Searching for a Heavy Higgs boson in a Higgs-portal B-L Model

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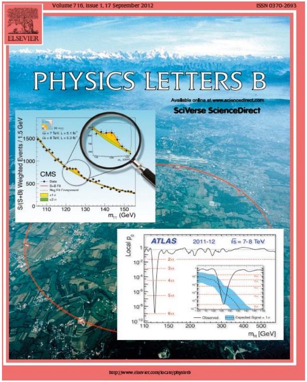
(with M. Mitra and M. Spannowsky)

Plan of my talk

- Introductory remarks
- The $U(1)_{B-L}$ model
- Limits on Z'
- Constraints on Higgs mixing
- Collider searches of Heavy Higgs
  - $pp \to H_2 \to ZZ \to 4\ell$ channel
  - $pp \to H_2 \to ZZ \to 2\ell + 2j$ channel
  - $pp \to H_2 \to WW \to \ell + \not{E}_T + 2j$ channel
- Prospects of studying the $H_2 \to H_1 H_1$ channel
- Non-standard heavy Higgs production channel
- Summary and Conclusions

Higgs discovery in 2012 !!!

- Existence of a scalar boson proposed by Higgs, Brout, Englert, Guralnik, Hagen and Kibble around 1964
- Discovery of the celebrated Higgs boson at a mass $\approx$ 125 GeV [a] announced on 4^{th} July, 2012
- Dedicated search methods devised by both the *CMS* and *ATLAS* collaborations at the *LHC* made this discovery possible



[a] CMS + ATLAS (combined) : $M_H = 125.09 \pm 0.21$ (stat.) ± 0.11 (syst.) GeV in the $H \to \gamma\gamma$ and the $H \to ZZ^* \to 4\ell$ channels.

Introductory remarks

- Search for a new scalar makes us look into several well motivated models like SUSY, models with extra spatial dimensions etc.
- A simple extension is the SM augmented with a gauge singlet
- We consider a $B - L$ singlet extension of the SM [E.E.Jenkins (1987), W.Buchmuller *et. al.* (1991)]
- There are three right handed neutrinos in the theory for anomaly cancellation [E.D. Carlson (1987)]
- The right handed neutrinos participate in generating the baryon asymmetry of the universe via leptogenesis [M. Fukugita and T. Yanagida (1986)]

Introductory remarks

- The total gauge group structure : $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$
- Main motivation of this talk is the discovery prospects of a heavy Higgs
- VEV of the gauge singlet Higgs breaks the $U(1)_{B-L}$ symmetry and generates masses for right handed neutrinos
- The $B-L$ breaking scale is considered $\mathcal{O}(TeV) \Rightarrow$ right handed neutrinos naturally $\mathcal{O}(TeV)$ [T.F. Pérez, T. Han and T. Li (2009), S. Iso, N. Okada and Y. Orikisa (2010), N. Okada, Y. Orikasa and T. Yamada (2012)]
- The second physical Higgs mixes with the SM-like Higgs with angle θ constrained by EWPD and Higgs coupling measurements from LHC
- Second Higgs dominantly produced in the ggF channel and dominantly decays to WW, ZZ and $H_1 H_1$

The minimal $U(1)_{B-L}$ model (Yang-Mills and fermionic Lagrangian)

- The full Lagrangian : $\mathcal{L} = \mathcal{L}_s + \mathcal{L}_{YM} + \mathcal{L}_f + \mathcal{L}_Y$
- $\mathcal{L}_{YM} = -\frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} - \frac{1}{4} W^b_{\mu\nu} W^{b,\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu}$, where $F'_{\mu\nu} = \partial_\mu B'_\nu - \partial_\nu B'_\mu$ is the kinetic term for $U(1)_{B-L}$ gauge group
-

$$\mathcal{L}_f = \sum_{i=1,2,3} \Big(i\,\overline{(Q_L)}_i \gamma^\mu D_\mu (Q_L)_i + i\,\overline{(u_R)}_i \gamma^\mu D_\mu (u_R)_i + i\,\overline{(d_R)}_i \gamma^\mu D_\mu (d_R)_i + i\,\overline{(L_L)}_i \gamma^\mu D_\mu (L_L)_i + i\,\overline{(e_R)}_i \gamma^\mu D_\mu (e_R)_i + i\,\overline{(N_R)}_i \gamma^\mu D_\mu (N_R)_i \Big),$$

where $D_\mu = \partial_\mu + i g_s t^a G^a_\mu + i g T^b W^b_\mu + i g_1 Y B_\mu + i g' Y_{B-L} B'_\mu$,

where $Y^{quarks}_{B-L} = \frac{1}{3}$ and $Y^{leptons}_{B-L} = -1$

The minimal $U(1)_{B-L}$ model (scalar Lagrangian)

- To break the $B-L$ gauge symmetry and to generate mass of the additional gauge boson Z' we introduce a complex Higgs filed χ
- χ : singlet under SM gauge group and $Y^{\chi}_{B-L} = +2$
- $B-L$ symmertry spontaneously broken by χ
- $Y^{H}_{B-L} = 0$
- $\mathcal{L}_s = (D^\mu H)^\dagger D_\mu H + (D^\mu \chi)^\dagger (D_\mu \chi) - V(\chi, H)$,
  where $V(\chi, H) = M_H^2 H^\dagger H + m_\chi^2 |\chi|^2 + \lambda_1 (H^\dagger H)^2 + \lambda_2 |\chi|^4 + \lambda_3 (H^\dagger H)|\chi|^2$

