



College of Physics and Electronic Information,  
Inner Mongolia Normal University



# Discovering new signals at the LHC

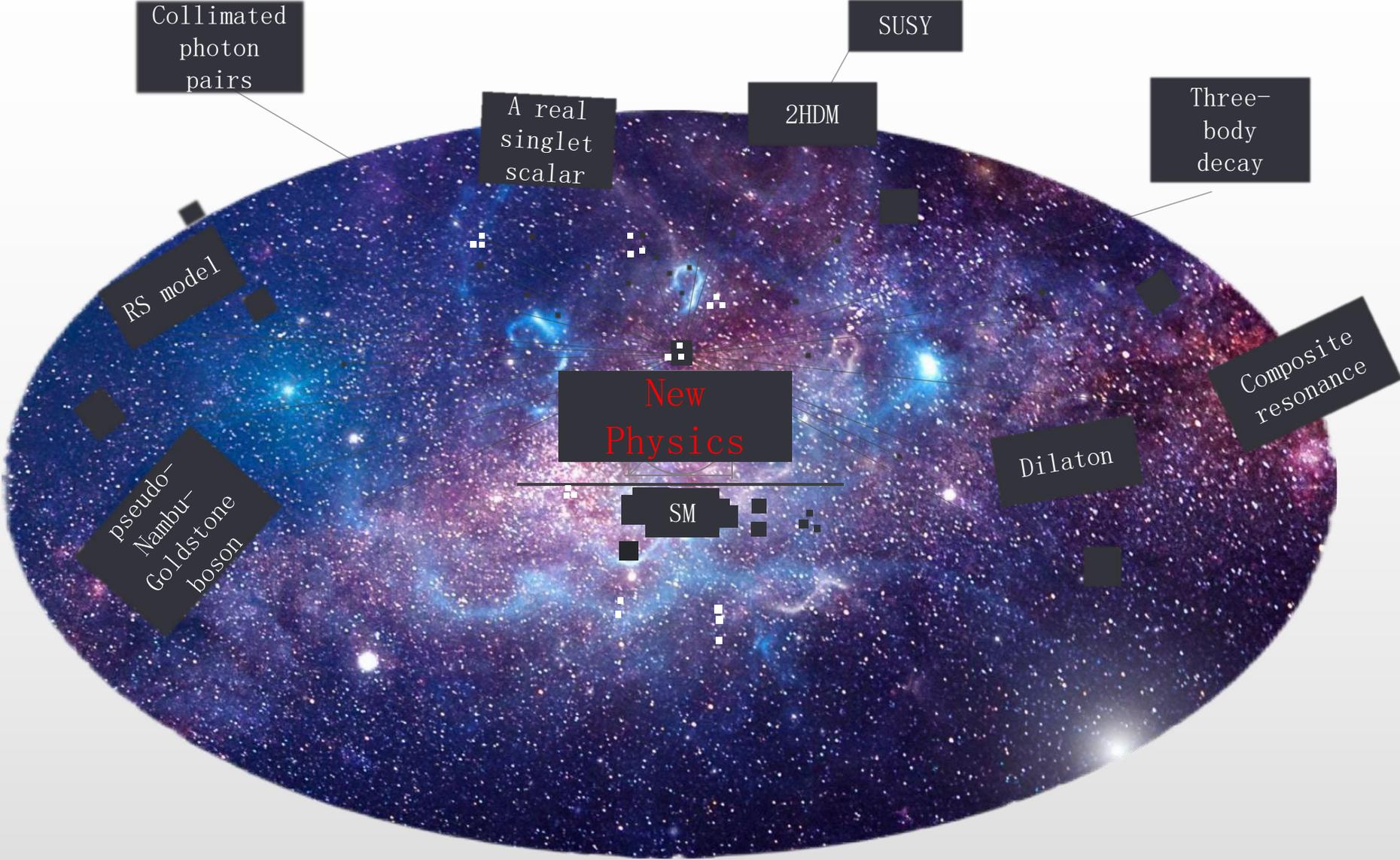
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IN COLLABORATION WITH: A. Arhrib, R. Benbrik, M. Krab, B. Manaut, S. Moretti And Q.S. Yan

2023-11-29

Higgs2023, Beijing

Many New Physics Models are proposed.



