

# Search for $H \rightarrow hh \rightarrow b\bar{b}\tau\tau$ , $4\tau$ at the LHC in the 2HDM

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# MOTIVATION : $H \rightarrow hh/aa \rightarrow 4f$ 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.  $H \rightarrow aa, hh$ )

Channel (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]
4 $\mu$	—
4 $\tau$	[15, 60]
2 $\mu$ 2 $\tau$	[3.6, 21]
4 $\tau$ / 2 $\mu$ 2 $\tau$	[4, 15]
2 $\mu$ 2 $\tau$	[15, 62.5]
4e	[10, 60]
2e2 $\mu$	[10, 60]

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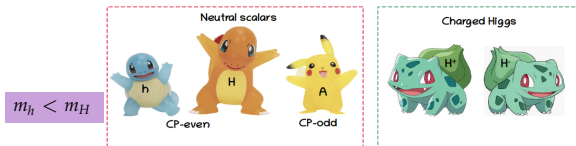
- Expected limits on  $Br(H \rightarrow aa \rightarrow b\bar{b}\tau\tau)$  are found to be in range (1.5–5.6)%, for  $m_a$  between 12 and 60 GeV, corresponding to observed limits in range (1.8–7.7)% at 95% CL

# 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

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

- \* To prevent FCNC at tree-level, a  $Z_2$  symmetry can be imposed  $\rightarrow$  removes  $\lambda_6, \lambda_7$
- \* Free parameters : 5 masses after EWSB,  $\tan \beta = v_2/v_1$ , mixing angle  $\alpha$  and  $m_{12}^2$



- \* 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



# 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

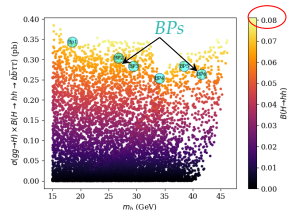
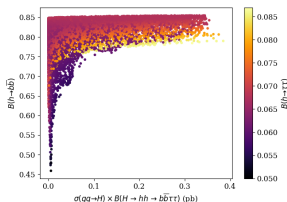
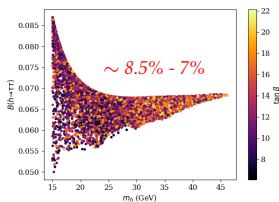
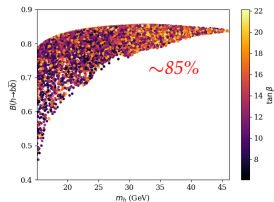
## SuperIso (F. Mahmoudi)

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

# 2b2τ ANALYSIS (2HDM TYPE-I)

- \* 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]
$\tan \beta$	$[0, m_A^2 \sin \beta \cos \beta]$



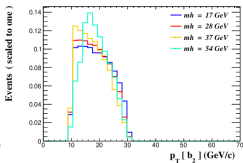
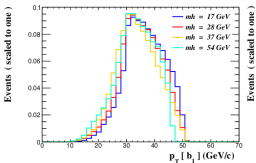
- \* Total width is dominated by  $h \rightarrow b\bar{b}$

- \* Upper limits of 12% and 16% are set by ATLAS and CMS respectively on  $B_{BSM}$

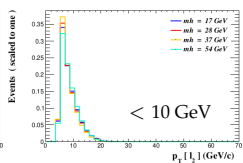
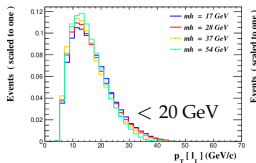
- \*  $\sigma_{b\bar{b}\tau\tau}$  reaches 0.4 pb when  $BR(H \rightarrow hh)$ ,  $BR(h \rightarrow \tau\tau)$  and  $BR(h \rightarrow b\bar{b})$  all reach their maximum values



# 2b2τ 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( $e/\mu$ )	0.10/0.15

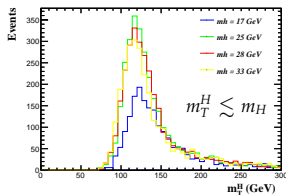
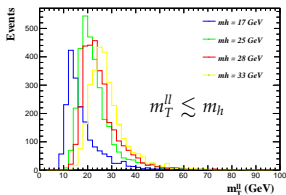
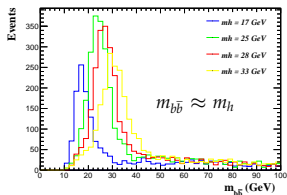


