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Search for the radion decay into a Higgs boson pair with $\gamma\gamma$+bb, $\tau\tau$+bb and bb+bb final states

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Abstract

The CMS discovery potential for the radion decay into two Higgs bosons with $\gamma\gamma$+bb, $\tau\tau$+bb and bb+bb final states is studied. The case of a radion mass of 300 GeV/c^2 and a Higgs boson mass of 125 GeV/c^2 is considered. The discovery reach with 30 fb^{-1} in the plane of two other parameters of the Randall-Sundrum model, ξ and Λ_ϕ, is evaluated.

1 Introduction

The Randall Sundrum model (RS) [1, 2] has recently received much attention because it could provide a solution to the hierarchy problem [3], by means of an exponential factor in a five–dimensional non-factorizable metric. In the simplest version, the RS model is based on a five–dimensional universe with two four-dimensional hypersurfaces (branes), located at the boundaries of the fifth coordinate y. The fluctuations in the metric in the fifth dimension are described in terms of a scalar field, the radion, which in general mixes with the Higgs boson. This scalar sector of the RS model is parametrized in terms of a dimensionless parameter ξ, of the Higgs and radion masses $\mathrm{m_h}$, $\mathrm{m_\phi}$ and the vacuum expectation value of the radion field Λ_ϕ.

The phenomenology of the Higgs boson and the radion at LHC has been subject to several studies [4–9] focusing mainly on Higgs boson and radion production. The Higgs boson and radion detection is not guaranteed in the whole parameter space. The presence in the Higgs boson–radion sector of trilinear terms opens the possibility of $\phi \to \mathrm{hh}$ and $\mathrm{h} \to \phi\phi$ decays. For example for $\mathrm{m_h} = 120$ GeV/c^2, $\Lambda_\phi = 5$ TeV and $\mathrm{m_\phi} \sim$ 250-350 GeV/c^2, the $\phi \to \mathrm{hh}$ branching ratio ranges between 20 and 30 %.

In this report, the CMS discoverya potential is estimated for the decay of a radion in a pair of Higgs bosons with $\gamma\gamma$+$\mathrm{b\bar{b}}$, $\tau\tau$+$\mathrm{b\bar{b}}$ and $\mathrm{b\bar{b}}$+$\mathrm{b\bar{b}}$ in the low luminosity run conditions of LHC (peak luminosity of 2×10^{33}cm^{-2}s^{-1}). The study has been carried out for a radion mass of 300 GeV/c^2 and a Higgs boson mass of 125 GeV/c^2. The visibility of a signal in the (ξ, Λ_ϕ) plane was evaluated, taking into account estimates of systematic incertainties. Signal events have been reconstructed with the full CMS simulation/reconstruction package, while background events have been analysed with fast simulation. The analysis has been performed considering an integrated luminosity of 30 fb^{-1}.

2 Analysis of the $\gamma\gamma\mathrm{b\bar{b}}$ final state

At the scale Λ_ϕ = 1 TeV, the maximal signal cross section times branching ratio for the $\gamma\gamma\mathrm{b\bar{b}}$ final state is 83 fb. A total of 2490 signal events is thus expected to be produced at best.

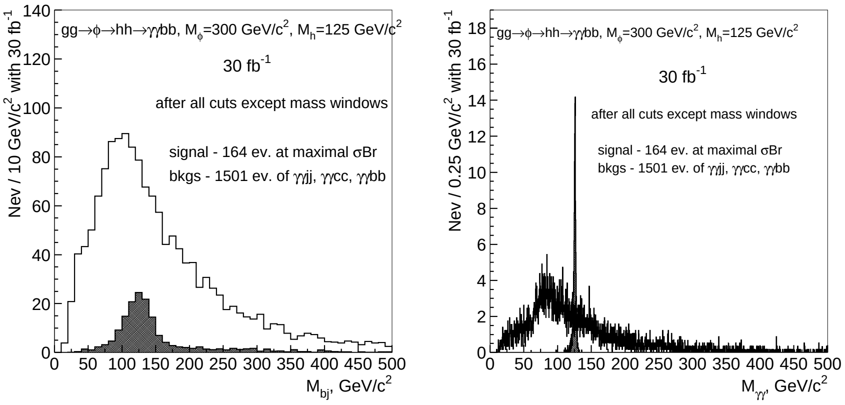
The irreducible di-photon background was generated with CompHEP [10] and with MadGraph [11]. The leading–order cross sections are shown in Table 1 together with the number of events expected to be produced. The reducible background from γ + three jets and four-jet processes still has to be evaluated. From preliminary studies, the reducible background was assumed to be of about 40 % of the total background after all selections.

