Search for $H \to hh \to b\bar{b}\tau\tau$ at the LHC in the 2HDM

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Beyond Standard Model : From Theory to Experiment (BSM- 2023)

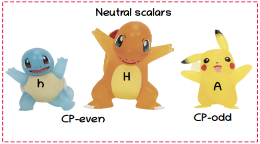
CP CONSERVING 2HDM

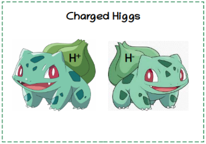
- The **Two-Higgs-Doublet** Model **(2HDM)** is an effective theory with **extra** $SU(2)_L$ doublet
- Simple, compatible with relevant experimental and theoretical constraints, (part) of the Higgs spectrum accessible at the LHC, properties testable at the LHC

$$\begin{aligned} V(\Phi_1, \Phi_2) &= m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - [m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}] + \frac{\lambda_1}{2}(\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) \\ &+ \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \left\{ \frac{\lambda_5}{2}(\Phi_1^\dagger \Phi_2)^2 + [\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)] \Phi_1^\dagger \Phi_2 + \text{h.c.} \right\} \end{aligned}$$

- To prevent FCNC at tree-level, a $\mathcal{Z}_2$ symmetry can be imposed $\rightarrow$ removes $\lambda_6, \ \lambda_7$
- Free parameters : 5 masses after EWSB, $\tan\beta = v_2/v_1$, mixing angle α and m_{12}^2

$m_h < m_H$





- Alignment limit (**the current LHC data favor the parameter space of the 2HDM around the alignment limit**)
  - **Standard hierarchy :** $\cos(\beta - \alpha) \ \rightarrow 0, \ h \equiv H_{SM}$
  - **Inverted hierarchy :** $\sin(\beta - \alpha) \ \rightarrow 0, \ H \equiv H_{SM}$ (our main focus)

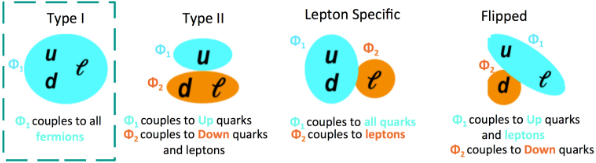
Couplings to fermions and gauge bosons lead to different phenomenology w.r.t the SM

The general structure of the Yukawa Lagrangian when both Higgs fields couple to all fermions :

$$\mathcal{L}_Y = \bar{Q}'_L(M'_u \tilde{H}_1 + Y'_u \tilde{H}_2)u'_R + \bar{Q}'_L(M'_d H_1 + Y'_d H_2)d'_R + \bar{L}'_L(M'_l H_1 + Y'_l H_2)l'_R + \text{h.c}$$

$\Longrightarrow$ **FCNC at tree level**

* $\mathcal{Z}_2$ **symmetry** $\rightarrow$ 4 scenarios based on how the **Higgs doublets** couple to **SM particles**



2HDM	y_u^h	y_d^h	y_ℓ^h	y_u^H	y_d^H	y_ℓ^H
Type-I	c_α/s_β	c_α/s_β	c_α/s_β	s_α/s_β	s_α/s_β	s_α/s_β

$$\frac{c_\alpha}{s_\beta} = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$$

$$\frac{s_\alpha}{s_\beta} = \cos(\beta-\alpha) - \cot\beta\sin(\beta-\alpha)$$

$$\frac{1}{s_\beta} \propto \frac{1}{\tan\beta}$$

Theoretical and experimental Constraints

* **Our Strategy :** Scan BSM parameter space, keeping only points passing various theoretical and experimental constraints

2HDMC Code (D. Eriksson, J. Rathsman and O. Stål)

* Unitarity, Perturbativity, Vacuum Stability
* EW Precision Observables (S, T and U)

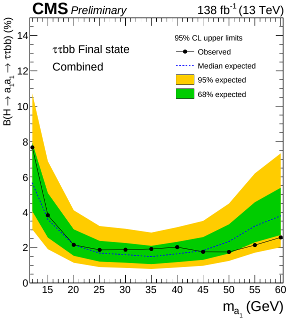
HiggsBounds (P. Bechtle et al), and **HiggsSignal** (P. Bechtle et al)

* Exclusion limits at 95% Confidence Level (CL) from Higgs searches at colliders (LEP, Tevatron and LHC)
* Constraints from the Higgs boson signal strength measurements

SuperIso (F. Mahmoudi)

* Constraints of flavour physics observables, namely, $B \to X_s\gamma,\ B_{s,d} \to \mu^+\mu^-$ and $\Delta m_{s,d}$