- \* Propose a new trigger :

- \* Double muon trigger : low  $p_T^\mu$  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



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



- \* Events selection requirements :

- \* 2-leptons ( $e^\pm \mu^\mp$ ) and 2 b-jets
- \*  $m_z$ -veto :  $|m_z - m_H| < 10$  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  $m_T^H < 62.5$  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 (BGs)	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
$m_2$ -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 < $m_{\tau\tau}^{\text{eff}}$ < 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
$m_{\tau\tau}^{\text{eff}} < 62.5$ GeV	8.1	15.86	15.14	12.94	16.24	14.84	18.18	27.18	16.63	11.98
$m_{b\bar{b}} < 62.5$ GeV	<b>8.1</b>	<b>15.86</b>	<b>15.12</b>	<b>12.94</b>	<b>16.24</b>	<b>14.76</b>	<b>18.18</b>	<b>27.04</b>	<b>16.60</b>	<b>11.97</b>

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

Signal (BGs)	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
$m_2$ -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 < $m_{\tau\tau}^{\text{eff}}$ < 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	5.36	4.5	5.32	4.8	5.54	8.2	5.25	3.13
$m_{\tau\tau}^{\text{eff}} < 62.5$ GeV	1.86	5.5	5.56	4.48	5.32	4.8	5.52	8.2	5.25	3.13
$m_{b\bar{b}} < 62.5$ GeV	<b>1.86</b>	<b>5.5</b>	<b>5.56</b>	<b>4.48</b>	<b>5.32</b>	<b>4.78</b>	<b>5.52</b>	<b>8.12</b>	<b>5.23</b>	<b>3.13</b>

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

Signal (BGs)	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
$m_2$ -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 < $m_{\tau\tau}^{\text{eff}}$ < 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
$m_{\tau\tau}^{\text{eff}} < 62.5$ GeV	5.232	11.36	10.76	8.92	10.76	9.82	11.9	17.5	10.961	7.363
$m_{b\bar{b}} < 62.5$ GeV	<b>5.232</b>	<b>11.34</b>	<b>10.75</b>	<b>8.92</b>	<b>10.76</b>	<b>9.78</b>	<b>11.9</b>	<b>17.38</b>	<b>10.948</b>	<b>7.363</b>

BGs	$Zb\bar{b}$			$t\bar{t}$		
NoE( $\mathcal{L}, \sigma$ )	2562000			117600		
$p_T(b_1/b_2)$ (GeV)	<b>15/10</b>	<b>20/15</b>	<b>20/20</b>	<b>15/10</b>	<b>20/15</b>	<b>20/20</b>
$e^\pm \mu^\mp$	15836.8	15836.8	15836.8	61413.5	61413.5	61413.5
$m_2$ -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 < $m_{\tau\tau}^{\text{eff}}$ < 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	-
$m_{\tau\tau}^{\text{eff}} < 62.5$ GeV	117.072	30.0678	-	14.2366	6.125	-
$m_{b\bar{b}} < 62.5$ GeV	<b>117.072</b>	<b>30.0678</b>	<b>-</b>	<b>14.2366</b>	<b>6.125</b>	<b>-</b>

- \* 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-60 GeV range

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

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

TABLE – Significances for our signal against the two dominant backgrounds with  $\sqrt{s} = 13 \text{ TeV}$  and integrated luminosity  $300 \text{ fb}^{-1}$  (left) as well as  $3000 \text{ fb}^{-1}$  (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 offer sensitivity to 2HDM Type-I

# 4 $\tau$ ANALYSIS (2HDM TYPE-X)

- \* The signal process is :

$$H \rightarrow hh \rightarrow \tau^+ \tau^- \tau^- \tau^+ \rightarrow \ell \nu_\ell \ell \nu_\ell \tau_j \tau_j$$

- \* Same sign (SS) leptons are required to improve the **experimental significance**

- \* Different background processes are considered :

