CMS Conference Report

Higgs bosons in non-minimal models at the LHC

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Abstract

While approaching the start of the data taking at the LHC, ATLAS and CMS perform studies involving the Higgs boson within non-minimal models besides Supersymmetric models. Highlights from both experiments are summarized; all results refer to LHC low luminosity conditions of 10^{33} cm^{-2} s^{-1}.

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Higgs boson in non-minimal models at the LHC

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1 Introduction

Despite its longstanding huge predictive power, the Standard Model of Electroweak interactions (SM) is affected by a few flaws. One of them is the famous "hierarchy problem": if radiative corrections to the Higgs boson mass are computed using an ultra-violet cut-off Λ, the resulting value for the Higgs boson mass is if the order of Λ unless a very delicate cancellation takes place. The most important radiative corrections to the Higgs boson mass arise from loops involving the top quark, gauge bosons and the Higgs itself. An extremely un-natural fine tuning is required to keep the Higgs boson mass of the order of the electroweak energy scale.

Aside from just passively accepting that Mother Nature might be so fine-tuned other viable theoretical solutions can be attempted, which either stabilize the Higgs boson mass through additional symmetries and/or shift the cut-off through some mechanism. Supersymmetry is nowadays the most credited solution to the hierarchy problem and many write-ups on the subject can be found in these proceedings.

This paper is devoted instead to present studies on simulated data devoted to investigate discovery prospects within other theoretical frameworks such as Little Higgs, Left-Right Symmetric and Randall-Sundrum models. Each of the following sections will be devoted to one of these models; a brief reminder about the phenomenological focal points if the model is followed by the relevant studies on simulated data.

2 Little Higgs Model

In the Little(st) Higgs model [1] the SM Higgs boson remains light because of the introduction of a global symmetry which breaks at the TeV energy scale. The global symmetry implies the existence of new heavy gauge bosons ($W^{\pm}_{H}$,Z_{H}, γ_{H}) and of a new heavy Top quark in the 1 TeV scale as well as a triplet of heavy Higgs bosons ($\Delta^{\pm\pm}$,$\Delta^{\pm}$,Δ^{0}) in the 10 TeV scale. They all contribute to cancel the one-loop quadratic divergences in the Higgs boson mass. From the phenomenological point of view is important to emphasize that a) the SM Higgs boson does still exist in the model and the experimental standard searches apply as usual b) the new Higgs bosons in the model have rather lose mass constraints.

2.1 Experimental expectations

The CMS Collaboration has investigated, using full detector simulation, the discovery potential of doubly-charged Higgs bosons in the Drell-Yan pair-production process ($q\overline{q} \rightarrow \Delta^{++}\Delta^{--}$) with the $\Delta^{\pm\pm}$ decaying to same-sign muon pairs [4]. The decay branching fraction to muon pairs was assumed to be 100%. The four-muon final state provides an exceptionally clear signature with SM background naturally small. The muon pair invariant mass shows the signal already after the online event selection and only fewer additional loose cuts enhance it to the level shown in Fig. 1 where distributions are shown for an integrated luminosity of 10 fb^{-1}. The statistical interpretation of the invariant mass spectrum leads to a discovery limit of 650 GeV and exclusion up to 760 GeV (Fig. 2). The search of doubly-charged Higgs bosons was also investigated by ATLAS in the single production via Vector Boson Fusion [5]. The results, however, were not very encouraging since the sensitivity was poor even with an integrated luminosity of 300 fb

3 Left-Right Symmetric Models

In Left-Right Symmetric Models (LRSM) two (left and right handed) Higgs boson triplets provide a parity-conserving Lagrangian so that all fermions are treated

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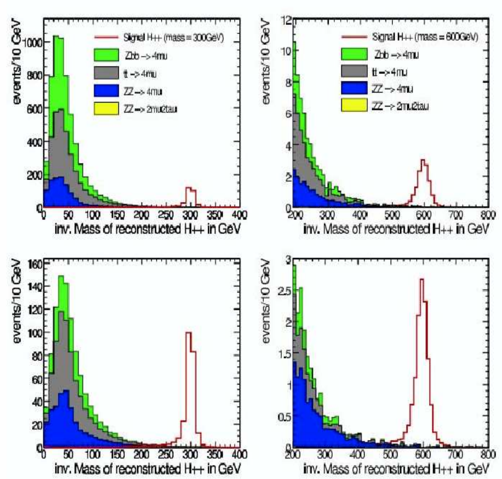

Fig. 1. Reconstructed same-sign muon invariant mass after online selection (upper plots) and after offline selection (lower plots). Plots correspond to an integrated luminosity of 10 fb^{-1}.

