Search for hadronic decays of $\mathrm{Z_H}$ and $\mathrm{W_H}$ in the Little Higgs model

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Abstract

The decay of heavy gauge bosons Z_H and W_H into hadrons is analysed in the context of the 'Little Higgs model'. The mass of these heavy bosons is assumed to be 1 or 2 TeV and decay modes involving b-quarks or t-quarks are investigated.

1 Introduction

Heavy gauge bosons Z_H and W_H are predicted in the context of the so-called 'Little Higgs model' [1]. These particles are similar to the usual gauge bosons Z and W, but their masses are expected to be in the TeV region. Within the simplest model, described in [2], Z_H and W_H are degenerate in mass. The discovery potential of ATLAS for these heavy particles has been investigated in detail elsewhere [3]. It has been shown that, if Z_H and W_H exist, they can be reconstructed using as discovery channels their leptonic decays, $Z_H \to e^+e^-$ and $W_H \to e\,\nu_e$, up to masses of 5 to 6 TeV. In this note, the much more challenging hadronic channels $Z_H \to b\,\bar{b}$, $t\,\bar{t}$ and $W_H \to t\,b$ are investigated. These channels are more difficult to detect but may provide very useful information about Z_H and W_H, in case a resonance is found in any of the leptonic channels mentioned before. More precisely, the detection of these hadronic decay channels should allow a measurement of the couplings between heavy gauge bosons and quarks.

2 Cross-sections and Branching ratios

According to [2], the couplings of Z_H and W_H depend on a single parameter: the θ angle. This value is not really constrained in the model, but for practical reasons, the value $\cot\theta = 1$ is assumed as an example in the following.

The cross-sections at LHC have been calculated using PYTHIA with proper couplings[1] and CTEQ5L PDF's. The results are displayed in table 1.

M (TeV)	σ (Z_H) pb	σ (W_H) pb
1	19	37
2	0.9	1.9

Table 1: Z_H and W_H production cross-sections at LHC assuming $\cot\theta = 1$.

The BR's and total widths of Z_H and W_H can be deduced from the information provided in [2]. Neglecting QCD corrections and fermion masses (also for top quark), the total widths of Z_H and W_H are equal. The result is:

$$\Gamma/M = [\,3.4\, cot^2\theta + 0.071\, cot^2 2\theta\,]\,\%$$

where the first term includes all possible fermion decays and the second term only the higgs decays $Z_H \to Zh$ and $W_H \to Wh$, where h is the standard model Higgs boson.

As a consequence of gauge symmetry, all branching ratios of Z_H and W_H to fermions are equal, except for the usual colour factor of 3 (in case of quarks) or 1 (in case of leptons). It follows that Zh and Wh decays vanish if $\cot\theta = 1$ (therefore $\cot 2\theta = 0$) and the Branching Ratios to heavy quarks are:

$$BR(Z_H \to b\,\bar{b}) = BR(Z_H \to t\,\bar{t}) = 1/8 = 12.5\%$$

$$BR(W_H \to t\,b) = 1/4 = 25\%$$

All possible values of $\cot\theta$ are considered in the following.

3 Event simulation

Events have been generated using the MC program PYTHIA coupled to ATLFAST [4] to simulate the detector response. The heavy gauge bosons Z' and W' of PYTHIA were used for Z_H and W_H. The corresponding couplings were taken from reference [2]. The production mechanisms 141 ($f\bar{f}_i \to \gamma/Z/Z'$) and 142 ($f_i\bar{f}_j \to W'$) were selected to generate Z_H and W_H, respectively.

[1] These proper couplings are the following in the case of Z':
PARU(I) = $\cos\theta_W$ (I = 121, ... 128), PARJ(I) = $\cos\theta_W$ (I = 180, ... 195),
where θ_W is the Weinberg angle. In this way the couplings of Z' agree with those of Z_H as defined in reference [2]. The couplings of W' and W_H agree without any further modification.

The following sets of events were used in the analysis:

- Signal: $Z_H \to b\,\bar{b}$, $t\,\bar{t}$ and $W_H \to t\,b$ with $\mathrm{M}(Z_H) = \mathrm{M}(W_H) = 1$ and 2 TeV. Samples of 10 000 events were generated for each decay and mass value except for $Z_H \to t\,\bar{t}$ (20 000 events) and $W_H \to t\,b$ (100 000 events) in both cases with M = 1 TeV.