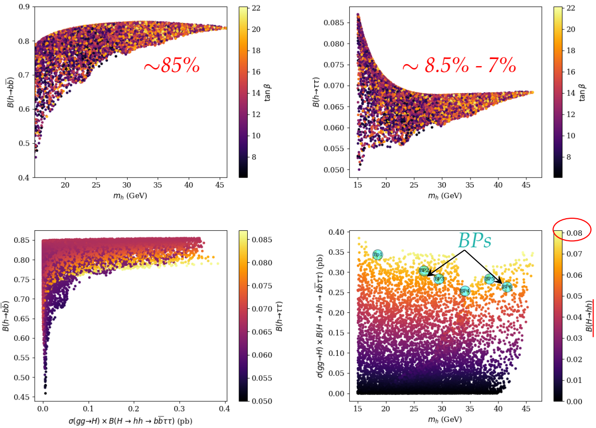
* Many BSM models motivate additional features of new di-Higgs final states (accessible by the LHC experiments in a variety of signatures, e.g. $H \to aa,\ hh$)



* Expected limits on $Br(H \to aa \to b\bar{b}\tau\tau)$ are found to be in range (1.5–5.6)%, for m_a between 12 and 60 GeV, corresponding to observed limits in range (1.8–7.7)% at 95% CL

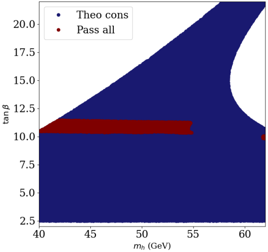
* Type-I can accommodate light scalars
* **Strategy :** random scan over Type-I parameter space
* Checking different BRs within the allowed region

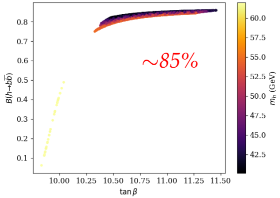
Inverted hierarchy	
parameters	scan
m_h (GeV)	[10, 61]
m_a (GeV)	[62 , 100]
m_H (GeV)	125
$m_{H^\pm}$ (GeV)	[100, 160]
$\sin(\beta-\alpha)$	[-0.25, 0]
$\tan\beta$	$[0, m_A^2 \sin\beta\cos\beta\,]$

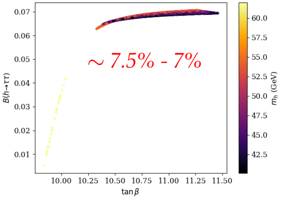


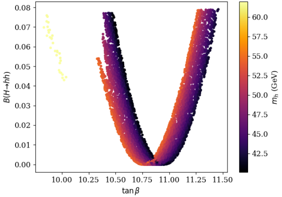
* Total width is dominated by $h \to b\bar{b}$
* Upper limits of 12% and 16% are set by ATLAS and CMS respectively on B_{BSM}
* $\sigma_{b\bar{b}\tau\tau}$ reaches 0.4 pb when $\text{BR}(H\to hh)$, $\text{BR}(h\to\tau\tau)$ and $\text{BR}(h\to b\bar{b})$ all reach their maximum values

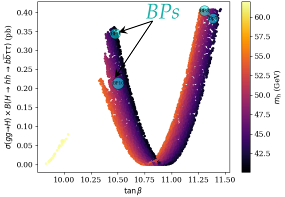
* Performing an additional scan with : $m_{H^\pm} = 165.58$ GeV, $m_A = 98.9$ GeV, $\sin(\beta - \alpha) = -0.10$, $m_{12}^2 = 154$ GeV^2



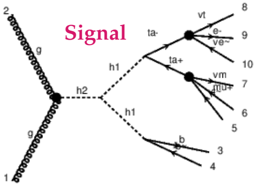








* Limited sensitivity to large $\tan\beta$
* $\sigma_{b\bar{b}\tau\tau}$ could also reach 0.4 pb
* BPs ⇒ MC simulation



- Samples of BPs for the signal given by $H \to hh \to b\bar{b}\ \tau_e\tau_\mu$ are considered
  - $\tau_e\tau_e$ and $\tau_\mu\tau_\mu$ are neglected to suppress DY
- Different background processes are considered :
  - $pp \to t\bar{t} \to e^\pm \mu^\mp b\bar{b} + E_T^{\text{miss}}$
  - Weak boson processes : Z-pair production, $Zb\bar{b}, Z\tau\tau, ZWj$
  - QCD processes $b\bar{b}jj$
- Cuts at generation level :
  - $p_T(b) > 10$ GeV, $p_T(l) > 5$ GeV,
  - $E_T^{\text{miss}} > 5$ GeV, $|\eta(b,l)| < 2.5$,
  - $\Delta R(ll, bl, bb) > 0.3$, $H_T < 70$ GeV