The minimal $U(1)_{B-L}$ model (Yukawa Lagrangian)

- $$\mathcal{L}_Y = -y^d_{ij}\overline{(Q_L)_i}(d_R)_j H - y^u_{ij}\overline{(Q_L)_i}(u_R)_j \widetilde{H} - y^e_{ij}\overline{(L_L)_i}(e_R)_j H$$
  $$-y^\nu_{ia}\overline{(L_L)_i}(N_R)_a \widetilde{H} - y^M_{ab}\overline{(N_R)^c_a}(N_R)_b \chi + h.c.,$$

  where $\widetilde{H} = i\sigma^2 H^*$ and i, j, a, b runs from 1-3
- VEV of χ breaks the $B-L$ symmetry and generates the Majorana masses for N_R, where $M_{N_R} = y^M v'$
- Masses of the light neutrinos are governed by y^ν

The minimal $U(1)_{B-L}$ model (Spontaneous symmetry breaking)

- In order for the potential to be bounded from below :

$$4\lambda_1\lambda_2 - \lambda_3^2 > 0,$$
$$\lambda_{1,2} > 0$$

- On minimising $V(\chi, H)$ w.r.t v and v' :

$$v^2 = \frac{4\lambda_2 M_H^2 - 2\lambda_3 M_\chi^2}{\lambda_3^2 - 4\lambda_1\lambda_2}, \quad {v'}^2 = \frac{4\lambda_1 M_\chi^2 - 2\lambda_3 M_H^2}{\lambda_3^2 - 4\lambda_1\lambda_2}$$

- The mass matrix in the (H, χ) basis is :

$$\mathcal{M}(H,\chi) = 2\begin{pmatrix} \lambda_1^2 v^2 & \lambda_3 v v'/2 \\ \lambda_3 v v'/2 & \lambda_2 {v'}^2 \end{pmatrix}$$

The minimal $U(1)_{B-L}$ model (Spontaneous symmetry breaking)

- The mass eigenstate is defined as :

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} H \\ \chi \end{pmatrix},$$

where the mixing $\theta \, (-\frac{\pi}{2} < \theta < \frac{\pi}{2})$ satisfies $\tan 2\theta = \frac{\lambda_3 v' v}{(\lambda_2 v'^2 - \lambda_1 v^2)}$

- The physical masses are :

$$M_{H_1}^2 = \lambda_1 v^2 + \lambda_2 v'^2 - \sqrt{(\lambda_1 v^2 - \lambda_2 v'^2)^2 + \lambda_3^2 v'^2 v^2},$$

$$M_{H_2}^2 = \lambda_1 v^2 + \lambda_2 v'^2 + \sqrt{(\lambda_1 v^2 - \lambda_2 v'^2)^2 + \lambda_3^2 v'^2 v^2}$$

The minimal $U(1)_{B-L}$ model (Higgs couplings)

$$H_1 f\bar{f} : -\frac{eM_f \cos\theta}{2M_W}, \qquad H_2 f\bar{f} : -\frac{eM_f \sin\theta}{2M_W},$$

$$H_1 W^+ W^- : \frac{M_W e \cos\theta}{s_w}, \qquad H_2 W^+ W^- : \frac{M_W e \sin\theta}{s_w},$$

$$H_1 ZZ : \frac{M_W e \cos\theta}{c_w^2 s_w}, \qquad H_2 ZZ : \frac{M_W e \sin\theta}{c_w^2 s_w},$$

$$H_1 Z' Z' : -8 \sin\theta {g'}^2 v', \qquad H_2 Z' Z' : -8 \cos\theta {g'}^2 v'$$

$$H_1 H_1 H_1 : -3\frac{1}{e}(4\cos^3\theta \sin\theta_w M_W \lambda_1 - 2\sin^3\theta e\lambda_2 v' -$$
$$\cos^2\theta \sin\theta e\lambda_3 v' + 2\sin\theta_w \sin^2\theta \cos\theta M_W \lambda_3),$$

$$H_2 H_1 H_1 : -\frac{1}{e}(12\cos^2\theta \sin\theta_w \sin\theta M_W \lambda_1 + 6\sin^2\theta \cos\theta e\lambda_2 v' +$$
$$(1 - 3\sin^2\theta)\cos\theta e\lambda_3 v' - 2(2 - 3\sin^2\theta)\sin\theta_w \sin\theta M_W \lambda_3)$$

Constraints on Z'

- The $B-L$ model has an additional Z' gauge boson with $M'_Z = 2v'g'_1$
- Z' interacts with ℓ, q, N, ν with interaction strengths proportional to g'
- Z' can in principle be seen in di-leptonic and di-jet signals at colliders
- A SSM Z' constrained by direct and indirect searches
- Indirect searches yield $\frac{M_{Z'}}{g'} \geq 6.9\,\mathrm{TeV}$ [L. Basso *et. al.* (2008), J. Heeck (2014), M. Carena *et. al.* (2004), G. Cacciapaglia *et. al.* (2006)]