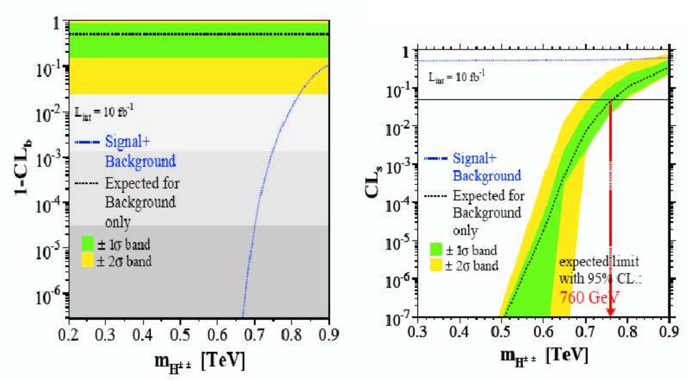

Fig. 2. Left: 1-CL_b as a function of the reconstructed $\Delta^{\pm\pm}$ mass: the discovery limit is 650 GeV. Right: CL_s as function of the reconstructed $\Delta^{\pm\pm}$ mass: the exclusion limit is 760 GeV. Results are shown for an integrated luminosity of 10 fb^{-1}.

symmetrically as Left Handed and Right Handed doublets [2].

Based on $\mathrm{SU(2)_L \times SU(2)_R \times U(1)_{B-L}}$, the new symmetry leads to the introduction of new neutrinos, bosons and Higgs bosons, in particular doubly-charged Higgses as it was the case in the Little Higgs model. A peculiar aspect of the LRSM is that the Yukawa couplings of the Higgs boson triplet allow the existence of Majorana mass terms of the Right-Handed neutrinos, rendering the see-saw mechanism possible [3]. The LRSM is hence capable to solve both the hierarchy problem and to naturally explain the experimental evidence of low, non-zero mass of the Left-Handed neutrinos [6].

3.1 Experimental expectations

The LRSM has a number of interesting signatures. The interest however is here concentrated on Higgs bosons.

As in the case of the Little Higgs, the observation of doubly-charged Higgs would provide important evidence of new physics. Search techniques of left-handed doubly-charged Higgs go along the lines of what already seen in Sec. 2. The ATLAS collaboration has also probed the discovery reach for right-handed doubly-charged Higgs [7], in single production via VBF with decay into lepton pairs (e,μ). Since the background is negligible, discovery can be claimed if the number of signal events is greater than 10. The discovery reach is illustrated in Fig. 3.

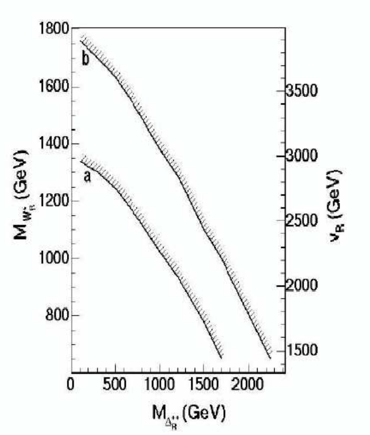

Fig. 3. Discovery reach for $\Delta_R^{++} \to l^+l^-$ in the $(\mathrm{m}_{\Delta_R^{++}}, \mathrm{m}_{W_R}^{+})$ plane for integrated luminosity of 100 fb^{-1} (a) and 300 fb^{-1} (b).