# 2HDM scalar potential

With CP-conserving, and a imposed  $Z_2$  symmetry

$$V = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 \Phi_1^\dagger \Phi_1 \Phi_2^\dagger \Phi_2 + \lambda_4 \Phi_1^\dagger \Phi_2 \Phi_2^\dagger \Phi_1 + \frac{\lambda_5}{2} \left[ (\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2 \right],$$

Three neutral Higgs bosons (h, H, A) and  $H^\pm$  :

$m_h, m_H, m_A, m_{H^\pm}$

$\alpha$ : mixing angle of neutral scalars  $\sin(\beta - \alpha)$

$\beta$ :  $\tan\beta \equiv \frac{v_2}{v_1}$

$m_{12}$ :

$$\Phi_a = \begin{pmatrix} \phi_a^+ \\ (v_a + \rho_a + i\eta_a) / \sqrt{2} \end{pmatrix}$$

Current experiments mainly focus on heavy particles

Heavy Higgs:

400-1000 GeV	tt H/A → tttt	2HDM of Type-II	JHEP 07(2023)203
200-1500 GeV	lept+b-jets	g2HDM	2307.14759
400-1200 GeV	lltt / vvbb	2HDM	2311.04033

light Higgs:

66-110 GeV	h → γγ		ATLAS-CONF-2023-035
70-110 GeV	hγγ		CMS-PAS-HIG-20-002
60-200 GeV	H/A → ττ	MSSM	JHEP 07 (2023) 073

Charged Higgs

300-700 GeV	$H^\pm \rightarrow W^\pm h$		JHEP 09 (2023) 032
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# 2HDM Type-I

Z2-symmetry



four types

Model	$u_R^i$	$d_R^i$	$e_R^i$
Type I	$\Phi_2$	$\Phi_2$	$\Phi_2$
Type II	$\Phi_2$	$\Phi_1$	$\Phi_1$
Lepton-specific	$\Phi_2$	$\Phi_2$	$\Phi_1$
Flipped	$\Phi_2$	$\Phi_1$	$\Phi_2$



$$\mathcal{L}_{\text{Yukawa}}^{2\text{HDM}} = - \sum_{f=u,d,\ell} \frac{m_f}{v} \left( \xi_h^f \bar{f} f h + \xi_H^f \bar{f} f H - i \xi_A^f \bar{f} \gamma_5 f A \right) - \left\{ \frac{\sqrt{2} V_{ud}}{v} \bar{u} (m_u \xi_A^u P_L + m_d \xi_A^d P_R) d H^+ + \frac{\sqrt{2} m_\ell \xi_A^\ell}{v} \bar{\nu}_L \ell_R H^+ + \text{H.c.} \right\}$$

$\phi$	$\xi_\phi^u$	$\xi_\phi^d$	$\xi_\phi^\ell$
$h$	$\cos \alpha / \sin \beta$	$\cos \alpha / \sin \beta$	$\cos \alpha / \sin \beta$
$H$	$\sin \alpha / \sin \beta$	$\sin \alpha / \sin \beta$	$\sin \alpha / \sin \beta$
$A$	$\cot \beta$	$-\cot \beta$	$-\cot \beta$

Study light charged Higgs with  $H^\pm + h$  production  $H^\pm \rightarrow W^\pm h$  decay

