Searching for light Higgs bosons in $2b2\tau$, 4τ final states at the LHC in the 2HDM

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Based on: 10.1103/PhysRevD.109.055020 & 2401.07289 [hep-ph]

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Motivation : $H \to hh/aa \to 4f$ at LHC

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

We focus here on

Resonant scenario → $2b2\tau$

10.1103/PhysRevD.109.055020

Resonant scenario → 4τ

arXiv : 2401.07289

Channel ($H \to aa \to 4f$)	Mass of a, m_a (GeV)
$4b$	$[20, 60]$
$2b2\tau$	$[15, 60]$
$2b2\mu$	$[20, 60]$
$2b2\mu$	$[20, 62.5]$
$2b2\mu$	$[16, 62]$
4μ	–
4τ	$[15, 60]$
$2\mu2\tau$	$[3.6, 21]$
4τ / $2\mu2\tau$	$[4, 15]$
$2\mu2\tau$	$[15, 62.5]$
$4e$	$[10, 60]$
$2e2\mu$	$[10, 60]$

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LHC Agenda : Exotic Higgs decays

- Experiments have placed upper limits on light Higgs decay rates
- 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

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

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

- 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

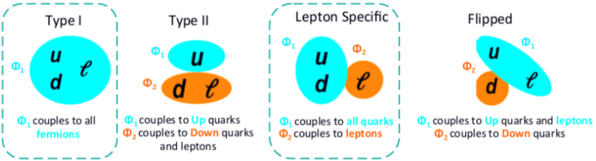
Minimal Flavour Violation

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

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

$\Longrightarrow$ **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
Type-X	c_α/s_β	c_α/s_β	$-s_\alpha/c_\beta$	s_α/s_β	s_α/s_β	c_α/c_β

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

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

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

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

* **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)

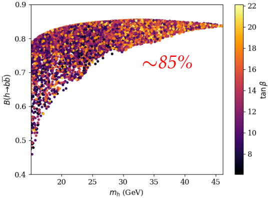
* Exclusion limits at 95% Confidence Level (CL) from Higgs searches at colliders (LEP, Tevatron and LHC)
* Constraints from the Higgs boson signal strength measurements

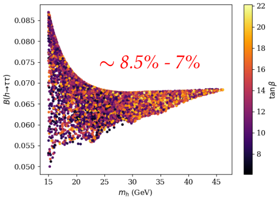
SuperIso (F. Mahmoudi)

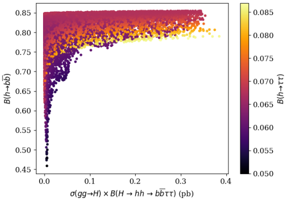
* Constraints of flavour physics observables, namely, $B \to X_s\gamma,\ B_{s,d} \to \mu^+\mu^-$ and $\Delta m_{s,d}$

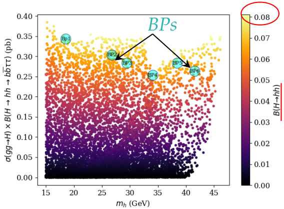
- Type-I can accommodate light scalars
- **Strategy :** random scan over Type-I parameter space
- Checking different BRs within the allowed region

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, $m_A^2 \sin\beta\cos\beta$]

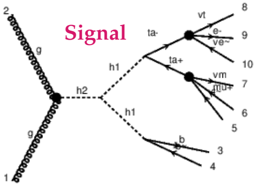








- Total width is dominated by $h \to b\bar{b}$
- Upper limits of 12% and 16% are set by ATLAS and CMS respectively on B_{BSM}
- $\sigma_{b\bar{b}\tau\tau}$ reaches 0.4 pb when BR$(H \to hh)$, BR$(h \to \tau\tau)$ and BR$(h \to b\bar{b})$ all reach their maximum values



* 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)

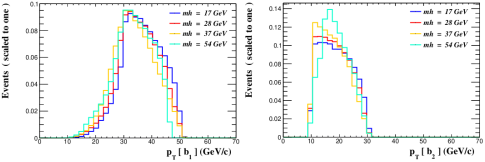
↓

Applying cuts and carry out analysis using `MadAnalysis`

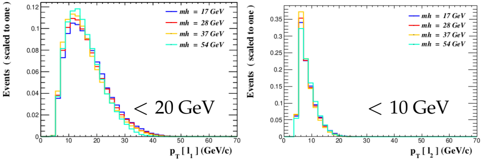
* QCD corrections to signal and background processes are considered through K-factor

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 : h WITHIN THE SUB-60 GEV RANGE



* Soft b-(anti quarks) $\Rightarrow$ b-tagging efficiency ?!



