Searching for light Higgs bosons in the 2HDM at the LHC

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Based on: 10.1103/PhysRevD.109.055020 & 2401.07289 & 24xx.xxxx [hep-ph]

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LHC Higgs Working Group WG3 (BSM)
Extended Higgs Sector subgroup

MOTIVATION : $H \to aa(hh) \to X_1X_1X_2X_2$ 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. $H \to aa,\ hh$)
- Experiments have placed upper limits on light Higgs decay rates

We focus here on

Resonant scenario → $2b2\tau$

10.1103/PhysRevD.109.055020

Resonant scenario → 4τ

arXiv : 2401.07289

Resonant scenario $2b2\gamma$ → 4γ

arXiv : 24xx.xxx

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]
4γ	[10, 60]
$2\gamma2j$	[20, 60]

LHC Agenda
Exotic Higgs decays

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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)

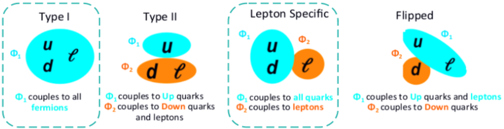
Couplings to fermions and gauge bosons lead to different phenomenology w.r.t the SM

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

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

$\rightarrow$ **FCNC at tree level!**

* $\mathcal{Z}_2$ **symmetry :** 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

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

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

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

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

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

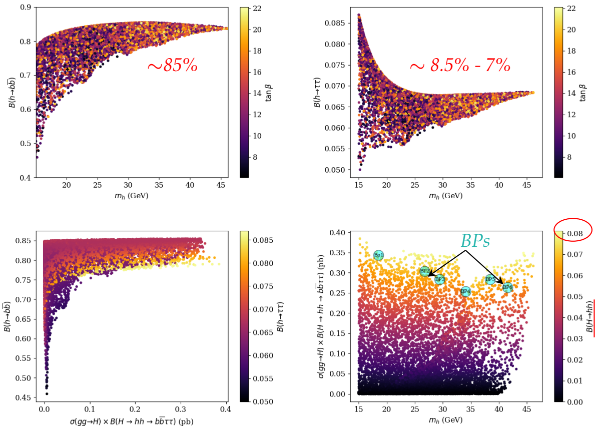
SuperIso (F. Mahmoudi)

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

$2b2\tau$ Analysis (2HDM Type-I)

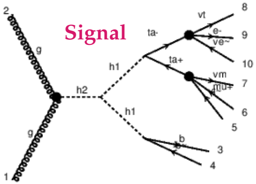
- Type-I can accommodate light scalars
- **Strategy :** random scan over Type-I parameter space
- Checking different BRs within the allowed region

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 $h \to b\bar{b}$
- 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

$2b2\tau$ ANALYSIS



* 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

↓

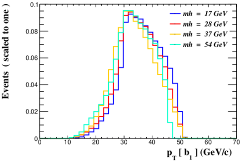
Applying detector simulation via `Delphes-3.5.0` (CMS card)

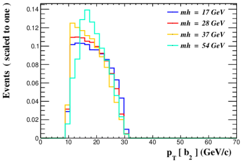
↓

Applying cuts and carry out analysis using `MadAnalysis`

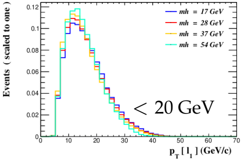
* QCD corrections to signal and background processes are considered through K-factor

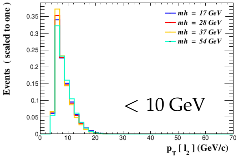
Background process	σ (pb)
$pp \to Z(\to b\bar{b})Z(\to ll), l = (e,\ \mu,\ \tau_{e,\ \mu})$	0.009 pb
$pp \to Z(\to ll)b\bar{b}, l = (e,\ \mu,\ \tau_{e,\ \mu})$	6.1 pb
$pp \to Z(\to b\bar{b})ll, l = (e,\ \mu,\ \tau_{e,\ \mu})$	0.015 pb
$pp \to ZW^{\pm}j,\ W^{\pm} \to l\nu_l\ (l = e,\ \mu, \tau_{e,\ \mu})$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





- Soft b-(anti quarks) ⇒ b-tagging efficiency ?!