$$m_{H^\pm} < m_t \quad m_h < 125$$

# Theoretical constraints

Perturbativity

Unitarity

Vacuum stability

# Experimental constraints

EW oblique parameters S, T, U

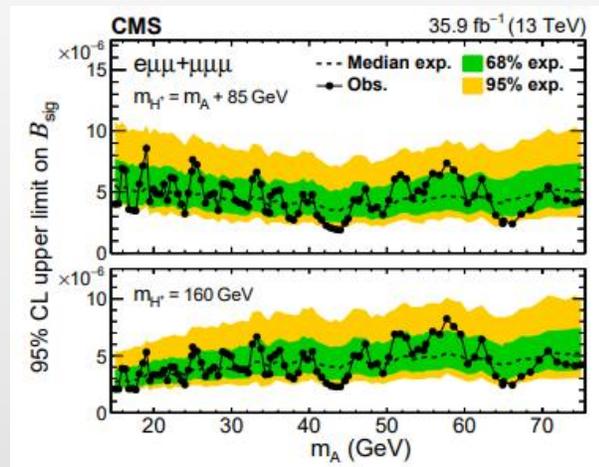
LEP, TeVatron and LHC data

Flavour physics

Direct search for a light  $H^\pm$  by

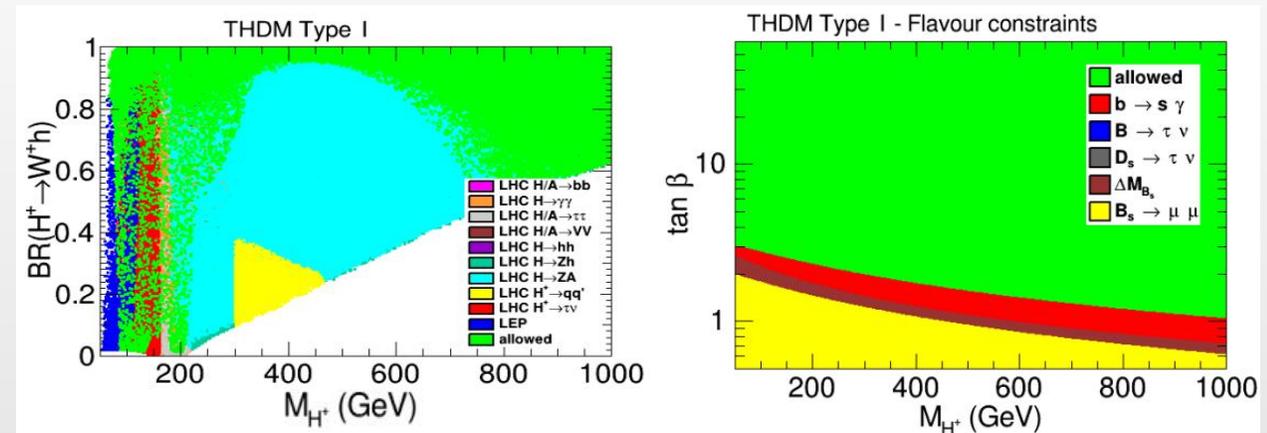
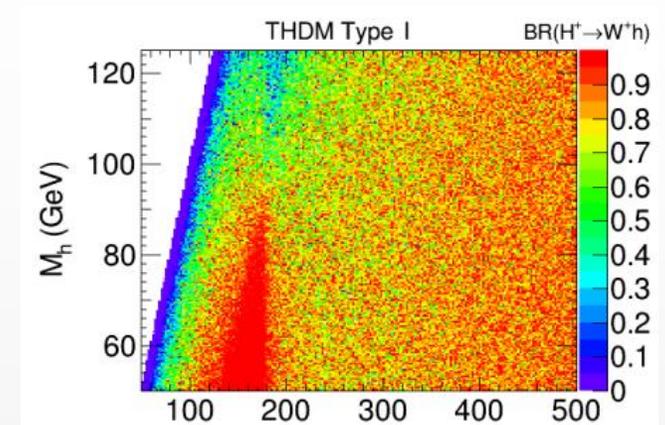
$$t \rightarrow H^+ b, H^+ \rightarrow W^+ A$$

no excess



The CMS Collaboration, Phys. Rev. Lett. 123, 131802 (2019)

many parameter spaces Still alive



$$\cos(\beta - \alpha) \rightarrow 1, m_H = 125 \text{ GeV}$$

[A. Arbey, F. Mahmoudi, O. Stal, T. Stefaniak, Eur.Phys.J. C78 (2018) no.3, 182]