* Soft leptons with low p_T
* Lepton triggers thresholds ?!

Challenge : $e\mu$ trigger

* The current CMS cross trigger requires :

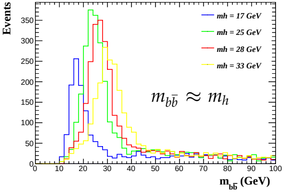
Selection criteria	$e\mu$
$p_T(e)$	23 $\rightarrow$ 10 GeV
$p_T(\mu)$	8 GeV
6 $p_T(b)$	$>$ 10 GeV
$\|\eta(e, \mu)\|$	$<$ 2.4
Isolation(e/μ)	0.10/0.15

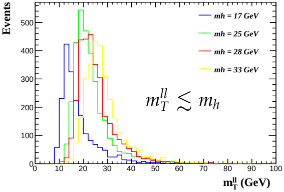
* Propose a new trigger :

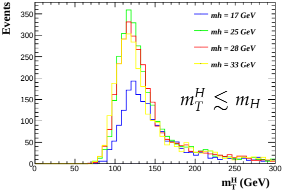
  * Double muon trigger : low p_T^{μ} from B meson decays
  * Triggering on electron pairs after applying a dR cut in Run 3
  * $e\mu$ trigger : $p_T^{e,\mu} \sim 10$ GeV with a rate in 2-5 KHz is feasible at Run 3

$2b2\tau$ Analysis

* 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

* To examine how the efficiencies can change, we adopt the following pre-selection rules :

$$p_T(b_1/b_2) > 15/10 \text{ GeV}, \; p_T(b_1/b_2) > 20/15 \text{ GeV}, \; p_T(b_1/b_2) > 20/20 \text{ GeV}$$

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

* Applying cuts on mass observables $\Rightarrow$ **effective suppression of 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-60 GeV range

$\Sigma = \frac{\mathcal{N}_S}{\sqrt{\mathcal{N}_S + \mathcal{N}_B}}$, 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)

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

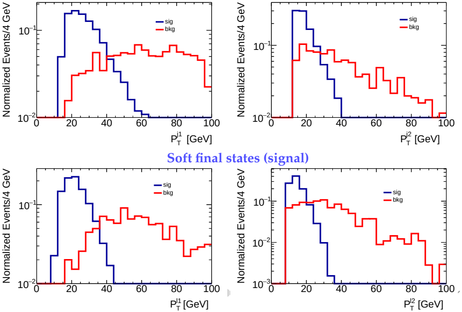
σ (fb)	BP1	BP2	BP3	BP4	BP5	BP6	BP7	BP8	BP9	BP10	BP11	BP12
parton level generation	8.95	11.37	7.38	9.05	13.32	11.33	10.43	23.16	19.26	15.81	17.00	12.75
selection of 2l2j	0.67	0.88	0.59	0.76	1.10	0.96	0.88	1.97	1.62	1.46	1.70	1.38
selection of SS 2l	0.337	0.438	0.31	0.41	0.59	0.52	0.50	1.14	0.92	0.83	0.93	0.75

TABLE III. Cross sections for signals in the parton level, detector level, and after selection of SS leptons at $\sqrt{s} =$ 14 TeV for 300 fb^{-1}.