Table 1: Irreducible background cross sections and number of events expected.

process	$\gamma\gamma$jj	$\gamma\gamma\mathrm{c\bar{c}}$	$\gamma\gamma$bb
cross-section, fb	13310	778	76
N events with 30 fb^{-1}	3.99×10^6	2.33×10^4	2.28×10^3

Two isolated photons with transverse energy greater than 40 and 25 GeV were required. The energy thresholds follow the standard CMS trigger selection on di-photon events [12]. Events with two calorimeter jets of $\mathrm{E_T} > 30$ GeV and within $|\eta| <$ 2.4 were selected. At least one jet had to be tagged as a b jet. Further selections require the di-jet (di-photon) mass, $\mathrm{M_{bj}}$ ($\mathrm{M_{\gamma\gamma}}$), to be in a window of ± 30 (2) GeV/c^2 around the peak of the Higgs boson mass distribution. Finally, the $\mathrm{M_{\gamma\gamma bj}}$ mass should be in a window of ± 50 GeV/c^2 around the fitted peak in the radion mass distribution.

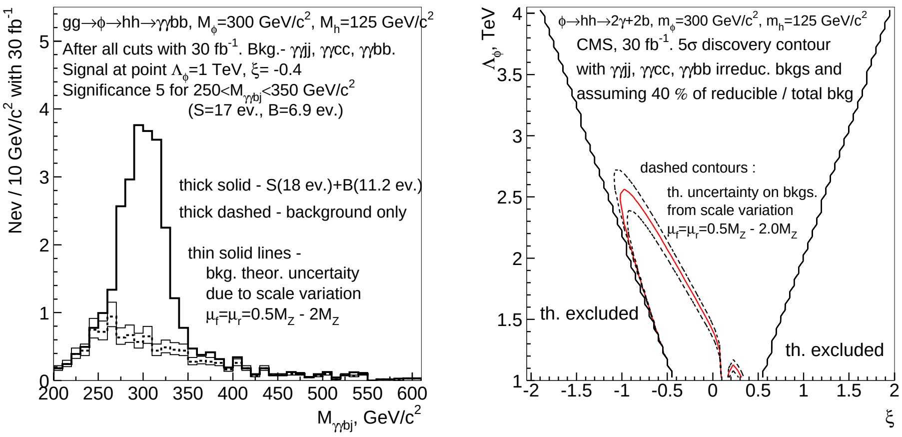
The whole selection efficiency for signal events is 3.7% , while the efficiency for the background events is about 7 $\times10^{-4}$. The expected irreducible background amounts to 6.9 events after all selections. Figure 1 shows the di-jet (a) and di-photon (b) mass distributions for the signal and background after all selections (except the mass window cuts). The signal is shown for the maximal cross section times branching ratio point in the (ξ, Λ_ϕ) plane. Figure 2a shows the radion invariant mass, $\mathrm{M_{\gamma\gamma bj}}$, for the background and signal–plus–background after all selections. The signal is shown for the (ξ,Λ_ϕ) point where a statistical significance of 5 is obtained. The CMS discovery reach was obtained in the (ξ, Λ_ϕ) plane with the expected number of the irreducible plus the reducible background events after all selections. Figure 2b shows the 5σ discovery contour in the (ξ, Λ_ϕ) plane. Theoretical uncertainties on the background cross section have also been considered (dashed contours). Systematic uncertainties due to the energy scale of the calorimeters and to the different shape of the mass distribution of the background events due to different factorization, normalization scale and different structure functions do not affect the final result significantly.



(a)

(b)

Figure 1: The background (open histogram) and signal (solid histogram) Higgs boson mass distributions after all selections except the mass window cuts. The di-jet mass is shown in (a), and the di-photon mass is shown in (b). The signal is shown for the maximal cross section times branching ratio point in the (ξ, Λ_ϕ) plane.