# Parameter space scans: production

alignment limit: maximise



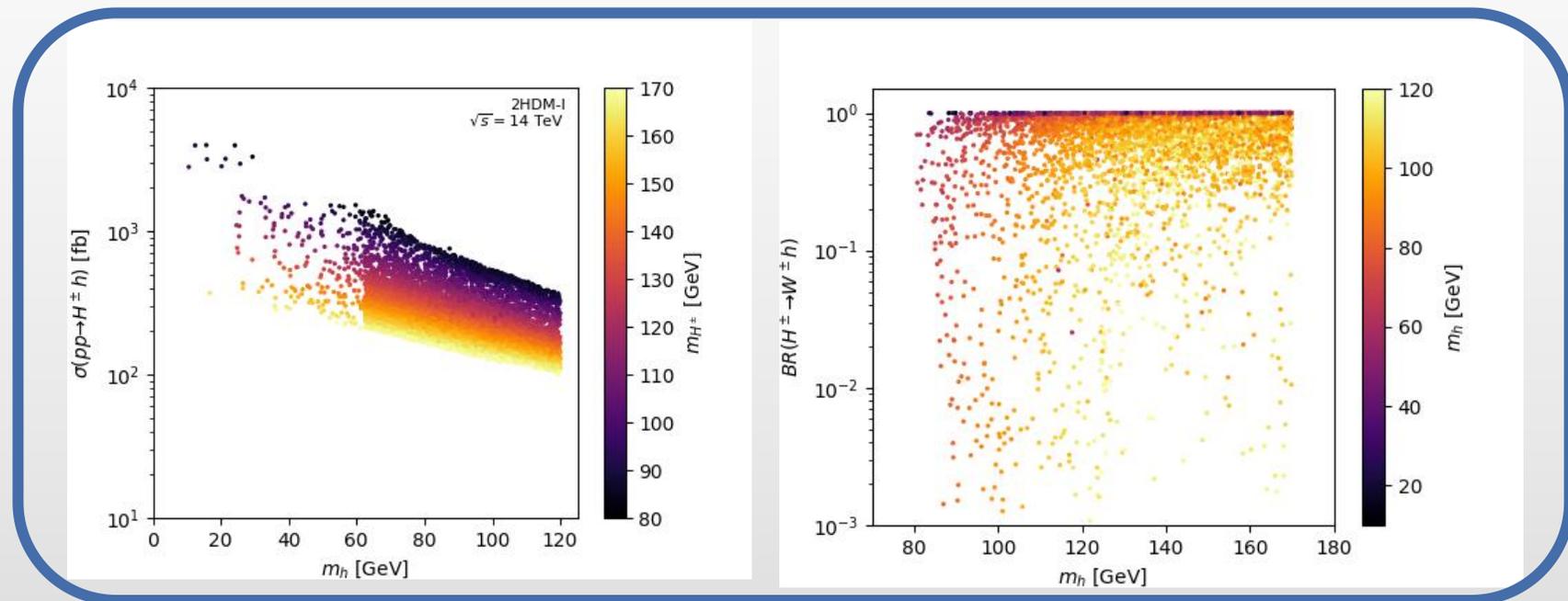
$$g_{hH^\pm W^\mp} \approx \cos(\beta - \alpha)$$