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

Challenge : $e\mu$ trigger

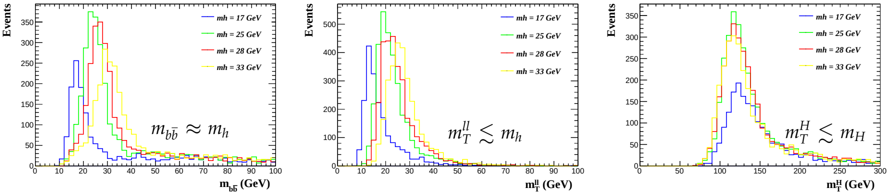
- The current CMS cross trigger requires :

Selection criteria	$e\mu$
$p_T(e)$	23 → 10 GeV
$p_T(\mu)$	8 GeV
6 $p_T(b)$	> 10 GeV
$\lvert\eta(e,\mu)\rvert$	< 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

- **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 : $|m_z - m_{ll}| < 10$ 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

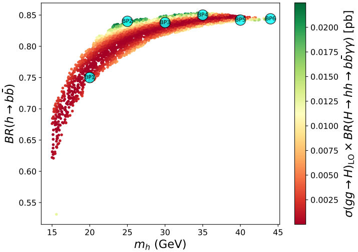
$\Sigma = \frac{\mathcal{N}_S}{\sqrt{\mathcal{N}_S+\mathcal{N}_B}}$, with $\mathcal{N}_{S(B)}$ is the signal (background) events number after applying the kinematic cuts

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

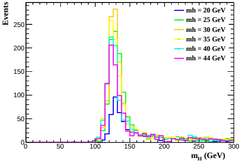
- The signal process is : $H \to hh \to b\bar{b}\gamma\gamma$

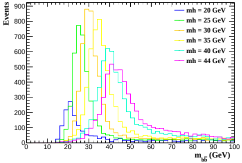


BP	BP_1	BP_2	BP_3	BP_4	BP_5	BP_6
m_h	20	25	30	35	40	44
$\sin(\beta-\alpha)$	-0.12	-0.07	-0.05	-0.06	-0.077	-0.11
$\tan\beta$	8	13	20	17	14	10
m_A	89	86	87	90	94	99
$m_{H\pm}$	125	119	109	108	116	145
Branching Ratios [%]						
BR(H → hh)	0.35	2.4	3.4	3	1.33	2.14
BR(h → bb)	79	83	84	85.2	84.2	84.3
BR(h → γγ)	6.4	2.9	2.3	2.08	3.17	2.85
Cross-section [pb]						
$\sigma^{LO}_{b\bar{b}\gamma\gamma}$	0.0061	0.02	0.022	0.0177	0.012	0.0174

- Different SM background processes are considered :
  - $pp \to t\bar{t}H,\ t \to bW^+,\ \bar{t} \to \bar{b}W^-,\ H(\to \gamma\gamma)$
  - $gg \to t\bar{t}H,\ t \to bW^+,\ \bar{t} \to \bar{b}W^-,\ H(\to \gamma\gamma)$
  - $pp \to Z(\to b\bar{b})H(\to \gamma\gamma)$
  - $pp \to Z(\to jj)H(\to \gamma\gamma),\ j = j,\ b,\ \bar{b}$
  - $pp \to b\bar{b}H(\to \gamma\gamma)$

- Cuts at generation level :
  - $|\eta(l,j)|<2.5,\ \ p_T(l,j)>10$ GeV
  - $\Delta R(ll,lj,jj) > 0.4,\ \ E_T^{\rm miss}>5$ GeV





A sharp mass peak around 125 GeV (Signal)

$2b2\gamma$ ANALYSIS (2HDM TYPE-I)

* Events selection requirements :
  * 2-photons and 2 b-jets
  * $m_{b\bar{b}} < 62.5$ GeV
  * $m_{\gamma\gamma} < 62.5$ GeV
  * $m_H < 150.0$ GeV
  * $\Delta m_h \equiv (m_{b\bar{b}} - m_{\gamma\gamma})/m_{\gamma\gamma} < 0.25$

BP	BP_1	BP_2	BP_3	BP_4	BP_5	BP_6
m_h (GeV)	20	25	30	35	40	44
NoE	823.5	2700	2970.000	2591	1980	3027
$\gamma\gamma$	172.14	593	635.10	518.87	402.19	600.67
2 b-jets	4.75	33.39	38.10	33.06	21.879	30.45
$m_{bb} < 62$ GeV	3.12	27.02	30.41	25.78	16.03	21.98
$m_{\gamma\gamma} < 62$ GeV	3.12	27.00	30.35	25.73	15.97	21.92
$\Delta m_h < 0.25$	1.92	20.68	25.33	21.09	13.26	18.8
$m_H < 150.0$ GeV	1.91	20.57	25.18	20.75	13.10	18.55

TABLE III. Signal events rates after applying basic and mass cuts for $\mathcal{L} = 300$ fb^{-1}.