Toolbox to generate and analyse MC events

MadGraph-v.9.2.5 is used to generate signal/background events

PYTHIA8 is used for showering and hadronising parton level events

Applying detector simulation via Delphes-3.5.0 (CMS card)

Applying cuts and carry out analysis using MadAnalysis

- QCD corrections to signal and background processes are considered through K-factor

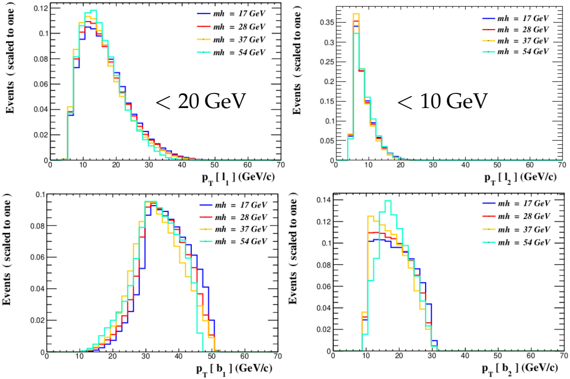
Background process	σ (pb)
$pp \to Z(\to b\bar{b})Z(\to ll), l = (e,\ \mu,\ \tau_{e,\ \mu})$	0.009 pb
$pp \to Z(\to ll)b\bar{b}, l = (e,\ \mu,\ \tau_{e,\ \mu})$	6.1 pb
$pp \to Z(\to b\bar{b})ll, l = (e,\ \mu,\ \tau_{e,\ \mu})$	0.015 pb
$pp \to ZW^\pm j,\ W^\pm \to l\nu_l\ (l = e,\ \mu, \tau_{e,\ \mu})$	0.0051 pb
$pp \to t\bar{t} \to e^\pm \mu^\mp b\bar{b} + E_T^{\text{miss}}$	0.28 pb

$2b2\tau$ Analysis

Challenge : $e\mu$ trigger

* Soft b-(anti quarks) ⇒ b-tagging efficiency ?!
* Soft leptons with low p_T
* Lepton triggers thresholds ?!

Selection criteria	$e\mu$
$p_T(e)$	23 → 10 GeV
$p_T(\mu)$	8 GeV
6 $p_T(b)$	> 10 GeV
$\|\eta(e,\mu)\|$	< 2.4
Isolation(e/μ)	0.10/0.15



$e\mu$ trigger : $p_T^{e,\mu} \sim 10$ GeV with a rate in 2- 5 KHz is feasible at Run 3

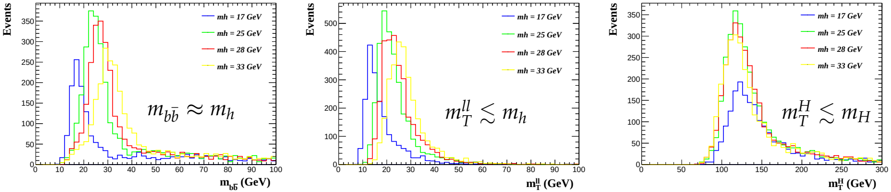
↑

Triggering on electron pairs after applying a dR cut in Run 3

↑

Double muon trigger : low p_T^{μ} from B meson decays

* Low kinematic variables for signal/Large values for BGs $\Rightarrow$ improving signal-to-background ratio



* Eevents selection requirements :
  * 2-leptons ($e^\pm \mu^\mp$) and 2 b-jets
  * m_z-veto : $|m_z - m_{ll}| < 10$ GeV
  * $62.5 < m_T^H < 125.5$ GeV
  * $\Delta m_h \equiv (m_{b\bar{b}} - m_{ll}^T)/m_{ll}^T < 0.5$
  * $m_{b\bar{b}} < 62.5$ GeV and $m_T^{ll} < 62.5$ GeV

✓ $p_T(b_1/b_2) > 15/10$ GeV
✓ $p_T(b_1/b_2) > 20/15$ GeV
✓ $p_T(b_1/b_2) > 20/20$ GeV

How the efficiencies can change?