$$pp \rightarrow H^\pm h \rightarrow W^{\pm*} hh$$

light charged Higgs,  $m_{H^\pm} < m_t$

with an **off-shell** W boson

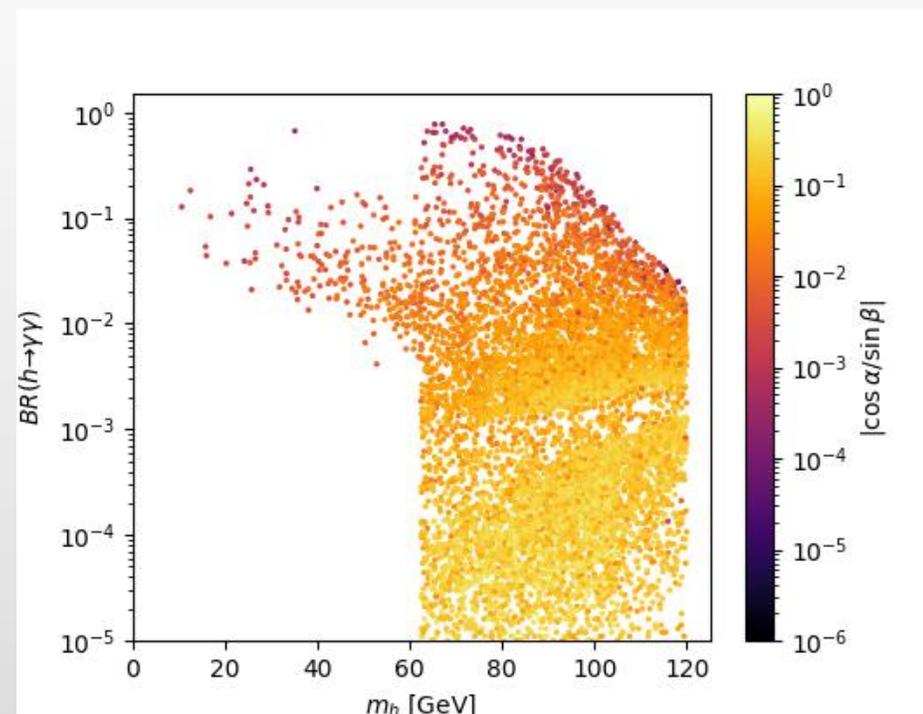
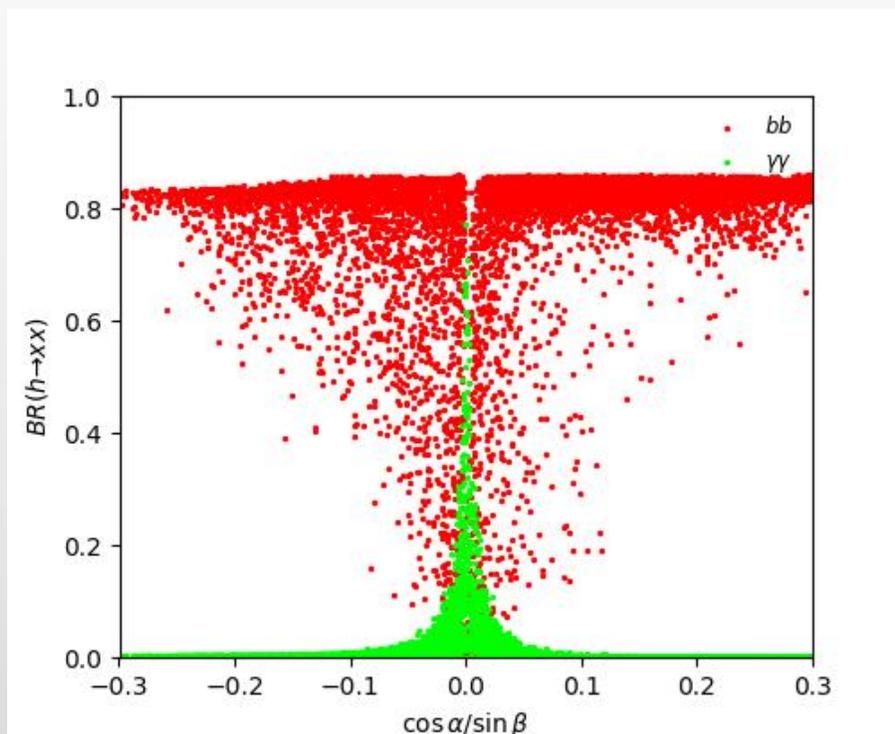
Parameters	Ranges
$m_h$	[10, 120]
$m_H$	125
$m_A$	[10, 500]
$m_{H^\pm}$	[80, 170]
$s_{\beta-\alpha}$	[-1, 1]
$\tan \beta$	[2, 25]
$m_{12}^2$	$[0, m_A^2 s_\beta c_\beta]$
$\lambda_6 = \lambda_7$	0



# Parameter space scans: decay

$$pp \rightarrow H^\pm h \rightarrow W^\pm hh \quad \left\{ \begin{array}{l} h \rightarrow \gamma\gamma \\ h \rightarrow b\bar{b} \\ h \rightarrow \tau^+\tau^- \end{array} \right.$$

$$\sin(\beta - \alpha) \sim 0$$



# First process

$$pp \rightarrow H^\pm h \rightarrow W^{\pm(*)} hh \rightarrow \ell \nu_\ell + 4\gamma$$