- The signal process is :
  $H \to hh \to \tau^+\tau^-\tau^-\tau^+ \to \ell\nu_\ell\ell\nu_\ell\tau_j\tau_j$
  - Same sign (SS) leptons are required to improve the experimental significance
- Different background processes are considered :
  - $pp \to t\bar{t} \to l\upsilon_l l\upsilon_l b\bar{b}$
  - $pp \to Wtb \to l\upsilon_l l\upsilon_l b\bar{b}$
  - $pp \to WWjj \to l\upsilon_l l\upsilon_l jj$
  - $pp \to Zjj \to l\upsilon_l l\upsilon_l jj$
  - $pp \to ZZ \to l\upsilon_l l\upsilon_l \tau\tau$
  - $pp \to t\bar{t}Z \to l\upsilon_l l\upsilon_l b\bar{b}\tau\tau$
  - $pp \to t\bar{t}ZZ \to l\upsilon_l l\upsilon_l l\upsilon_l b\bar{b}\tau\tau$
  - $pp \to t\bar{t}WW \to l\upsilon_l l\upsilon_l l\upsilon_l jj$ where j refers here to parton.
- Cuts at generation level :
  - $|\eta(l,j)|<2.5, \;\; p_T(l,j)>10$ GeV
  - $\Delta R(ll, lj, jj) > 0.4, \;\; E_T^{miss}>5$ GeV

σ (fb)	$t\bar{t}$	$W^{\pm}tb$	W^+W^-jj	Zjj	ZZ	$t\bar{t}Z$	$t\bar{t}ZZ$	$t\bar{t}W^+W^-$
parton level generation	16060	518.3	1053	317600	18.89	0.49	1.14×10^{-4}	0.02
selection of 2l2j	8787.7	289.9	530.1	151086	10.0	0.33	1.1×10^{-4}	0.018
selection of SS 2l	19.43	0.62	1.99	0	2.51	0.079	3.3×10^{-5}	7.6×10^{-3}

TABLE IV. Background rates after the acceptance cuts at $\sqrt{s} =$ 14 TeV for 300 fb^{-1}.



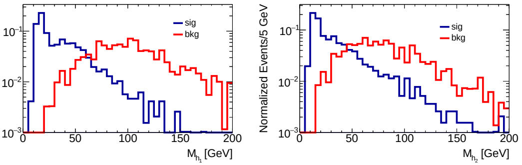
Soft final states (signal)

4τ Analysis (2HDM Type-X)

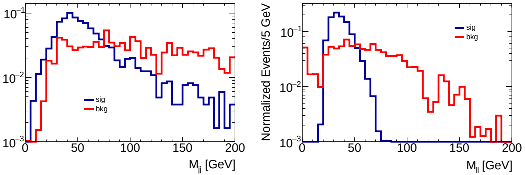
Kinematic variables : $M_{lj},\ M_{ll},\ M_{jj},\ M_H$

* Pairing 2l and 2j to find a combination which minimizes χ^2,

$$\chi^2 = (M_{lj}^1 - M_h)^2 + (M_{lj}^2 - M_h)^2$$

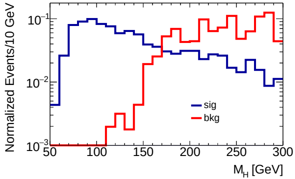


* Combining 2l and 2j together ($M_{ll},\ M_{jj}$)



* Hard background spectra (lepton and jet pairs always come from a heavy resonance)

* Reconstruction of m_H with two leptons and two jets but without any MET



* M_H is lower than the real SM-like Higgs boson mass, but it is still useful!

4τ ANALYSIS (2HDM TYPE-X)

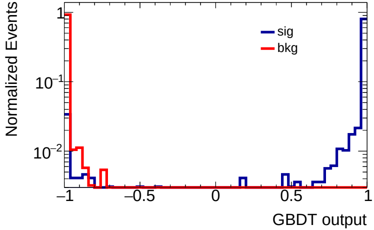
A Gradient-Boosted Decision Tree (GBDT) approach is further applied

Ten input variables in total are used for the GBDT/TMVA analysis :

- ∗ M_{h_1}, M_{h_2}, M_H, M_{ll}, H_T
- ∗ 5 angles between pairs of objects in the final state,

Energy variables	$M^1_{l\tau_j}$	$M^2_{l\tau_j}$	M_{ll}	M_{jj}	H_T
Angular variables	$\cos(\theta_{h_1h_2})$	$\cos(\theta_{l_1j_1})$	$\cos(\theta_{l_1j_2})$	$\cos(\theta_{l_2j_1})$	$\cos(\theta_{l_2j_2})$

TABLE V. The input observables used in the GBDT analysis.