$2b\tau$ ANALYSIS : DETECTOR LEVEL

$p_T(b_1/b_2) > 15/10$ GeV

Signal (BPs)	BP1	BP2	BP3	BP4	BP5	BP6	BP7	BP8	BP9	BP10
m_h (GeV)	17.67	25.9	28.56	33.20	37.56	40.68	47.27	54.03	43.44	49.39
NoE($\mathcal{L},\sigma$)	912.86	727.65	687.432	573.3	771.74	769.18	1086.62	1528.8	900.000	771.750
$e^{\pm}\mu^{\mp}$	156.934	151.874	141.094	114.84	146.44	136.2	160.54	204.94	151.226	111.163
m_Z-veto	156.934	151.874	141.094	114.84	146.44	136.2	160.54	204.94	151.226	111.163
2 b-jets	33.0	42.88	39.98	32.32	38.84	34.94	40.9	53.2	38.09	26.28
65 GeV $< m_T^H <$ 125 GeV	11.78	20.56	19.1	16.42	20.4	18.78	23.02	33.92	20.95	15.15
$\Delta m_h < 0.5$	8.1	15.88	15.16	12.96	16.24	14.84	18.18	27.34	16.95	12.015
$m_T^{ll} <$ 62.5 GeV	8.1	15.86	15.14	12.94	16.24	14.84	18.18	27.18	16.63	11.98
$m_{bb} <$ 62.5 GeV	8.1	15.86	15.12	12.94	16.24	14.76	18.18	27.04	16.60	11.97

$p_T(b_1/b_2) > 20/20$ GeV

Signal (BPs)	BP1	BP2	BP3	BP4	BP5	BP6	BP7	BP8	BP9	BP10
m_h (GeV)	17.67	25.9	28.56	33.20	37.56	40.68	47.27	54.03	43.44	49.39
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m_Z-veto	156.934	151.874	141.094	114.84	146.44	136.2	160.54	204.94	151.226	111.163
2 b-jets	13.6	20.38	19.02	15.3	17.86	16.02	18.34	23.7	17.39	11.06
65 GeV $< m_T^H <$ 125 GeV	2.68	7.16	6.84	5.72	6.84	6.16	6.14	11.38	6.80	4.19
$\Delta m_h < 0.5$	1.86	5.5	5.56	4.5	5.32	4.8	5.54	8.2	5.25	3.13
$m_T^{ll} <$ 62.5 GeV	1.86	5.5	5.56	4.48	5.32	4.8	5.52	8.2	5.25	3.13
$m_{bb} <$ 62.5 GeV	1.86	5.5	5.56	4.48	5.32	4.78	5.52	8.12	5.23	3.13

$p_T(b_1/b_2) > 20/15$ GeV

Signal (BPs)	BP1	BP2	BP3	BP4	BP5	BP6	BP7	BP8	BP9	BP10
m_h (GeV)	17.67	25.9	28.56	33.20	37.56	40.68	47.27	54.03	43.44	49.39
NoE($\mathcal{L},\sigma$)	912.86	727.65	687.432	573.3	771.74	769.18	1086.62	1528.8	900.000	771.750
$e^{\pm}\mu^{\mp}$	156.934	151.874	141.094	114.84	146.44	136.2	160.54	204.94	151.226	111.163
m_Z-veto	156.934	151.874	141.094	114.84	146.44	136.2	160.54	204.94	151.226	111.163
2 b-jets	23.9	32.38	30.8	23.24	29.36	25.76	28.56	40.036	28.125	18.714
65 GeV $< m_T^H <$ 125 GeV	7.76	13.72	13.372	11.32	13.82	12.38	14.58	22.56	13.890	9.470
$\Delta m_h < 0.5$	5.232	11.36	10.77	8.94	10.76	9.84	11.92	17.56	10.973	7.373
$m_T^{ll} <$ 62.5 GeV	5.232	11.36	10.76	8.92	10.76	9.82	11.9	17.5	10.961	7.363
$m_{bb} <$ 62.5 GeV	5.232	11.34	10.75	8.92	10.76	9.78	11.9	17.38	10.948	7.363

BGs	$Zb\bar{b}$			$t\bar{t}$		
NoE($\mathcal{L},\sigma$)	2562000			117600		
$p_T(b_1/b_2)$ (GeV)	15/10	20/15	20/20	15/10	20/15	20/20
$e^{\pm}\mu^{\mp}$	15836.8	15836.8	15836.8	61413.5	61413.5	61413.5
m_Z-veto	15801.4	15801.4	15801.4	54511.6	54511.6	54511.6
2 b-jets	1512.57	1059.63	503.558	16871.4	13778.6	8843.26
65 GeV $< m_T^H <$ 125 GeV	272.439	154.314	33.2724	35.2954	18.8916	3.087
$\Delta m_h <$ 0.5 GeV	117.072	30.0678	-	17.5266	7.6678	-
$m_T^{ll} <$ 62.5 GeV	117.072	30.0678	-	14.2366	6.125	-
$m_{bb} <$ 62.5 GeV	117.072	30.0678	-	14.2366	6.125	-