Searches	Constraints	$M_{Z'}(SSM)$
Boosted $t\bar{t}$	$\sigma \times B \leq 1 - 2\,\mathrm{pb}$	-
di-lepton-CMS	$R < 7 \times 10^{-6}$	2.90 TeV
di-lepton-ATLAS	$\sigma \times B \leq 4 \times 10^{-2}\,\mathrm{pb}$	2.90 TeV
di-jet-ATLAS	$\sigma \times B \times A \leq 0.2 - 0.3\,\mathrm{pb}$	1.70 TeV
$\tau^+\tau^-$-ATLAS	$\sigma \times B \leq 0.1\,\mathrm{pb}$	1.90 TeV
$b\bar{b}$-CMS	-	$1.20 - 1.68$ TeV

Constraints on Z' (ATLAS di-lepton channel)

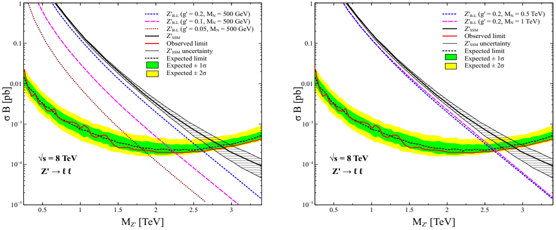


Figure : The comparison between the limits from ATLAS di-lepton search with the $B-L$ predictions.

With decreasing g' the mass bound on $M_{Z'}$ relaxes !!!

M_N (TeV)	g'	$M_{Z'}(B-L)$ (TeV)
0.5	0.2	2.62
1.0	0.2	2.65
0.5	0.1	2.25
0.5	0.05	1.83

Constraints on Higgs mixing (From LHC)

- CMS and ATLAS already puts bounds on many BSM models simply from Higgs coupling measurements
- Here we employ the κ framework where we define :

$g_{H_1 ff} = \kappa_f . g_{Hff}^{\mathrm{SM}}$ and $g_{H_1 VV} = \kappa_V . g_{HVV}^{\mathrm{SM}}$

- Assumption by experimental collaborations :
  - loop level couplings parametrized in terms of tree level ones
  - no new particles in loops
  - Invisible BR of SM-like Higgs is ~ 0
- In this model : $\kappa_t = \kappa_b = \kappa_W = \kappa_Z = \kappa_\tau = \cos\theta$

κ_W	κ_Z	κ_t	κ_b	κ_τ
		CMS		
[0.66, 1.24]	[0.69, 1.37]	[0.51, 1.22]	[0.07, 1.46]	[0.47, 1.25]
		ATLAS		
[0.63, 1.19]	$[-1.20, -0.67] \bigcup [0.67, 1.26]$	[0.59, 1.39]	$[-1.29, 1.31]$	$[-1.46, -0.61] \bigcup [0.62.1.47]$

Table : The 95% CL ranges on various signal strength modifiers, κ, as reported by CMS and ATLAS.

Constraints on Higgs mixing (From LHC and ILC)

- Using these ranges, $\sin^2\theta < 0.31(0.33)$ for CMS (ATLAS)
- A projection study by M. Peskin shows that :
  - $\sin\theta < 0.36$ at the 14 TeV LHC with $\mathcal{L} = 300\ \text{fb}^{-1}$
  - $\sin\theta < 0.25$ at the 250 GeV ILC with $\mathcal{L} = 250\ \text{fb}^{-1}$

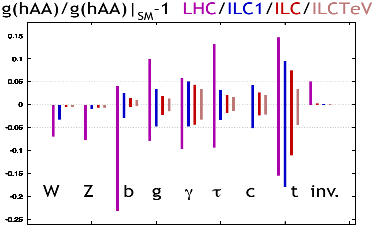
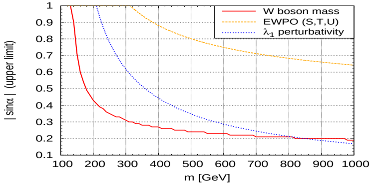


Figure : Higgs couplings predictions from LHC at 300 fb^{-1} and future ILC runs [M. Peskin (2012)]

- For our purposes we work with the benchmark $\sin\theta = 0.2$

Constraints on Higgs mixing (Theoretical)

- Constraints from M_W
  - Comes from one-loop correction to the W-boson mass, $M_W = 80.385 \pm 0.015\,\mathrm{GeV}$
  - Results are made to lie within 2σ of the quoted value
  - For high M_{H_2}, stronger constraint from M_W than from S, T, U
  - Upper bound on $\sin\theta$ decreases from 0.35 to 0.2 as M_{H_2} increases from 250 GeV to 900 GeV [T. Robens and T. Stefaniak (2015)]



- Perturbative unitarity also poses strong constraint on $\tan\beta = v/v'$
- All the couplings in the potential are required to obey $\lambda_{1,2,3} \leq 4\pi$

Collider searches of heavy Higgs

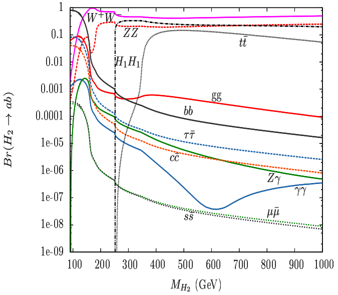


Figure : Left panel : Branching ratios of H_2 (as a function of M_{H_2}). Right panel : NNLO Cross section (fb) times Branching ratio as functions of M_{H_2}. $\sin\theta = 0.2$ for all the cases.