* A significant improvement in the isolation of signal events from background noise due to kinematic cuts

Process	$Z(\to b\bar{b})H$	$Z(\to jj)H$	$pp \to t\bar{t}H$	$gg \to t\bar{t}H$	$pp \to b\bar{b}H$
m_h (GeV)	120	120	120	120	120
NoE	32.940	210	183	138	147.00
$\gamma\gamma$	9.54	60.27	56.005	42	49.74
2 b-jets	2.65	3.24	21.55	16.51	7.70
$m_{bb} < 62$ GeV	0.48	0.33	1.93	1.04	2.34
$m_{\gamma\gamma} < 62$ GeV	0.001	-	0.009	0.004	0.001
$\Delta m < 0.25$	-	-	0.005	-	-
$m_H < 150.0$ GeV	-	-	0.002	-	-

TABLE IV. Backgrounds events rates after applying basic and mass cuts for $\mathcal{L} = 300$ fb^{-1}.

* BPs are within the discovery reach at Run 3 of the LHC, with a significance above 5σ

Benchmark Points (BP)	BP_1	BP_2	BP_3	BP_4	BP_5	BP_6
m_h (GeV)	20	25	30	35	40	44
Significance (Σ)	2.18	7.07	7.9	7.2	5.72	6.8

TABLE V. Significances for our signal with $\sqrt{s} = 14$ TeV and $\mathcal{L} = 300$ fb^{-1}.

4τ Analysis (2HDM Type-X)

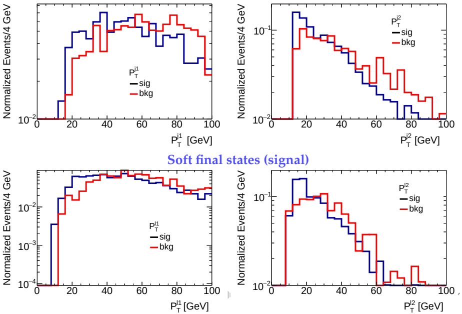
- The signal process is :
  $H \to hh \to \tau^+\tau^-\tau^-\tau^+ \to \ell\nu_\ell\ell\nu_\ell\tau_j\tau_j$
  - Same sign (SS) leptons are required to improve the experimental significance
- Different background processes are considered :
  - $pp \to t\bar{t} \to l\upsilon_l l\upsilon_l b\bar{b}$
 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

σ (fb)	BP1	BP2	BP3	BP4	BP5	BP6	BP7	BP8	BP9
parton level generation	9.260	11.688	12.432	12.442	10.310	12.978	12.976	15.475	15.493
selection of 2l2j	2.548	3.184	3.246	3.192	2.027	2.413	2.320	2.638	2.660
selection of SS 2l	1.196	1.494	1.522	1.498	1.007	1.239	1.141	1.301	1.295

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}.

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 in Eq. (6) at $\sqrt{s}=$ 14 TeV for 300 fb^{-1}.

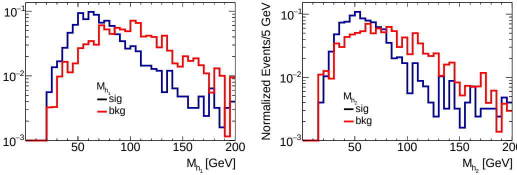


4τ Analysis (2HDM Type-X)

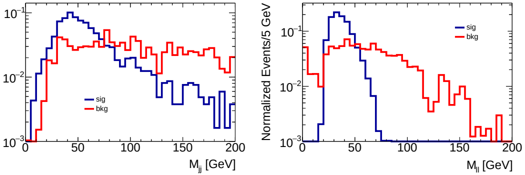
Kinematic variables : $M_{lj},\ M_{ll},\ M_{jj},\ M_H$

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

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

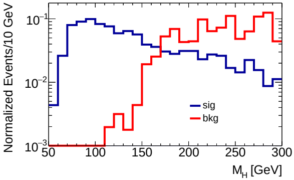


* Combining 2l and 2j together $(M_{ll},\ M_{jj})$



* 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)

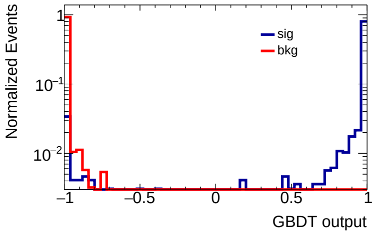
A Gradient-Boosted Decision Tree (GBDT) approach is further applied

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	$\cos(\theta_{h_1 h_2})$	$\cos(\theta_{l_1 j_1})$	$\cos(\theta_{l_1 j_2})$	$\cos(\theta_{l_2 j_1})$	$\cos(\theta_{l_2 j_2})$

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



* A very good separation between signal and background!