* Cuts on mass observables can greatly suppress the BGs
* Maximising the signal events with loose cuts
* Loss of signal for large p_T^b ; an expected outcome for h within the sub-50 GeV range

$2b2\tau$ Analysis : Detector Level

$\Sigma = \frac{\mathcal{N}_S}{\sqrt{\mathcal{N}_S+\mathcal{N}_B}}$, with $\mathcal{N}_{S(B)}$ is the signal (background) events number after applying the kinematic cuts

BP	Significance (Σ), $\mathcal{L} = 300$ fb^{-1}			Significance (Σ), $\mathcal{L} = 3000$ fb^{-1}		
	15/10 (GeV)	20/15 (GeV)	20/20 (GeV)	15/10 (GeV)	20/15 (GeV)	20/20 (GeV)
BP1	0.68	0.81	**1.36**	2.15	2.56	**4.30**
BP2	1.30	1.64	**2.34**	4.11	5.18	**7.39**
BP3	1.24	1.57	**2.35**	3.92	4.96	**7.43**
BP4	1.07	1.32	**2.11**	3.38	4.17	**6.67**
BP5	1.33	1.57	**2.3**	4.20	4.96	**7.27**
BP6	1.22	1.44	**2.18**	3.85	4.55	**6.89**
BP7	1.48	1.71	**2.34**	4.68	5.40	**7.39**
BP8	2.14	2.37	**2.84**	6.76	7.49	**8.9**
BP9	1.36	1.59	**2.28**	4.3	5.02	**7.2**
BP10	1.0	1.11	**1.76**	3.16	3.51	**5.56**

TABLE – Significances for our signal against the two dominant backgrounds with $\sqrt{s} = 13$ TeV and integrated luminosity 300 fb^{-1} (left) as well as 3000 fb^{-1} (right)

* A better significance with a pre-selection cut of 20/20 GeV
* Difficulty in discovering/ruling out some of the BPs at Run 3
* HL-LHC can can offer sensitivity to 2HDM Type-I

Conclusion

* The possibility of optimising searches for very light Higgses in 2HDM Type-I
* Focusing on the $hh \to b\bar{b}\tau_e\tau_\mu$ decay pattern
* A potential improve of the analysis sensitivity due to the trigger choice
* Run3 and HL-LHC phase can offer sensitivity to 2HDM Type-I signal

Thank you for listening

Backup

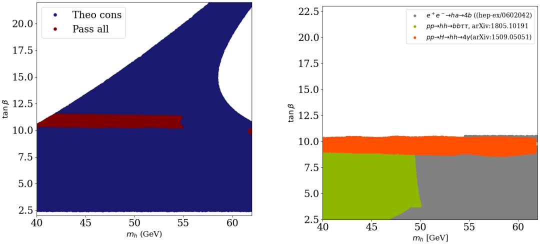

FIGURE – Allowed (left panel) and excluded (right panel) parameter space over the $(m_h,\ \tan\beta)$ plane. Here, $m_{H^\pm} = 165.58\,\text{GeV},\ m_A = 98.9\,\text{GeV},\ \sin(\beta-\alpha) = -0.10,\ m_{12}^2 = 154\,\text{GeV}^2$

The triple Higgs coupling *Hhh* is written as follows :

$$Hhh = -\frac{g c_{\beta-\alpha}}{2 m_W s_{2\beta}^2}\left[(2m_h^2 + m_H^2) s_{2\alpha} s_{2\beta} - 2(3 s_{2\alpha} - s_{2\beta}) m_{12}^2\right]$$

Backgrounds at parton level

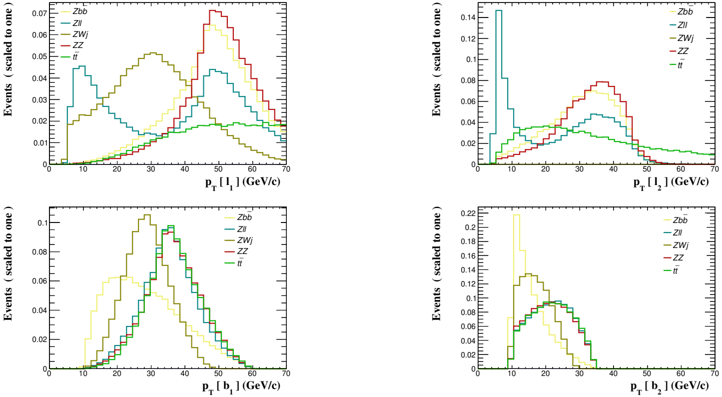

FIGURE – The p_T distributions of the leading (subleading) lepton and b-(anti)quark of different background processes are shown at parton level