(a)

(b)

Figure 2: (a) The signal (thick solid line) plus background (thick dashed line) $\mathrm{M}_{\gamma\gamma\mathrm{bj}}$ distribution is shown for the (ξ, Λ_ϕ) point where a statistical significance of 5 is obtained. The thin solid histograms correspond to the uncertainties on the irreducible background cross section. (b) The 5σ discovery contour for the $\phi \rightarrow \mathrm{hh} \rightarrow \gamma\gamma$+$\mathrm{b\bar{b}}$ channel (m_ϕ=300 GeV/c^2, $\mathrm{m_h}$=125 GeV/c^2). Irreducible and reducible backgrounds were taken into account. The dashed line contours present the discovery regions when the irreducible background cross sections uncertainties have been considered.

3 Analysis of the $\tau\tau\mathrm{b\bar{b}}$ final state

The signature in which one τ decays leptonically and another decays hadronically (producing a τ jet) was considered. For the signal, the highest cross section times branching ratio for this signature is 0.96 pb at ξ=$-$0.35 and Λ_ϕ=1 TeV. About 29 000 signal events are expected to be produced at best. The background processes considered are shown in Table 2. They were generated with PYTHIA 6.158 [13] apart from the $\mathrm{Zb\bar{b}}$ background which was generated using CompHEP. Next-to-leading order cross sections have been used for all the background samples [14]. The $\mathrm{t\bar{t}}$ background when both W bosons decay into τ's was not simulated, but its contribution to the total background was estimated to be about 10%.

The lepton–plus–τ-jet trigger [12] was used in the analysis. The τ-jet isolation criteria was found to be essential

Table 2: The next-to-leading order cross section times branching ratio and the number of events expected for the backgrounds.

background process	σ (pb)	$\sigma \times$ BR (pb)	N ev. with 30 fb^{-1}
$\mathrm{t\bar{t}} \rightarrow \ell + \nu + \mathrm{jets} + \mathrm{b\bar{b}}$	825	245	$7.3{\times}10^6$
$\mathrm{t\bar{t}} \rightarrow \ell + \nu + \tau\,\mathrm{jet} + \mathrm{b\bar{b}}$	825	27	$8{\times}10^5$
$\mathrm{Zb\bar{b}} \rightarrow \tau\tau + \mathrm{b\bar{b}}$	525	8	2.4×10^5
Z + jets $\rightarrow \tau\tau$ + X ($\hat{\mathrm{p}}_\mathrm{T} >$ 20 GeV/c)	23300	355	10.6×10^6
W + jets $\rightarrow \ell + \nu$ + X ($\hat{\mathrm{p}}_\mathrm{T} >$ 80 GeV/c)	4100	900	27×10^6

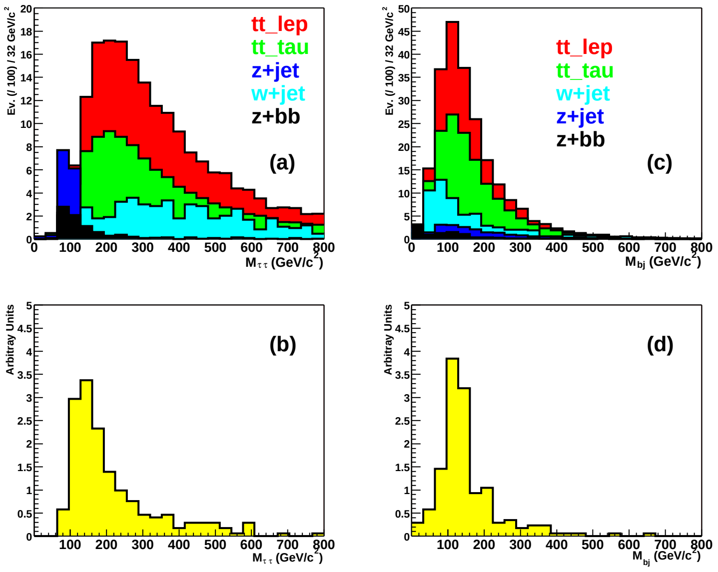


Figure 3: The distributions of $\mathrm{M}_{\tau\tau}$ and M_bj for the background (a,c) and the signal (b,d).

for the background suppression. In the following the assumption is made that the radion is discovered with the $\gamma\gamma\mathrm{b\bar{b}}$ final state and that the Higgs boson mass is known from the observed peak in the di-photon mass distribution of the $\gamma\gamma\mathrm{bj}$ events.