∗ A very good separation between signal and background can be obtained

$L = 300$ fb^{-1}	S	$t\bar{t}$	$t\bar{t}W^+W^-$	$t\bar{t}Z$	$t\bar{t}ZZ$	Wtb	W^+W^-jj	ZZ	B	Σ
Acceptance	262.6	2.17×10^6	2.3	63	0.01	53751.6	119699	2790.8	2.35×10^6	0.17
SS Leptons	131.5	5829.8	1.5	23.6	0.01	186.6	595.5	754.1	7391.1	1.52
$H_T \in [40, 200]$	129.9	1040.7	0.002	0.5	1e-05	40.4	127.9	379.1	1588.7	3.13
$M_{ll} \in [10, 80]$	129.8	905.8	0.001	0.5	1e-05	32.7	58.4	283.8	1281.1	3.45
$M_{h_1} \in [0, 150]$	128.7	809.4	0.001	0.4	1e-05	31.1	56.9	271.4	1169.2	3.57
$M_{h_2} \in [0, 150]$	126.9	732.3	0.001	0.4	8e-06	28	55.3	260.5	1076.5	3.66
$M_H \in [20, 230]$	96.9	269.8	0	0.2	5e-06	10.9	26.9	124.3	432	4.21
GBDT $\in [0.5, 1]$	92.6	0	0	0.02	0	0	3.2	7.1	10.2	9.13

TABLE VI. Response to our selection cuts for the signal (e.g., BP2) and background (separately and total) rates computed at $\sqrt{s} =$ 14 TeV for 300 fb^{-1}.

∗ Kinematic selection is quite efficient in separating signal from background

Σ	BP1	BP2	BP3	BP4	BP5	BP6	BP7	BP8	BP9	BP10	BP11	BP12
after selecting SS leptons	1.17	1.52	1.06	1.40	2.04	1.79	1.71	3.89	3.15	2.86	3.18	2.58
after kinematic cuts, w/o GBDT	3.09	4.21	2.66	3.79	5.20	4.50	4.50	8.84	7.58	6.65	7.41	6.24
after kinematic cuts, w/ GBDT	7.65	9.13	6.27	8.61	10.41	9.45	9.34	14.32	12.91	11.25	12.14	10.74

TABLE VII. Significances following our different selections for all signals (BP1–BP12) at $\sqrt{s} =$ 14 TeV for 300 fb^{-1}.

∗ Exploitation of the GBDT output ⇒ doubles the final significance

Conclusion

* The possibility of optimising searches for very light Higgses in 2HDM Type-I/X
* Focusing on the $hh \to b\bar{b}\tau_e\tau_\mu,\ \tau_l\tau_l\tau_h\tau_h$ decays pattern
* A potential improve of the analysis sensitivity due to the trigger choice
* Sensitivity to 2HDM Type-I signal with Run-3 and HL-LHC
* The possibility of observing $H \to hh \to 4\tau$ at the end of Run 3 of the LHC, following a dedicated selection based on kinematic and TMVA analysis

Thank you for listening

Backup

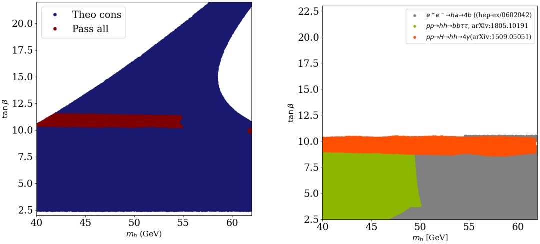


FIGURE – Allowed (left panel) and excluded (right panel) parameter space over the $(m_h,\ \tan\beta)$ plane. Here, $m_{H^\pm} = 165.58\,\text{GeV},\ m_A = 98.9\,\text{GeV},\ \sin(\beta-\alpha) = -0.10,\ m_{12}^2 = 154\,\text{GeV}^2$