- \*  $pp \rightarrow t\bar{t} \rightarrow l\nu_l l\nu_l b\bar{b}$
- \*  $pp \rightarrow Wtb \rightarrow l\nu_l l\nu_l b\bar{b}$
- \*  $pp \rightarrow WWjj \rightarrow l\nu_l l\nu_l jj$
- \*  $pp \rightarrow Zjj \rightarrow l\nu_l l\nu_l jj$
- \*  $pp \rightarrow ZZ \rightarrow l\nu_l l\nu_l \tau\tau$
- \*  $pp \rightarrow t\bar{t}Z \rightarrow l\nu_l l\nu_l b\bar{b}\tau\tau$
- \*  $pp \rightarrow t\bar{t}ZZ \rightarrow l\nu_l l\nu_l l\nu_l b\bar{b}\tau\tau$
- \*  $pp \rightarrow t\bar{t}WW \rightarrow l\nu_l l\nu_l l\nu_l jj$  where j refers here to parton.

- \* Cuts at generation level :

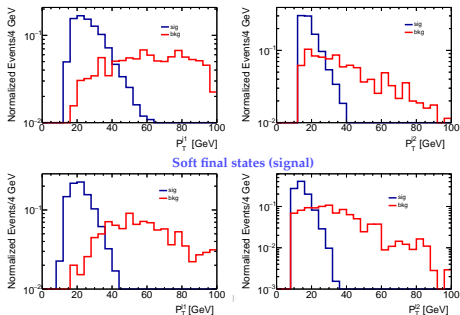
- \*  $|\eta(l, j)| < 2.5, p_T(l, j) > 10 \text{ GeV}$
- \*  $\Delta R(l, l_j, jj) > 0.4, E_T^{\text{miss}} > 5 \text{ GeV}$

$\sigma$ (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  $\sqrt{s} = 14 \text{ TeV}$  for  $300 \text{ fb}^{-1}$ .

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

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



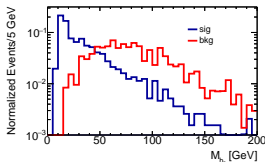
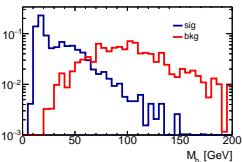
# 4 $\tau$ ANALYSIS (2HDM TYPE-X)

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

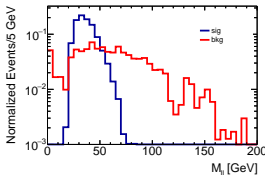
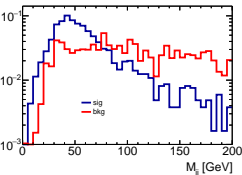


- \* Pairing 2l and 2j to find a combination which minimizes  $\chi^2$ ,

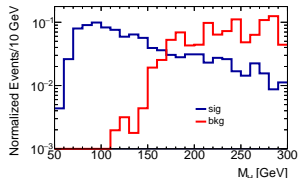
$$\chi^2 = (M_{lj}^1 - M_h)^2 + (M_{lj}^2 - M_h)^2$$



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



- \* 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!

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

# 4T 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	$M_{l\tau_j}^1$	$M_{l\tau_j}^2$	$M_{ll}$	$M_{jj}$	$H_T$
Angular variables	$\cos(\theta_{h_1 h_2})$	$\cos(\theta_{l_1 j_1})$	$\cos(\theta_{l_1 j_2})$	$\cos(\theta_{l_2 j_1})$	$\cos(\theta_{l_2 j_2})$

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

$L = 300 \text{ fb}^{-1}$	$S$	$t\bar{t}$	$t\bar{t}W^+W^-$	$t\bar{t}Z$	$t\bar{t}ZZ$	$Wtb$	$W^+W^-jj$	$ZZ$	$B$	$\Sigma$
Acceptance	262.6	$2.17 \times 10^6$	2.3	63	0.01	53751.6	119699	2790.8	$2.35 \times 10^6$	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

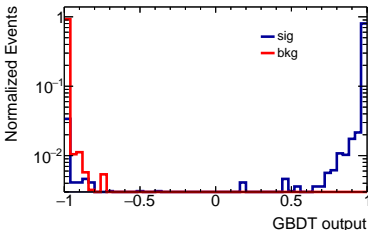
TABLE VI. Response to our selection cuts for the signal (e.g., BP2) and background (separately and total) rates computed at  $\sqrt{s} = 14 \text{ TeV}$  for  $300 \text{ fb}^{-1}$ .