- Background: Standard Model final states containing $b\bar{b}$, $t\bar{t}$, 2 jets and $W + jets$. Since only events with very high p_T jets and large center of mass energy are relevant in the analysis, it was imposed at the generation level that $\sqrt{s^*} > 0.5(1.0)$ TeV and $p_T^* > 0.1(0.25)$ TeV, where $\sqrt{s^*}$ and p_T^* are the center-of-mass energy and transverse momentum of the hard process. The low cuts were used in the background estimation for M = 1 TeV, and the high cuts for M = 2 TeV. Samples of 100 000 events were generated for each final state, except for the $t\,\bar{t}$ sample with low cuts (2M events).

The event samples are such that the statistical fluctuations correspond aproximately to $\mathcal{L} = 3 \cdot 10^4 pb^{-1}$ for M = 1 TeV and $\mathcal{L} = 3 \cdot 10^5 pb^{-1}$ for M = 2 TeV.

4 Event analysis

For the analysis of the decay $Z_H \to b\,\bar{b}$, the following cuts are applied for M = 1 (2) TeV, respectively:

- 2 b-jets with $p_T > 250$ (500) GeV and $|\eta| < 2.5$.

The b-tagging of very high p_T jets for this mode and also for the following modes is discussed in the Appendix. Two background sources have been analysed: $b\,\bar{b}$ production (irreducible background) and 2 jet production (reducible background).

For the analysis of the decay $Z_H \to t\,\bar{t}$, the following cuts are applied for M = 1 (2) TeV, respectively, assuming that one of the t-quarks decays leptonically:

- A lepton (electron or muon) with $p_T > 25$ GeV and $|\eta| < 2.5$, and in addition $(E_T)_{miss} > 25$ GeV (this cut is also useful to fulfil the trigger requirements).

- 2 b-jets with $p_T > 25$ GeV and $|\eta| > 2.5$, the first jet such that Δ(b-lepton) < 2 and the second such that Δ(b-lepton) > 2. The distance Δ is defined in the usual way as

$$\Delta = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$

where ϕ is the azimuthal angle and η is the pseudorapidity.

It is noted that the Δ cut is useful to identify the b-jet from the leptonic decay of the top-quark and the b-jet from the hadronic decay of the top-quark (see fig. 1), but does not provide any significant discrimination against the background, since this background is mainly irreducible.

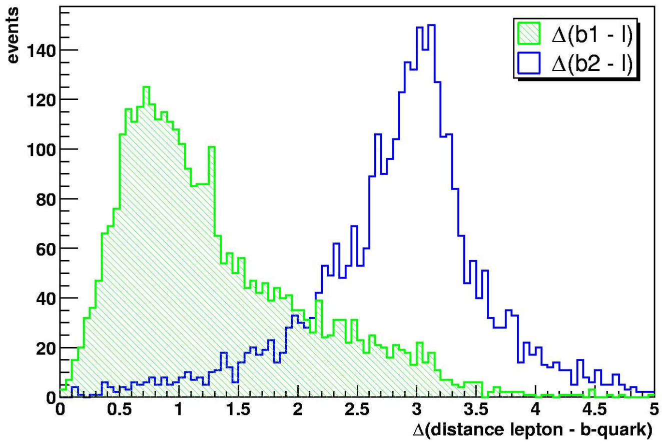


Fig. 1. Distribution of Δ(b-lepton) in the process $Z_H \to t\,\bar{t}$ for M = 1 TeV. The b-jet from the top leptonic decay is called b1 and the b-jet from the top hadronic decay is called b2. The event scale is arbitrary.

- The first t-quark is reconstructed using the first b-quark, the lepton, and the missing energy, assuming that the missing neutrino is parallel to the lepton. The second t-quark is reconstructed using the second b-quark and all other jets, within a distance of 2. The p_T of the reconstructed t-quarks should satisfy the cut $p_T > 250$ (500) GeV.

For the analysis of the decay $W_H \to t\,b$, where the t-quark is assumed to decay leptonically, the selection proceeds in the same way as in the $Z_H \to t\,\bar{t}$ case, except that no energy is collected around the second b-quark. For both decays, $Z_H \to t\,\bar{t}$ and $W_H \to t\,b$, the dominant background is $t\,\bar{t}$ production (irreducible). Another background source, $W + jets$ production (reducible), has been considered as well.

The kinematical efficiencies achieved for signal events by the selection cuts described before are summarized in table 2:

M(GeV)	$b\bar{b}$	$t\bar{t}$	tb
1000	49%	27%	25%
2000	51%	21%	18%

Table 2: Kinematical efficiencies (all BR and tagging efficiencies excluded).

The reconstructed mass peaks are shown in fig. 2a – 2f. The corresponding mean values and widths resulting from gaussian fits are reported in table 3.