$L = 300$ 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/S	Σ
Acceptance	806.1	2.17128e+06	2.3	63	0.01	53751.6	119699	2790.8	2912.3	0.53
SS Leptons	449.1	5829.8	1.5	23.6	0.01	186.6	595.5	754.1	16.5	5.07
$HT \in [40, 200]$	206	1040.7	0.002	0.5	1e-05	40.4	127.9	379.1	7.7	4.86
$M_{ll} \in [10, 100]$	188.6	982.9	0.001	0.5	1e-05	35.8	69.5	330.9	7.5	4.7
$M^1_{lj} \in [0, 120]$	182	770.9	0.0008	0.4	1e-05	31.1	60	287.5	6.3	4.99
$M^2_{lj} \in [0, 120]$	174.3	674.5	0.0008	0.4	8e-06	26.4	45.8	263.4	5.8	5.06
$M_H \in [20, 230]$	115.5	269.8	0	0.2	5e-06	10.9	26.9	135.7	3.8	4.89
GBDT $\in [0.5, 1]$	88	0	0	0.08	3e-06	0	11.1	37	0.5	7.54

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
after selecting SS leptons	4.07	5.06	5.16	5.07	2.81	3.33	3.2	3.63	3.66
after kinematic cuts, w/o GBDT	3.98	4.87	4.96	4.89	2.44	2.88	2.78	3.13	3.16
after kinematic cuts, w/ GBDT	**6.46**	**7.53**	**7.63**	**7.54**	**5.54**	**6.16**	**6.02**	**6.5**	**6.53**

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

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

CONCLUSION

* The possibility of optimising searches for very light Higgses in 2HDM Type-I/X
* Focusing on the $hh \to b\bar{b}\gamma\gamma,\ b\bar{b}\tau_e\tau_\mu, \tau_l\tau_l\tau_h\tau_h$ decays pattern
* A potential improve of the analysis sensitivity due to the trigger choice
* Sensitivity to 2HDM Type-I signatures with Run-3 and HL-LHC.
* 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

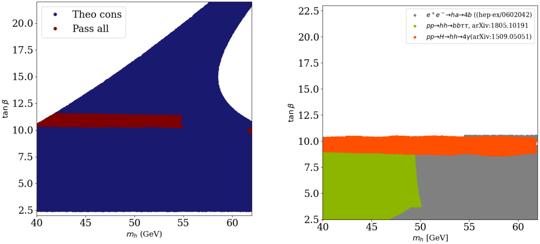


FIGURE – Allowed (left panel) and excluded (right panel) parameter space over the $(m_h,\ \tan\beta)$ plane. Here, $m_{H\pm} = 165.58\,\text{GeV},\ m_A = 98.9\,\text{GeV},\ \sin(\beta-\alpha) = -0.10,\ m_{12}^2 = 154\,\text{GeV}^2$

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

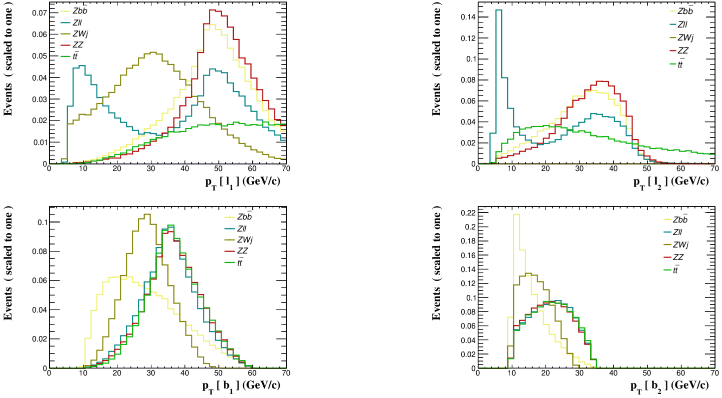
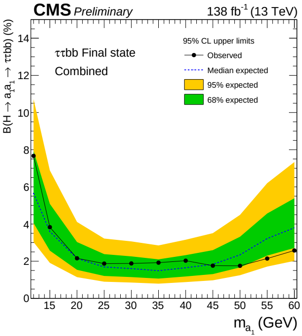
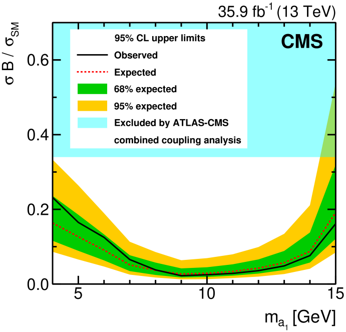


FIGURE – The p_T distributions of the leading (subleading) lepton and b-(anti)quark of different background processes are shown at parton level

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

* 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 :

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

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

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

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