- \* Kinematic selection is quite efficient in separating signal from background

$\Sigma$	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	<b>7.65</b>	<b>9.13</b>	<b>6.27</b>	<b>8.61</b>	<b>10.41</b>	<b>9.45</b>	<b>9.34</b>	<b>14.32</b>	<b>12.91</b>	<b>11.25</b>	<b>12.14</b>	<b>10.74</b>

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

- \* Exploitation of the GBDT output  $\Rightarrow$  double the final significance



- \* A very good separation between signal and background can be obtained

- \* The possibility of optimising searches for very light Higgses in 2HDM Type-I/X
- \* Focusing on the  $hh \rightarrow b\bar{b}\tau_e\tau_\mu$ ,  $\tau_l\tau_l\tau_h\tau_h$  decays pattern
- \* A potential improve of the analysis sensitivity due to the trigger choice
- \* Run3 and HL-LHC phase can offer sensitivity to 2HDM Type-I signal
- \*  $H \rightarrow hh \rightarrow 4\tau$  could be found at the end of Run 3 of the LHC, following a dedicated selection based on kinematic and TMVA analysis

Thank you for listening

# Backup



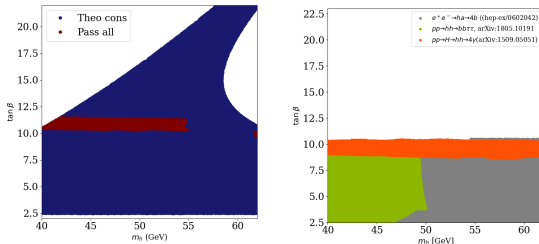


FIGURE – Allowed (left panel) and excluded (right panel) parameter space over the  $(m_h, \tan \beta)$  plane. Here,  $m_{H^\pm} = 165.58$  GeV,  $m_A = 98.9$  GeV,  $\sin(\beta - \alpha) = -0.10$ ,  $m_{12}^2 = 154$  GeV<sup>2</sup>

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

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

# BACKGROUNDS AT PARTON LEVEL

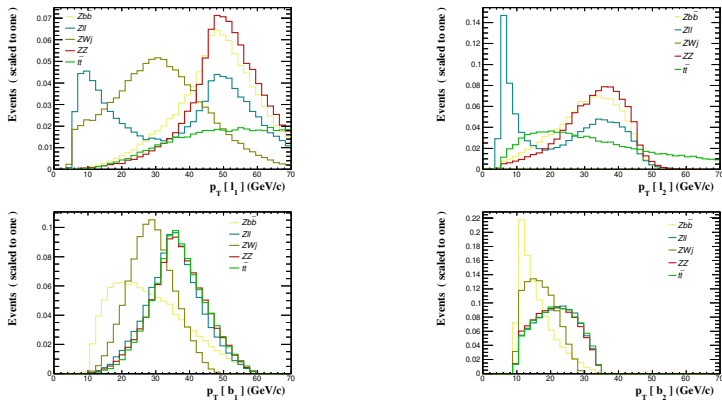
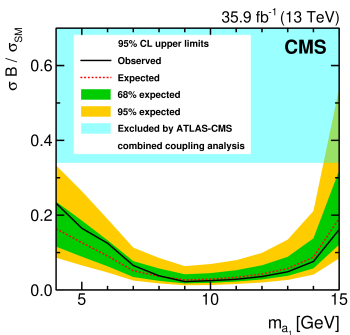
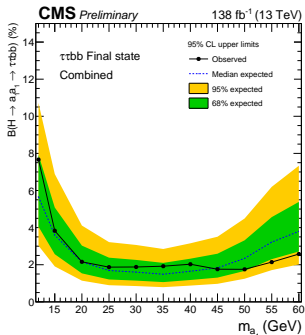


FIGURE – The  $p_T$  distributions of the leading (subleading) lepton and  $b$ -(anti)quark of different background processes are shown at parton level

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



- \* Expected limits on  $Br(H \rightarrow aa \rightarrow b\bar{b}\tau\tau)$  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  $m_T^{\parallel}$  variable is defined from  $p_{\parallel}$  (the total four-momentum of the leptons) and  $E_T^{\text{miss}}$  as :

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

For the sake of convenience, we denote  $E_T^{\text{miss}}$  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,  $\phi_{\parallel, E_T^{\text{miss}}}$  denotes the perpendicular angle between the di-lepton system and  $E_T^{\text{miss}}$ .

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

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

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