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

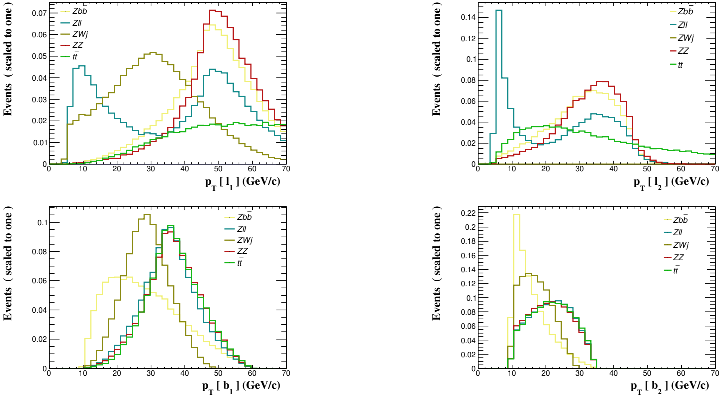
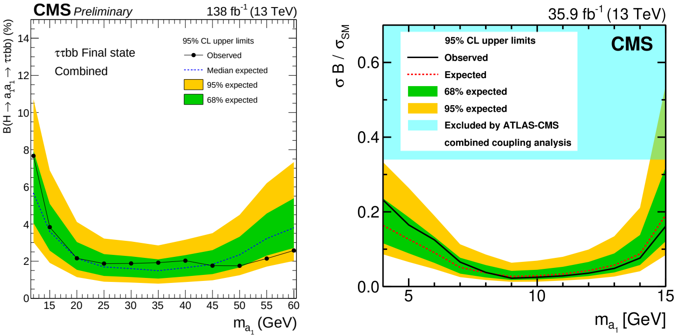


FIGURE – The p_T distributions of the leading (subleading) lepton and b-(anti)quark of different background processes are shown at parton level

$H \to aa \to 2b2\tau$

- 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

The m_T^{ll} variable is defined from p_{ll} (the total four-momentum of the leptons) and E_T^{miss} as :

$$m_T^{ll} = \sqrt{p_{ll}^0 E^0 - |p_{ll}^T||E^T| \cos(\phi_{ll,E_T^{\text{miss}}})}. \tag{1}$$

For the sake of convenience, we denote E_T^{miss} as (E^0, E^T, p_z), where p_z is the unknown z-component of the missing momentum and E^T is a 2D vector defined in the (x, y) plane perpendicular to the beam direction. Here, $\phi_{ll,E_T^{\text{miss}}}$ denotes the perpendicular angle between the di-lepton system and E_T^{miss}.

m_T^H is defined from the two b-jet four-momenta $p_{b\bar{b}} = p(b) + p(\bar{b})$, p_{ll} and E_T^{miss}. To define m_T^H, we first express the visible momentum, which equals $p_{\text{vis}} = p_{b\bar{b}} + p_{ll}$, so that we have

$$m_T^H = \sqrt{p_{vis}^0 E^0 - |p_{vis}^T||E^T| \cos(\phi_{\text{vis},E_T^{\text{miss}}})}\,, \tag{2}$$

where $\phi_{\text{vis},E_T^{\text{miss}}}$ denotes the perpendicular angle between visible momentum and E_T^{miss}.

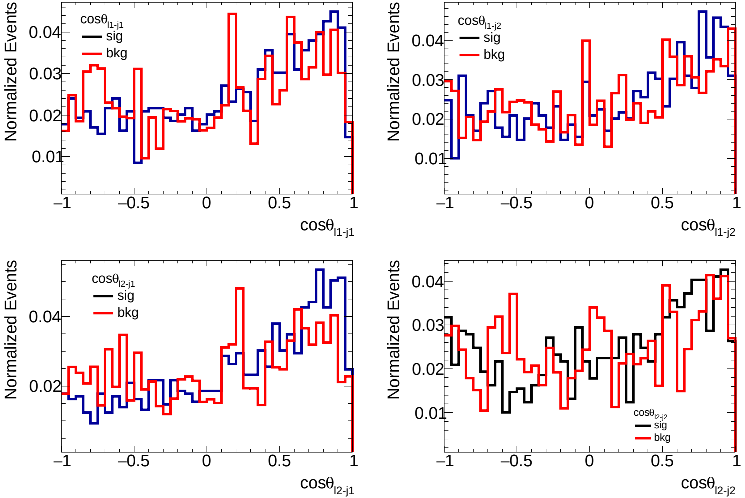


FIGURE – Distributions in the (cosine of the) angle between pairs of jets/leptons for BP2 and backgrounds