4 ExtraDimensions: Randall-Sundrum model

In its basic formulation [8] the Randall-Sundrum model introduces only one extra dimension so that the Universe is described in terms of two four-dimensional Minkowskian branes bounding a five-dimensional bulk. The so called "weak gravity" brane is the one where the world we know sits, i.e. where the ElectroWeak and TeV scale processes occur. At the other end of the five-dimensional space, separated by a distance proportional to the "compactification radius" r_c, there is instead the so called "strong gravity" brane, where gravity is at the Plank scale. The law describing the relation between the two branes is a decreasing exponential governed by the "warp factor" kr_c. The hierarchy between the Planck and ElectroWeak scale is removed if $\mathrm{kr}_c \sim 12$ so that the compactification radius is extremely small ($\sim 10^{-32}$m) and no deviations from Newton's law are visible at experimental level. The RS model makes a number of predictions, the existence of the graviton being the central one. However more interesting in the context of this paper is the fact that to stabilize the size of the extra dimension (i.e. $\mathrm{kr}_c \sim 12$) it was necessary, after the first formulation of the model, to introduce the radion Φ [9], representing the fluctuations of the distance between the two branes. The RS scalar sector has only four free parameters (m_Φ= radion mass, m_h= SM Higgs mass, Λ_Φ= radion v.e.v. and ξ= Φ-h mixing). Very important aspects are that $\Lambda_\Phi \sim$1TeV and $m_\Phi <$1 TeV without need of fine tuning, the radion and the SM Higgs boson couplings to gauge bosons and fermions are very similar and, finally, that the radion and the Higgs boson mix. The latter point implies that for certain regions of the parameter space the decay channel $\Phi \rightarrow$hh opens up and can be investigated in the classical Higgs boson decay channels, i.e. $\gamma\gamma b\overline{b}$, $\tau\tau b\overline{b}$ and $b\overline{b}b\overline{b}$.

4.1 Experimental expectations

ATLAS and CMS have both concentrated their work on the $\gamma\gamma b\overline{b}$ and $\tau\tau b\overline{b}$ final states [10,11], $b\overline{b}b\overline{b}$ being very difficult and almost hopeless because of the huge multi–jet background which affects it. ATLAS and CMS adopt two different approaches for the search in $\gamma\gamma b\overline{b}$; while ATLAS assumes that the SM Higgs has already been discovered and its mass measured, CMS has developed an analysis strategy aiming to discovering the radion and the Higgs boson at the same time.

The general event selection is based on requiring two high-p_T, isolated photons and two high-p_T jets of which at least one must come from a b-quark. Backgrounds to this channel come from $\gamma\gamma b\overline{b}$, $\gamma\gamma$bj, $\gamma\gamma$jj, $\gamma\gamma$cj and $\gamma\gamma c\overline{c}$ but they are on overall small. PYTHIA and fast detector simulation were used by ATLAS for both signal and background; PYTHIA and full detector simulation were used by CMS to produce signal samples while MadGraph [12], CompHep [13] and fast detector simulation were used for the backgrounds.

In ATLAS the di-photon and di-jet invariant masses were calculated and mass window cuts applied: $m_{\gamma\gamma}$=$m_h \pm 2$ GeV and m_{bj}=$m_h \pm 20$ GeV. Photons and jets satisfying these conditions were combined to calculate the $m_{\gamma\gamma bj}$ invariant mass as shown in Fig. 4.

A constraint of the Higgs boson invariant mass to its "known" value improves the resolution. Since the background in this channel is low, a discovery can be claimed if at least ten signal events are found. An integrated luminosity of 30 fb^{-1} leads to a reach in Λ_ϕ up to 2.2 TeV for m_Φ=300 GeV and up to 0.6 GeV for m_Φ=600 GeV.

According to its different approach, CMS would attempt a simultaneous discovery of the Higgs boson and of the radion. The observation of a peak in the di-photon mass distribution obtained from the selected sample of $\gamma\gamma$bj events would indicate the presence of one of the two Higgs bosons (Fig. 5). Di-photon events falling in a window of 4 GeV around the peak and di-jets events falling within 60 GeV from the $\gamma\gamma$ peak can be considered to isolate the radion signal.

The radion can be discovered from the excess of events over the background level expected after the same set of selection requirements have been applied (Fig. 6). The statistical interpretation of CMS discovery strategy leads to a reach in Λ_Φ up to $\sim$ 2.5 TeV.

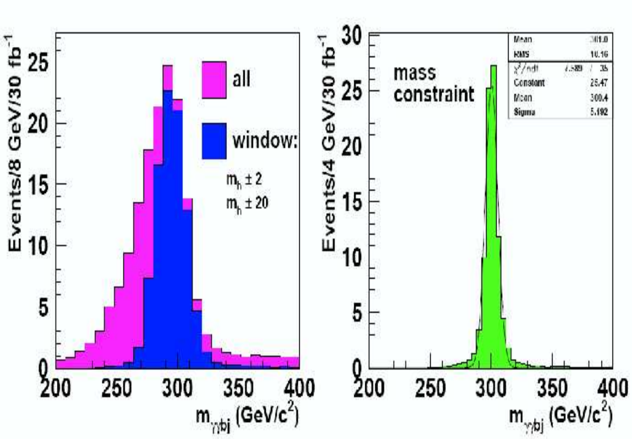

Fig. 4. Reconstructed $\gamma\gamma$bj invariant mass distribution for m_h=125 GeV, m_Φ=300 GeV, ξ = 0, Λ_Φ = 1 TeV and for 30 fb^{-1}. The plot on the left shows all combinations as well as those fulfilling the mass window cuts. The plot on the right is obtained by constraining the reconstructed masses m_{bj} and $m_{\gamma\gamma}$ to the light Higgs mass m_h, after the mass window cuts.

