1100 GeV, the resonant production of Higgs boson pair in multilepton and diphoton final states for masses between 260 and 360 GeV, as well as additional Higgs boson-like states in the diphoton spectrum for masses between 110 and 150 GeV. The observations are compatible with expectations from standard model processes, and upper limits at 95% confidence-level are extracted on the cross section of new particles production. A summary of the results presented here can be found for the spin-0 case in figure 9.

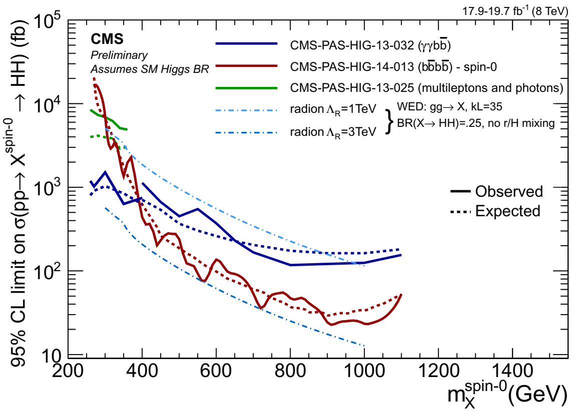

Figure 9: The expected and observed upper limit of spin-0 X to HH production at 95% CL$_s$ provided by combining the searches performed by the CMS experiment looking at the $b\bar{b}\gamma\gamma$ [7], $b\bar{b}b\bar{b}$ [9], and multileptons and photons [10] final states . Theoretical cross sections for the RS1-radion, with $\Lambda_R = 1$ and 3 TeV, $kL = 35$, and no radion-Higgs boson mixing are overlaid.

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