- Branching ratios to WW, ZZ, H_1H_1 are the maximum
- Even though branching ratios of W, Z to di-jet final states are large, we still consider the leptonic/semi-leptonic final states because these are very clean channels
- We study the discovery prospects of H_2 at the HL-LHC (14 TeV @ 3000 fb^{-1})

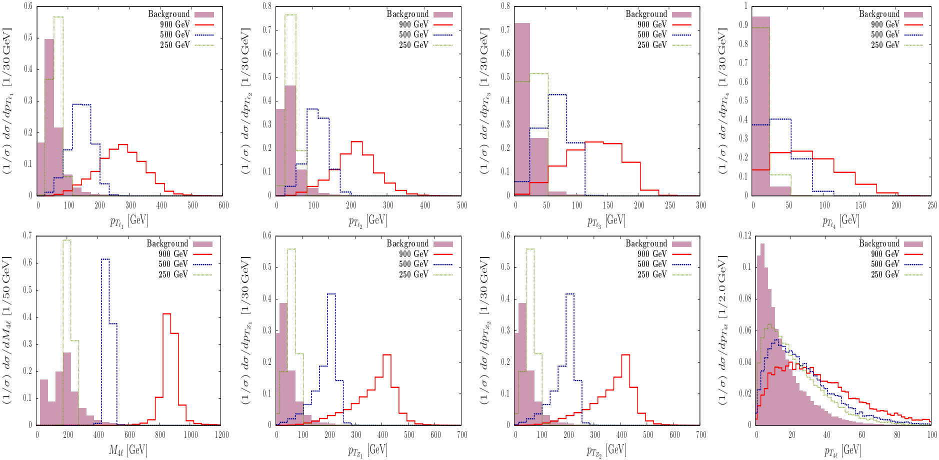
Cut based analysis versus Multivariate analysis

- In cut-based analysis rectangular cuts are imposed on kinematic variables in order to optimise the significance $n = \mathcal{N}_{\mathcal{S}}/\sqrt{\mathcal{N}_{\mathcal{S}} + \mathcal{N}_{\mathcal{B}}}$
- In multivariate analyses, the Boosted Decision Tree (BDT) algorithm is employed
  - A set of kinematic variables with maximal discriminating power between signal and background is chosen
  - Both signal and background are trained by the BDT algorithm
  - The Kolmogorov-Smirnov (KS) test is used to check if the samples are over-trained or not
  - Test sample not over-trained if KS probability lies within (0.1,0.9) with the critical value being 0.01
  - We ensure that the samples are not overtrained
- Finally a binned log-likelihood hypothesis test also used to estimate LHC's potential in excluding H_2

$pp \to H_2 \to ZZ \to 4\ell$ channel

- M_{H_2} varied between 250 GeV and 900 GeV
- H_2 decays to a pair of on-shell Z bosons which subsequently decay to 4ℓ
- Major background is ZZ production with the same final state
- After basic trigger cuts, the following selection cuts are employed
  - Invariant mass of the four lepton system: M_{4l} to lie in the range, $M_{H_2} \pm 10$ GeV
  - Transverse momentum of leading lepton: $p_{T_{\ell_1}} > 90$ GeV
  - Transverse momentum of sub-leading lepton: $p_{T_{\ell_2}} > 70$ GeV
  - Transverse momentum of the other two leptons: $p_{T_{\ell_3}} > 50$ and $p_{T_{\ell_4}} > 20$ GeV
  - Invariant mass of the reconstructed Z bosons: M_{Z_1}, $M_{Z_2} \in M_Z \pm 10$ GeV
  - Transverse momentum of the two reconstructed Z bosons: $p_T(Z_1)$, $p_T(Z_2) > 100$ GeV

$pp \to H_2 \to ZZ \to 4\ell$ channel (kinematic distributions)



$pp \to H_2 \to ZZ \to 4\ell$ channel (BDT)

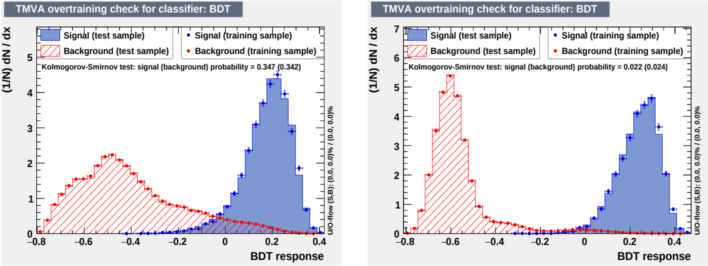


Figure : Normalised signal and background distributions against BDT response for (a) $M_{H_2} = 250$ GeV and (b) $M_{H_2} = 500$ GeV for the channel $pp \to H_2 \to ZZ \to 4\ell$.