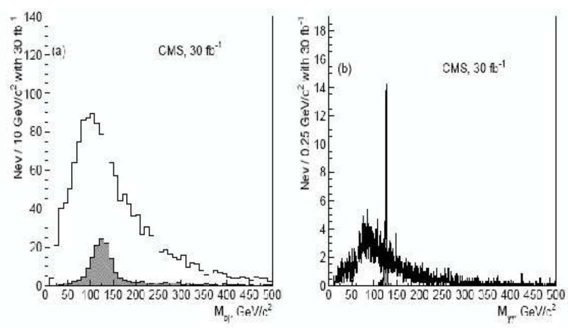

Fig. 5. (a) Di-jet invariant mass and (b) di-photon invariant mass. The signal is shown by the solid histograms. The distributions were obtained after all selection criteria but the mass window had been applied. The signal is shown for the more favourable point in the (ξ, Λ_Φ) plane.

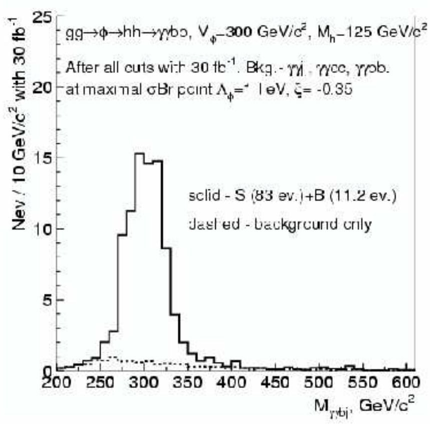

Fig. 6. $\gamma\gamma$bj invariant mass after all selection requirements, including the mass windows for signal (solid line) and background (dashed line).

The study of the $\tau\tau b\overline{b}$ final state, with one τ decaying leptonically and the other hadronically, was also

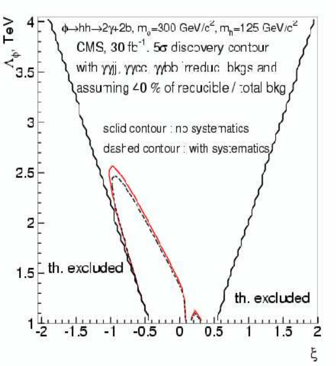

Fig. 7. The 5-σ contour for $\Phi \rightarrow \gamma\gamma b\overline{b}$ for m_h=125 GeV, m_Φ=300 GeV, $\xi = -0.35$, $\Lambda_\Phi = 1$ TeV and for 30 fb^{-1}. The dashed and solid contour lines refer to the discovery region accessible with and without including the systematic uncertainties arising from background evaluation and from renormalization and factorization scales.

performed by both ATLAS [10] and CMS [11], assuming that the Higgs mass is already known. Results obtained with this channel, however, are not so encouraging as for the $\gamma\gamma b\overline{b}$ channel. In general the signal efficiency is low and the analysis risks to be largely dominated by systematic errors due to the evaluation of the background. The expected reach in Λ_Φ is up to $\sim$1 TeV.

5 Conclusions

Non-minimal models such as those briefly presented in this paper, are becoming popular as alternative solutions to the hierarchy problem which afflicts the Standard Model. Both ATLAS and CMS Collaborations are investigating the discovery potential of the new “zoo” of particles necessarily introduced by the models to cancel the divergent radiative corrections to the Higgs boson mass.

The search of doubly-charged Higgs bosons was investigated both in VBF and Drell-Yan production. The sensitivity at large masses (> 1 TeV) seems to be rather poor, however discovery can be achieved up to ~ 650 GeV (exclusion up to ~ 750 GeV).

Right Handed doubly-charged Higgs bosons appearing in the LRSM can be probed in the purely leptonic channel up to ~ 1.7 TeV (100 fb^{-1}).

Finally, it should be possible to probe the Randall-Sundrum scalar sector up to $\Lambda_\Phi \sim 2.5$ TeV by looking at $\Phi \rightarrow hh \rightarrow \gamma\gamma b\overline{b}$.

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