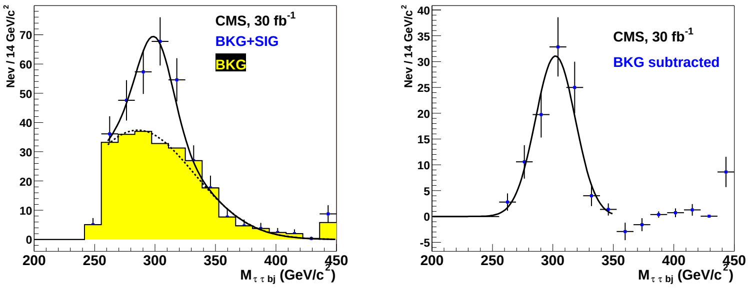
The original τ energy was reconstructed using the missing energy measurement and the collinear approximation [15]. In this way it is possible to reconstruct the $\tau\tau$ invariant mass $\mathrm{M}_{\tau\tau}$. Figures 3(a,b) show the $\mathrm{M}_{\tau\tau}$ distribution for both the signal and the background. In order to reconstruct also the second Higgs boson, the presence of at least two jets with transverse energy greater than 30 GeV was required. At least one of them had to be tagged as a b jet. Figure 3 (c,d) show the invariant mass distribution of the two jets, M_bj, for both the signal and the background. The following cuts were applied to select signal events:

- b-tagged jet reconstructed invariant mass: $100 < M_\mathrm{bj} <$150 GeV/c^2;
- τ jet reconstructed invariant mass: $100 < M_{\tau\tau} <$160 GeV/c^2.

In order to increase the resolution of the reconstructed radion invariant mass, jet energies were rescaled with a kinematical fit imposing that the reconstructed invariant masses be equal to the known Higgs boson mass.

Figure 4a shows the reconstructed radion mass for signal−plus−background after all selections and the kinematical fit for the maximal signal cross section. The solid line is the result of the fit to the signal plus background distribution, and the dashed line is the shape of the expected background. Figure 4b shows the same distribution after the subtraction of the background.

A further cut on this reconstructed mass is then applied, $290 < M_{\tau\tau\mathrm{bj}} < 330$ GeV/c^2. The final signal efficiency is about 0.27%, while the background efficiency is less than $3{\times}10^{-5}$. The total number of background events



(a) (b)

Figure 4: (a) Reconstructed radion mass, for signal plus background. (b) Reconstructed radion mass after having subtracted the expected background.

after all the selections is 84, in which the $\mathrm{t\bar{t}}$ production gives the largest contribution (64 events) while the W+jets sample is negligible. The contribution of $\mathrm{t\bar{t}}$ with two τ's in the final state has been estimated to be an additional eight events, so that the number of background events increases to about 92. For the highest cross section of 0.96 pb (ξ=$-$0.35 and Λ_ϕ=1 TeV), about 79 signal events are expected in the same running period, for a statistical significance greater than 8. Figure 5a shows the 5σ discovery contour in the (ξ, Λ_ϕ) plane considering statistical and NLO uncertainties. Figures 5 (b,c) show the effect of a systematic uncertainty of 5 and 10% on the number of background events.

4 Analysis of $\mathrm{b\bar{b}b\bar{b}}$ final state

The four b-jet final state yields the biggest rate for the signal. The maximal cross section times branching ratio at Λ_ϕ= 1 TeV is 10.3 pb giving about of 3.1$\times$10^5 signal events with 30 fb^{-1}. The effective triggering and selection in off-line analysis of these events is, however, a big challenge due to the huge multi-jet background rate, about 7×10^{12} background events are expected. The channel requires a dedicated trigger with double b tagging. The backgrounds considered in the analysis of the four b-jet final state were QCD multi-jet production, $\mathrm{t\bar{t}}$ and $\mathrm{Zb\bar{b}}$ (generated with CompHEP). The main contribution comes from QCD with $\hat{\mathrm{p}}_\mathrm{T} > 100$ GeV/c with a cross section of about 3 μb. The most dangerous scenario is expected with four bottom quarks in the final state coming from initial and final state radiation and gluon splitting in QCD multi-jet production. The event selection is based on the jet transverse energy, the identification of the b jet and their association to the right Higgs boson. The request that the two reconstructed masses were compatible with each other was also made.