$pp \to H_2 \to ZZ \to 4\ell$ channel (CBA vs MVA)

- For BDT, we choose 18 kinematic variables, *viz.* $M_{4\ell}$, $p_{T_{\ell_i}}$, $\Delta R_{\ell_i \ell_j}$, M_{Z_k}, $p_T(Z_k)$, $\eta(Z_k)$ and $p_T(4\ell)$, where $i, j = 1 - 4$, $k = 1, 2$ and the 4 leptons and 2 Zs are p_T sorted (BDT clearly wins over CBA !!!)

M_{H_2} (GeV)	σ^{TC} (fb)	σ^{SC} (fb)	$\mathcal{N}_S^{CBA}$	$\mathcal{N}_B^{CBA}$	n_{CBA}	$\mathcal{N}_S^{BDT}$	$\mathcal{N}_B^{BDT}$	n_{BDT}
300	0.126	0.010	30	105	2.62	227	555	8.12
350	0.132	0.042	125	162	7.37	262	419	10.03
400	0.113	0.047	142	131	8.60	246	361	9.99
450	0.078	0.034	101	101	7.14	168	243	8.29
500	0.051	0.021	63	81	5.26	93	132	6.19
550	0.034	0.013	40	48	4.23	54	70	4.82
600	0.022	0.008	24	45	2.87	42	112	3.42
650	0.015	0.005	14	32	2.12	23	60	2.54
700	0.010	0.003	9	24	1.57	16	87	1.58
SM	28.626	-	-	-	-			

Table : NNLO cross sections after trigger cuts (σ^{TC}) and selection cuts (σ^{SC}). $\mathcal{N}_S$ and $\mathcal{N}_B$ represent the number of signal and background events, respectively, while the superscript and subscripts *CBA* and *BDT* represent the cut-based and BDT analysis. n is the significance. The number of events have been computed for an integrated luminosity 3000 fb^{-1}. All the cross-sections include the higher order corrections to the NNLO level.

$pp \to H_2 \to ZZ \to 4\ell$ channel (CLs)

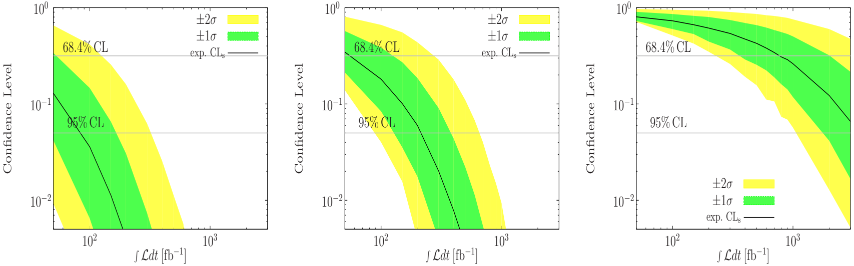


Figure : Confidence level contours for M_{H_2} = (a) 250 GeV, (b) 500 GeV and (c) 700 GeV. We show results for integrated luminosities ($\int \mathcal{L}dt$) from 50 to 3000 fb^{-1}. We assume a flat systematic uncertainty on the backgrounds of 10%.

While an H_2 with $M_{H_2} = 250$ GeV can be excluded at 95% CL with 100 fb^{-1} in this channel, excluding $M_{H_2} = 700$ GeV requires 3000 fb^{-1}

$pp \to H_2 \to ZZ \to 2\ell + 2j$ channel

- This channel benefits from larger branching ratio of Z to jets
- Major background is the continuum ZZ background
- Reconstruction (adapted from [C. Hackstein and M. Spannowsky (2010)]) :
  - Leptonic Z reconstruction : Demand two isolated muons with $p_T > 15\,\mathrm{GeV}$ and $\eta < 2.5$. We further demand an invariant mass window of $10\,\mathrm{GeV}$ around M_Z
  - Hadronic Z reconstruction : Demand an invariant mass window of $10\,\mathrm{GeV}$ around M_Z
  - Heavy Higgs reconstruction : $M_{H_2}^2 = (p_{Z_{lep}} + p_{Z_{had}})^2$ Higgs mass windows used for the four benchmark masses are $(300 \pm 30, 350 \pm 50, 400 \pm 50, 500 \pm 70, 600 \pm 100)$ GeV
  - ZZ separation : $\Delta R_{Z_\ell Z_{had}} < 3.2$. For $Z + \mathrm{jets}$, ΔR between Z_ℓ and $\mathrm{fake} - \mathrm{Z}$ from QCD jets often become large to account for large Higgs invariant mass

$pp \to H_2 \to ZZ \to 2\ell + 2j$ channel (results)

M_{H_2} (GeV)	$\sigma_{SC}^{ggF+VBF}$ (fb)	σ_{SC}^{bkg} (fb)	S/B	$S/\sqrt{S+B}_{100}$	$S/\sqrt{S+B}_{3000}$
300	0.048	2.10	0.023	0.331	1.811
400	0.290	19.21	0.015	0.657	3.602
500	0.223	18.01	0.012	0.522	2.858
600	0.121	11.83	0.010	0.351	1.920