M (GeV)	$Z_H \to b\bar{b}$	$Z_H \to t\bar{t}$	$W_H \to tb$
1000	961 ± 117	993 ± 119	953 ± 110
2000	1950 ± 248	1938 ± 248	1856 ± 238

Table 3: Central value of the reconstructed mass (M) and width ($\pm\Delta M$) for the various decay channels analysed.

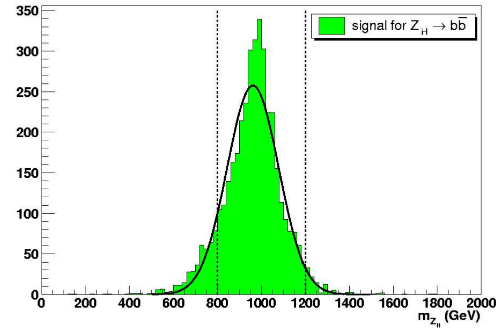
Since the natural width of Z_H and W_H is 34 GeV for M = 1 TeV (assuming cotθ = 1), the reconstructed mass width is dominated by experimental effects (fragmentation and detector resolution). The invariant mass distributions showing the signal on top of the expected background are shown in fig. 3a – 3f. By applying mass cuts of ± 200 (400) GeV around the expected mass values of M = 1 (2) TeV, it is possible to obtain the number of signal and background events reported in tables 4 and 5 for an integrated luminosity of $\mathcal{L} = 3 \cdot 10^5\, pb^{-1}$, corresponding to 3 years of running at high luminosity. The significance of the expected signal is indicated as well for all decays. The significance has in general a large value around M = 1 TeV, well above the discovery threshold of 5, but only the decay $W_H \to t\, b$ yields a signal which can be clearly separated from the background as shown in fig. 3.

M = 1 TeV	$b\bar{b}$	$t\bar{t}$	tb
signal	3461	13170	67038
irreducible bkg	63764	116191	45532
reducible bkg	24388	126	3188
significance	11.7	38.6	303.7

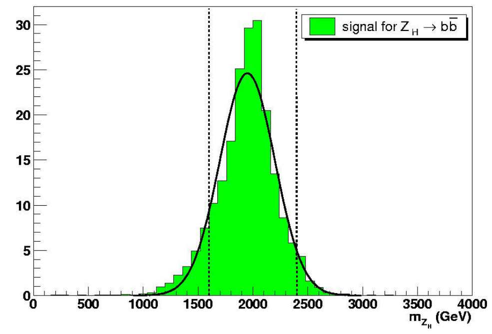
Table 4: Signal and background inside a mass window of ± 200 GeV around M = 1 TeV for $\mathcal{L} = 3 \cdot 10^5\, pb^{-1}$ and cotθ = 1.

M = 2 TeV	$b\bar{b}$	$t\bar{t}$	tb
signal	174	74	813
irreducible bkg	1605	520	401
reducible bkg	18623	2	67
significance	1.2	3.2	37.6

Table 5: Signal and background inside a mass window of ± 400 GeV around M = 2 TeV for $\mathcal{L} = 3 \cdot 10^5\, pb^{-1}$ and cotθ = 1.



(a)



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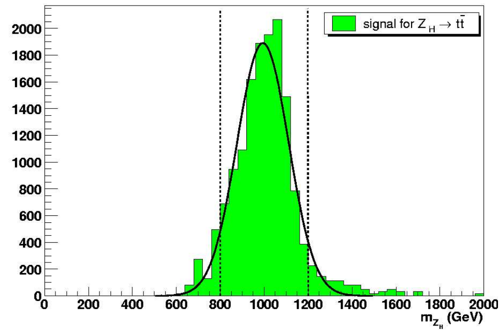

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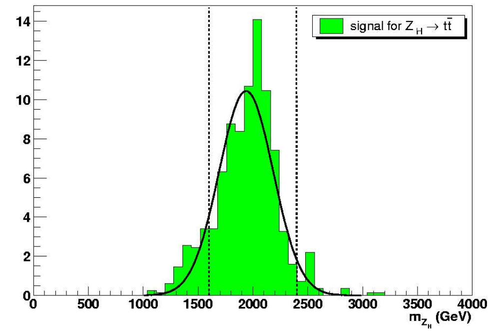