The four jet invariant mass distribution of the signal events has the same shape of the background distribution. The signal significance can be extracted only using a counting experiment and even a systematic uncertainty on the number of expected background events of 0.1% would prevent a 5σ discovery. This makes the access to this final state essentially hopeless.

5 Conclusions

The CMS discovery potential has been estimated for the radion dacay into two Higgs bosons ($\phi \rightarrow \mathrm{hh}$) in the $\gamma\gamma$+$\mathrm{b\bar{b}}$, $\tau\tau$+$\mathrm{b\bar{b}}$ and $\mathrm{b\bar{b}}$+$\mathrm{b\bar{b}}$ final states. The point with m_ϕ=300 GeV/c^2 and $\mathrm{m_h}$=125 GeV/c^2 was chosen and the observability in the (ξ, Λ_ϕ) plane was evaluated. It was found that the $\gamma\gamma$+$\mathrm{b\bar{b}}$ topology provides the best discovery potential.

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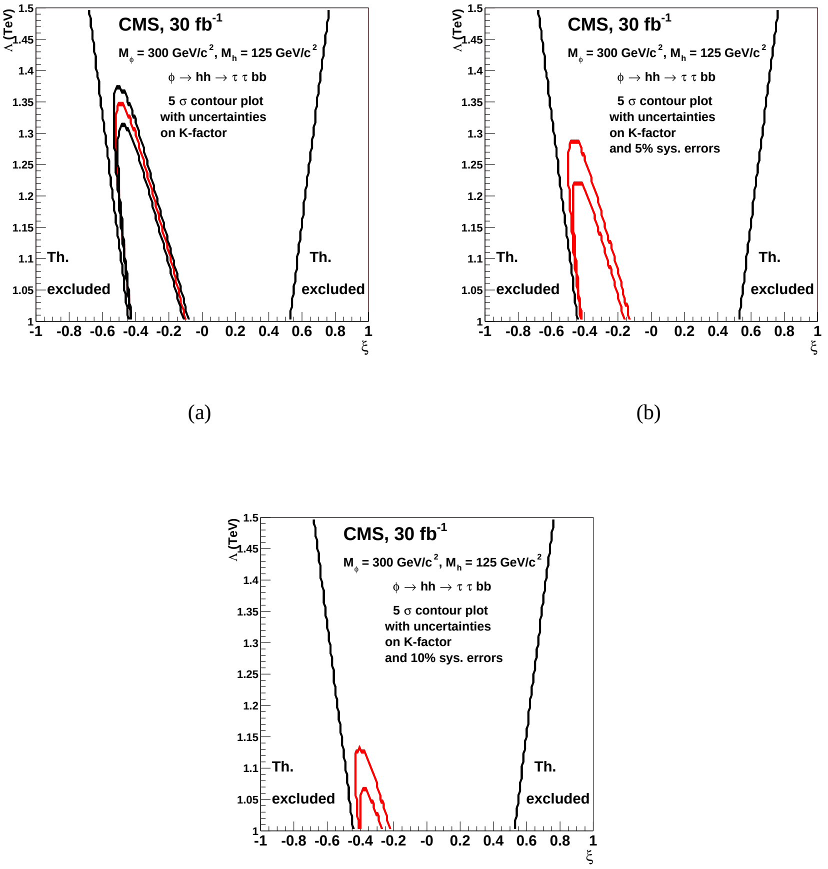

(a) (b)

(c)

Figure 5: (a) The 5σ discovery contour. The central line takes into account only statistical uncertainties, upper and bottom lines show the variation due to the uncertainties in the NLO cross section. The other plots show the 5σ discovery contour considering systematic uncertainties of 5% (b) and 10% (c) on background, and NLO uncertainties on the background cross sections.

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