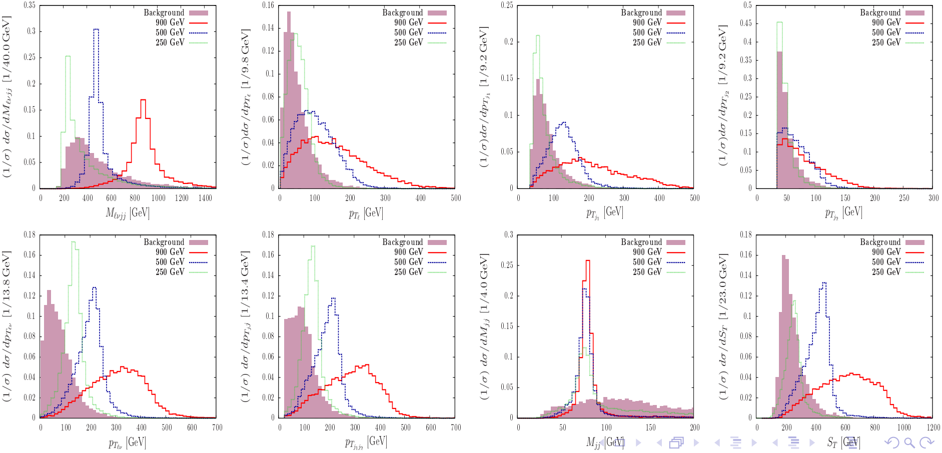
Table : $\sigma_{SC}^{ggF+VBF}$ is the production cross-section of H_2 from the ggF and VBF channels combined after employing the selection cuts discussed in [C. Hackstein and M. Spannowsky (2010)]. σ_{SC}^{bkg} is the background cross-section for the same set of selection cuts.

The sensitivity in the $H_2 \to 2\ell 2j$ channel alone is fairly small for the $U(1)_{B-L}$ model, based on the reconstruction of boosted Z bosons. However, this channel can be combined with the other channels in a global fit.

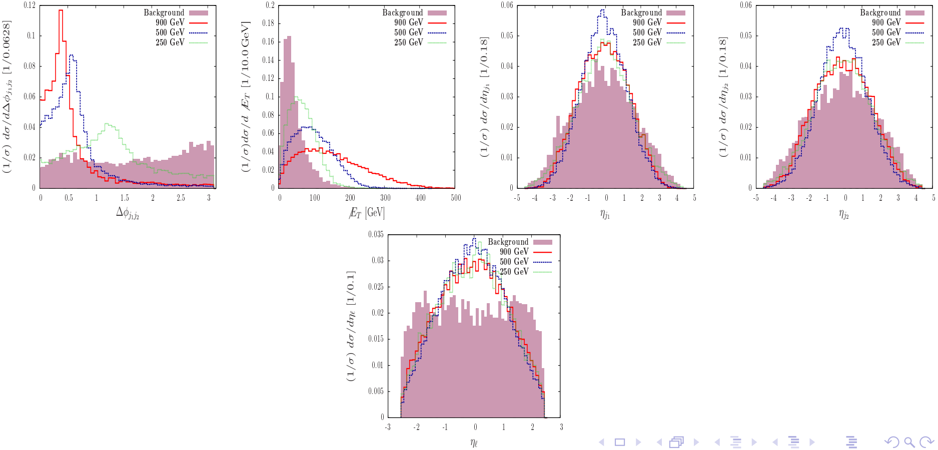
$pp \to H_2 \to WW \to \ell + \not{E}_T + 2j$ channel

- H_2 decays to W^+W^- followed by subsequent decay of one W to lepton and $\not{E}_T$ and the other one decaying to jets
- For heavy H_2, the intermediate Ws are expected to be highly boosted and the leptons and jets are expected to have large $\Delta R(\ell, j)$
- For W_ℓ, $p_z\nu$ is obtained by imposing the constraint $M_W^2 = (p_l + p_\nu)^2$
- After this M_{H_2} is reconstructed using both on-shell Ws

$pp \to H_2 \to WW \to \ell + \not{E}_T + 2j$ channel (kinematic distributions)



$pp \to H_2 \to WW \to \ell + \not{E}_T + 2j$ channel (kinematic distributions)



$pp \to H_2 \to WW \to \ell + \not{E}_T + 2j$ channel (background reduction)

- Major background is non-resonant W^+W^- production with subsequent decays
- The p_T distributions show large overlap with background for low M_{H_2}
- For low masses, $M_{H_2} \approx 250\,\mathrm{GeV}$, the invariant mass of $\ell jj\not{E}_T$ also overlaps
- The p_T distributions of the reconstructed Ws peak at $p_T > 100\,\mathrm{GeV}$ for signal while for background they peak at lesser values
- The signal also has larger $\not{E}_T$
- For M_{H_2} varying between 300 GeV and 900 GeV, the partonic cross-section of signal varies between few tens of fb to $\mathcal{O}(0.1)\,\mathrm{fb}$; whereas the background cross-section is $\approx 3380\,\mathrm{pb}$

$pp \to H_2 \to WW \to \ell + \not{E}_T + 2j$ channel (background reduction)

- Hence to reduce background we categorise the signal into four mass regions
- Stringent cuts are applied at both the generation as well as the detector level

M_{H_2} (GeV)	$p_T(\ell/j_1/j_2)$ (GeV)	$\Delta R(j_1, j_2)_{\min}$	$\Delta R(j_1, j_2)_{\max}$	$\not{E}_T$ (GeV)
350	30	0.4	1.4	50
500	40	0.2	1.0	60
700	50	0.2	0.8	70
900	70	0.2	0.6	90

Table : Basic trigger cuts used to separate the signal from background.