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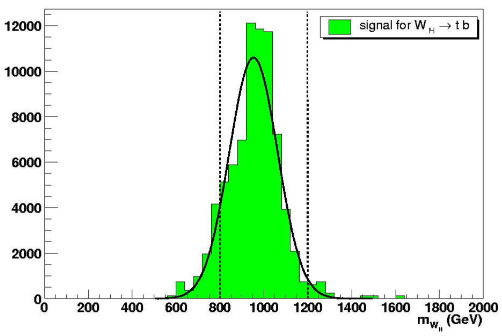
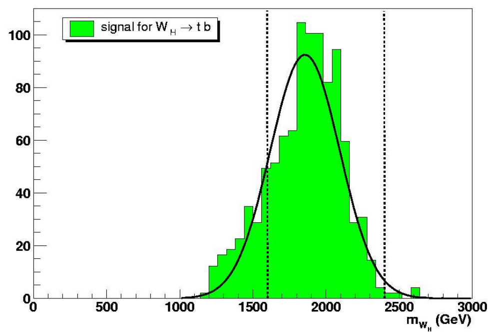


(e)



(f)

Fig. 2. Reconstructed mass peaks for the 3 decay modes $Z_H \to b\,\overline{b}$, $t\,\overline{t}$ and $W_H \to t\,b$ and the 2 mass values, M = 1 and 2 TeV. The curves on top of the data are gaussian fits. The event scale is arbitrary.