M_{H_2} (GeV)	$p_{T,\ell/j_{1,2}}$ (GeV)	$p_{T,W_{1,2}}$ (GeV)	$\Delta R^{\max}_{j_1,j_2}$	$\not{E}_T$ (GeV)	S_T (GeV)	$\lvert M_{ljj\not{E}_T} - M_{H_2} \rvert$ (GeV)	$\lvert M_{jj} - M_W \rvert$ (GeV)
350	35	100	1.35	55	225	50	20
500	45	100	0.9	70	250	50	20
700	55	100	0.75	75	250	50	20
900	75	100	0.58	95	600	50	20

Table : Selection cuts to separate out signal from the background.

$pp \to H_2 \to WW \to \ell + \not{E}_T + 2j$ channel (background reduction)

- After these specialised cuts the backgrounds reduce considerably to $\approx 1.7\,\mathrm{pb}, 0.36\,\mathrm{pb}, 0.08\,\mathrm{pb}$ and $0.01\,\mathrm{pb}$ for $M_{H_2} = 350, 500, 700$ and 900 GeV respectively
- However, still even though we can get a good $S/\sqrt{S+B}$, S/B is still very small ($\lesssim 1/100$)
- We choose 27 kinematic variables for BDT analysis, *viz.* $M_{\ell jj\nu}$, $p_T(\ell)$, $\eta(\ell)$, $p_T(j_i)$, $\eta(j_i)$, $\not{E}_T$, $\phi(\not{E}_T)$, $p_T(\ell, \not{E}_T)$, $p_T(j_1, j_2)$, $|\Delta\phi(W_1, W_2)|$, $|\Delta\phi(\ell, j_1)|$, $\Delta\eta(\ell, j_2)$, $\Delta\eta(\ell, j_i)$, $|\Delta\phi(j_1, j_2)|$, $\Delta\eta(j_1, j_2)$, $|\Delta\phi(j_i, \not{E}_T)|$, S_T, $M_{j_i\ell}$, $M_{j_1j_2\ell}$, $\Delta R(\ell, j_i)$ and $\Delta R(j_1 j_2)$.

$pp \to H_2 \to WW \to \ell + \not{E}_T + 2j$ channel (CBA vs BDT)

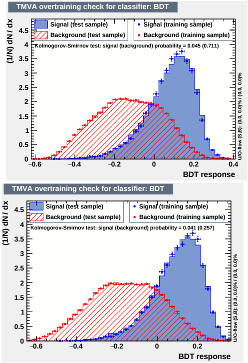


Figure : Normalised signal and background distributions against BDT response for (a) $M_{H_2} = 350$ GeV and (b) $M_{H_2} = 500$ for the channel $pp \to H_2 \to WW \to \ell\nu jj$.

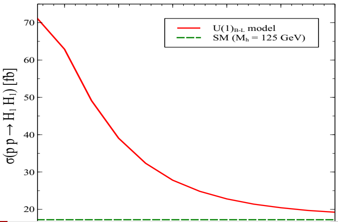
Assuming zero systematic uncertainties, the statistical significance are quoted

M_{H_2} GeV	$\mathcal{L}$ [fb^{-1}]	n_{CBA}	n_{BDT}
350	100	1.34	1.73
	3000	7.36	9.45
500	100	1.80	2.24
	3000	9.86	12.26
700	100	0.94	1.11
	3000	5.17	6.10
900	100	0.26	0.33
	3000	1.41	1.81

Table : The significance for cut-based and multivariate analysis for integrated luminosity $100\,\text{fb}^{-1}$ and $3000\,\text{fb}^{-1}$.

Prospects of studying the $H_2 \to H_1 H_1$ channel

- $H_2 \to H_1 H_1$ channel has been studied by both theorists and experimentalists [Martin-Lozano *et. al.* (2015), M.J. Dolan *et. al.* (2013), A. Falkowski *et. al.* (2015)]
- CMS and ATLAS has studied this in the $b\bar{b}b\bar{b}$ and $b\bar{b}\gamma\gamma$ channels
- Naive leading order estimate of $pp \to H_1 H_1$ cross-section with $v' = 3.75\,\mathrm{TeV}$ and $\sin\theta = 0.2$ reveals that for $M_{H_2} \sim 500\,\mathrm{GeV}$, there is enhancement w.r.t. the SM expectation
- For High M_{H_2}, H_2 decouples and the cross-section tends to the SM value



Non-standard heavy Higgs production channel

- In addition to ggF, VBF, VH_2, $t\bar{t}H_2$, H_2 can also be produced in association with Z' [L. Basso *et. al.* (2008), G. Pruna (2011)]
- In the decoupling regime, $\sin\theta \sim 0$ all the other modes give negligible contribution except H_2 in association with Z' because the vertex $Z'Z'H_2$ is proportional to $\cos\theta$

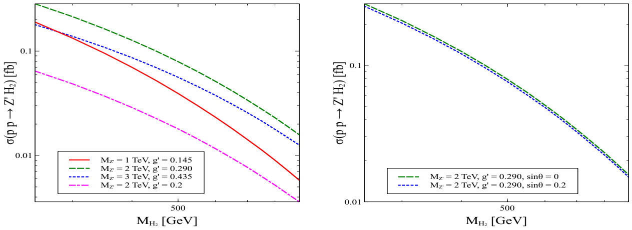


Figure : Left panel: The LO cross-section for the associated production $pp \to Z'H_2$ for mixing $\theta = 0$ and different values of $M_{Z'}$ and g' such that $\frac{M_{Z'}}{g'} \geq 6.9\,\mathrm{TeV}$. Right panel: Comparison between the associated production $pp \to Z'H_2$ between $\sin\theta = 0$ and $\sin\theta = 0.2$.

Summary and Conclusions

- $B-L$ breaking scale considered to be few TeVs, the Z' and heavy neutrinos are hence naturally of the TeV scale
- Mixing θ between the SM-like Higgs and the heavy Higgs from the singlet severely constrained from Higgs coupling measurements and also from one-loop correction to W-boson mass
- A benchmark value of $\sin\theta = 0.2$, satisfying the present constraints was considered throughout this study
- The prospects of discovering a heavy Higgs ensuing from this model was studied in the $pp \to H_2 \to ZZ \to 4\ell$, $pp \to H_2 \to ZZ \to 2\ell + 2j$ and $pp \to H_2 \to WW \to \ell jj \not{E}_T$ channels of which the former is found to be the cleanest

Summary and Conclusions

- For the 4ℓ final state, a heavy Higgs with mass $\lesssim 500\,\mathrm{GeV}$ can be detected with $\sim 5\sigma$ significance in this model at the HL-LHC with $\mathcal{L} = 3000\mathrm{fb}^{-1}$
- For the $ZZ \to 2\ell 2j$ final state with larger cross section, the S/B and sensitivity is found to be somewhat less in this model
- The $pp \to H_2 \to WW \to \ell jj \not{E}_T$ channel has even larger cross-section of $\mathcal{O}(10)\mathrm{fb}$. However, this channel is plagued with severe background of $\mathcal{O}(10^3)\mathrm{pb}$
- Severe background reduction techniques were implemented at both generation and detector level by separate hard cuts in different mass regimes. Even though these techniques were successful in reducing the backgrounds considerably, they were just not sufficient for $S/B \gtrsim 1/100$

Backup slides

Seesaw mechanism and neutrino mass generation

- In SM, no straightforward way to generate experimentally observed neutrino masses and oscillations
- $B - L$ model provides a natural solution : the presence of right handed neutrinos gives rise to the seesaw mechanism
- After SSB, the Dirac neutrinos combine to six Majorana mass eignestates
- $$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix},$$

  where $m_D = \frac{y_\nu^*}{\sqrt{2}} v$ and $\mathcal{M} = \sqrt{2} y^M v'$
- Once the gauge hierarchy $\Lambda_D \ll \Lambda_M$ is assumed to be true, the diagonalisation of the mass matrix realises the seesaw mechanism [T.Yanagida (1979)]

Seesaw mechanism and neutrino mass generation

- After this procedure, we have three light Majorana neutrinos ν_l and three heavy Majorana neutrinos ν_h
- $M_l \simeq m_D M^{-1} m_D^T = \frac{1}{2\sqrt{2}} y^\nu (y^M)^{-1} (y^\nu)^T \frac{v^2}{v'}$ and $M_h \simeq M = \sqrt{2} y^M v'$
- The mass scale Λ_M needed to obtain neutrino masses can be roughly estimated [G.L. Fogli *et. al.* (2006), (2007)] by taking $\Lambda_\ell < 1\,\mathrm{eV}$ and $\Lambda_D \sim \mathrm{EW\,scale}$, one obtains $\Lambda_\ell \simeq \frac{\Lambda_D^2}{\Lambda_M} < 1\,\mathrm{eV} \Rightarrow \Lambda_\mathrm{M} > 10^{13}\,\mathrm{GeV}$
- Λ_D could be several orders of magnitude smaller than the weak scale (electron mass for example). For such cases much smaller scales for Λ_M are allowed
- A generalised condition is $v|y^\nu| \ll v'|y^M|$

Statistical significance

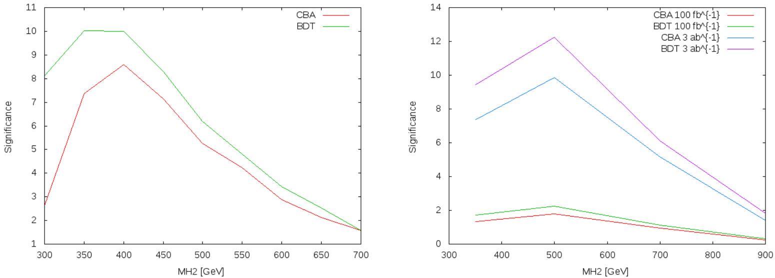


Figure : Left panel : Statistical significance for the heavy Higgs discovery in the $pp \to H_2 \to ZZ \to 4\ell$ channel. Right panel : Same in the $pp \to H_2 \to WW \to \ell \not{E}_T 2j$ channel.