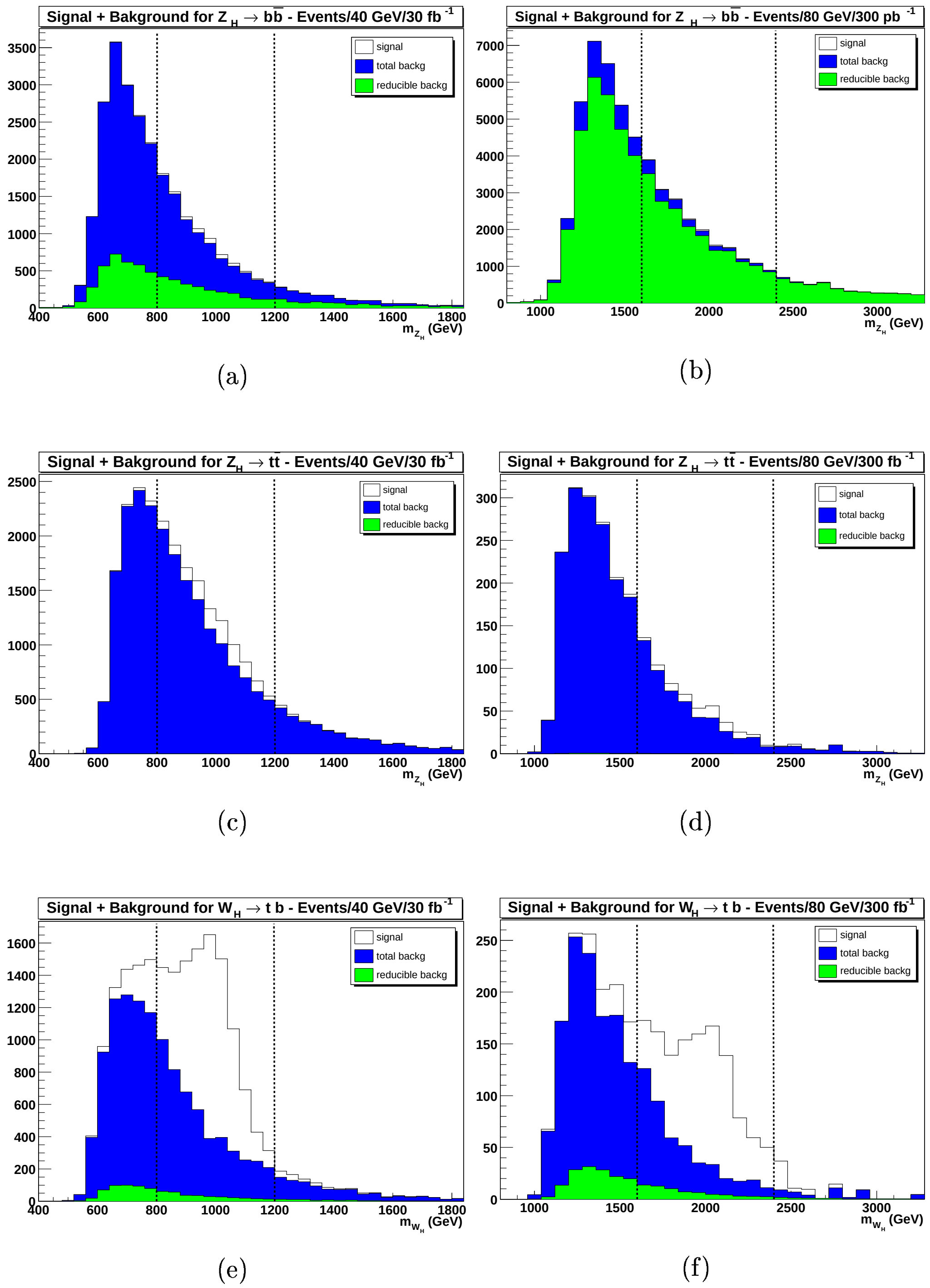


Fig. 3. The same as in fig. 2, but including both signal and background. The mass windows used to calculate the significance are indicated in the figures. A Luminosity of $\mathcal{L} = 3 \cdot 10^4\ pb^{-1}$ is assumed for M = 1 TeV and $\mathcal{L} = 3 \cdot 10^5\ pb^{-1}$ for M = 2 TeV.

Assuming that for the $W_H \to t\,b$ channel the signal can be extracted, it is possible to deduce the discovery region for this decay indicated in fig. 4. The discovery region is the region with significance exceeding the value of 5. This region has been obtained assuming that the cross-section is proportional to $(cot\theta)^2$ and extrapolating the results (for both signal and background) obtained for masses of 1 and 2 TeV to other mass values.

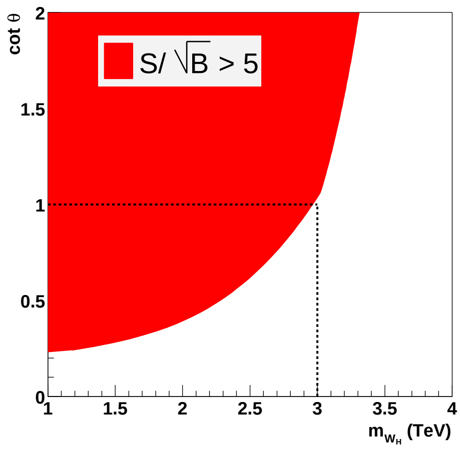


Fig. 4. Discovery region for the decay $W_H \to t\,b$ in the Mass-Cotθ plane, assuming an integrated luminosity of $\mathcal{L} = 3 \cdot 10^5\ pb^{-1}$.

5 Summary and conclusions

The decays $Z_H \to b\,\bar{b}$, $t\,\bar{t}$ and $W_H \to t\,b$ have been investigated using the simulation program ATLFAST for Z_H and W_H mass values of 1 and 2 TeV. The analysis of expected signals and backgrounds shows that the decays $Z_H \to b\,\bar{b}$ and $t\,\bar{t}$ are difficult to detect, but the decay $W_H \to t\,b$, on the contrary, might yield a signal clearly separable from the background, up to W_H masses of 3 TeV, if cotθ is assumed to be equal to 1. The detection of the $W_H \to t\,b$ signal will allow a measurement of BR($W_H \to t\,b$) and, by comparison with BR($W_H \to l\,\nu$), an interesting test for the couplings of the W_H boson.

Acknowledgements

We would like to thank Javier Sánchez and José Enrique García for help and comments.

A Appendix: High p_T b-tagging

In all the decays analysed in the note, the tagging of very high p_T b-jets is required. The average p_T of these jets is reported in table 6:

$< p_T >$	$Z_H \to b\bar{b}$	$Z_H \to t\bar{t}$	$W_H \to tb$
M = 1 TeV	400	200	250
M = 2 TeV	800	400	500

Table 6: Average p_T (in GeV) of final state b-jets for the various channels studied in this note.

The tagging of b-jets has been studied in detail within ATLAS (see for example [5]), but in all these studies the average p_T of b-jets was typically below 200 GeV. In order to investigate the b-tagging performance for larger p_T values, the following event samples have been generated and analysed:

$$Z_H(2\,TeV) \to b\,\bar{b},\ c\,\bar{c},\ u\,\overline{u}$$

Each sample contained 20 000 events and was processed using the full reconstruction provided by DC1 software. The b-tagging results were already used in a previous note [6].

The standard b-tagging algorithm was used. Since this algorithm is not optimized for high p_T jets, the results should be considered conservative, and further improvements might be expected in the future.

The efficiencies (ϵ) and rejections ($R = 1/\epsilon$) reported in table 7 have been applied in the analysis presented in this note.

mass	decay	ϵ_b	R_c	R_u
1 TeV	$b\bar{b}$	0.1	140	1000
	$t\bar{t}$	0.5	10	100
	tb	0.7	3	8
2 TeV	$b\bar{b}$	0.1	45	90
	$t\bar{t}$	0.2	30	130
	tb	0.4	5	12

Table 7: Efficiencies and rejections applied in the b-tagging analysis.

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