soft  $\gamma$  from  $h \rightarrow \gamma\gamma$

	$M_h$	$M_A$	$M_{H^\pm}$	$\sin(\beta - \alpha)$	$\tan \beta$	$m_{12}^2$	$\sigma_{13}(W + 4\gamma)$ [fb]	$\sigma_{14}(W + 4\gamma)$ [fb]
BP1	25.57	72.39	111.08	-0.074	13.58	11.97	101.40	112.55
BP2	35.12	111.24	151.44	-0.075	13.32	16.66	167.75	186.20
BP3	45.34	162.07	128.00	-0.136	7.57	80.96	10.76	11.93
BP4	53.59	126.09	91.49	-0.127	8.00	51.16	27.05	29.88
BP5	63.13	85.59	104.99	-0.056	18.09	190.24	179.31	198.61
BP6	65.43	111.43	142.15	-0.087	11.52	325.36	174.49	194.30
BP7	67.82	79.83	114.09	-0.111	8.94	326.32	177.72	197.23
BP8	69.64	195.73	97.43	-0.111	8.86	357.10	196.04	217.18
BP9	73.18	108.69	97.34	-0.122	8.06	594.64	193.56	214.57
BP10	84.18	115.26	148.09	-0.067	14.82	473.88	61.92	68.98
BP11	68.96	200.84	155.40	-0.112	8.64	531.46	62.02	69.14
BP12	71.99	91.30	160.10	-0.104	9.74	472.22	58.99	65.80
BP13	74.09	102.49	163.95	-0.092	10.56	503.74	55.58	62.04
BP14	81.53	225.76	168.69	-0.101	9.75	501.29	51.85	57.91

all BPs:  $m_H = 125$  GeV,  $m_{H^\pm} < m_t$

on-shell W boson

off-shell W boson

large signal

cross sections

Signal:  $pp \rightarrow H^\pm h \rightarrow W^{\pm(*)} hh \rightarrow l\nu_e + 4\gamma$

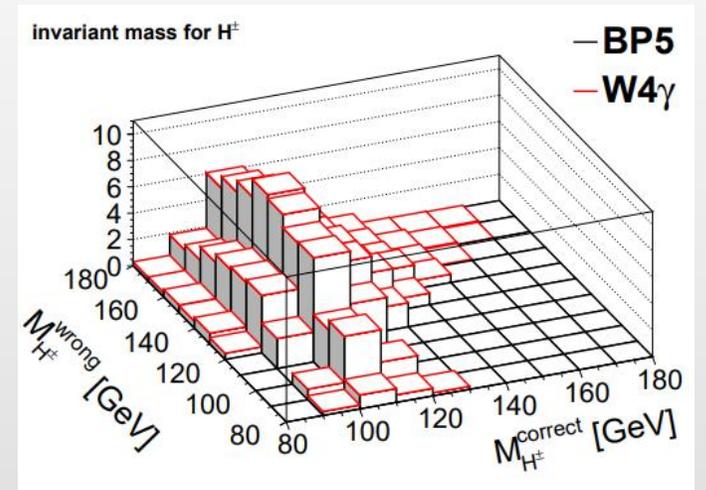
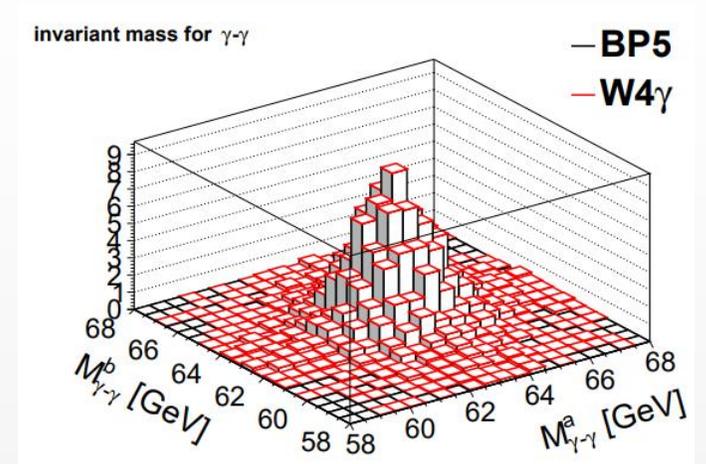
SM Backgrounds: with fake photons ( $j \rightarrow \gamma$ )

After selecting  $l+4\gamma$ , almost SM background free !

Process	Cross section (fb)	After selection
$W^\pm + 4j0\gamma$	145890	0
$W^\pm + 3j1\gamma$	1730	0
$W^\pm + 2j2\gamma$	10.2	$2.55 \times 10^{-4}$
$W^\pm + 1j3\gamma$	0.0282	$1.52 \times 10^{-4}$
$W^\pm + 0j4\gamma$	$1.69 \times 10^{-5}$	$5.71 \times 10^{-6}$

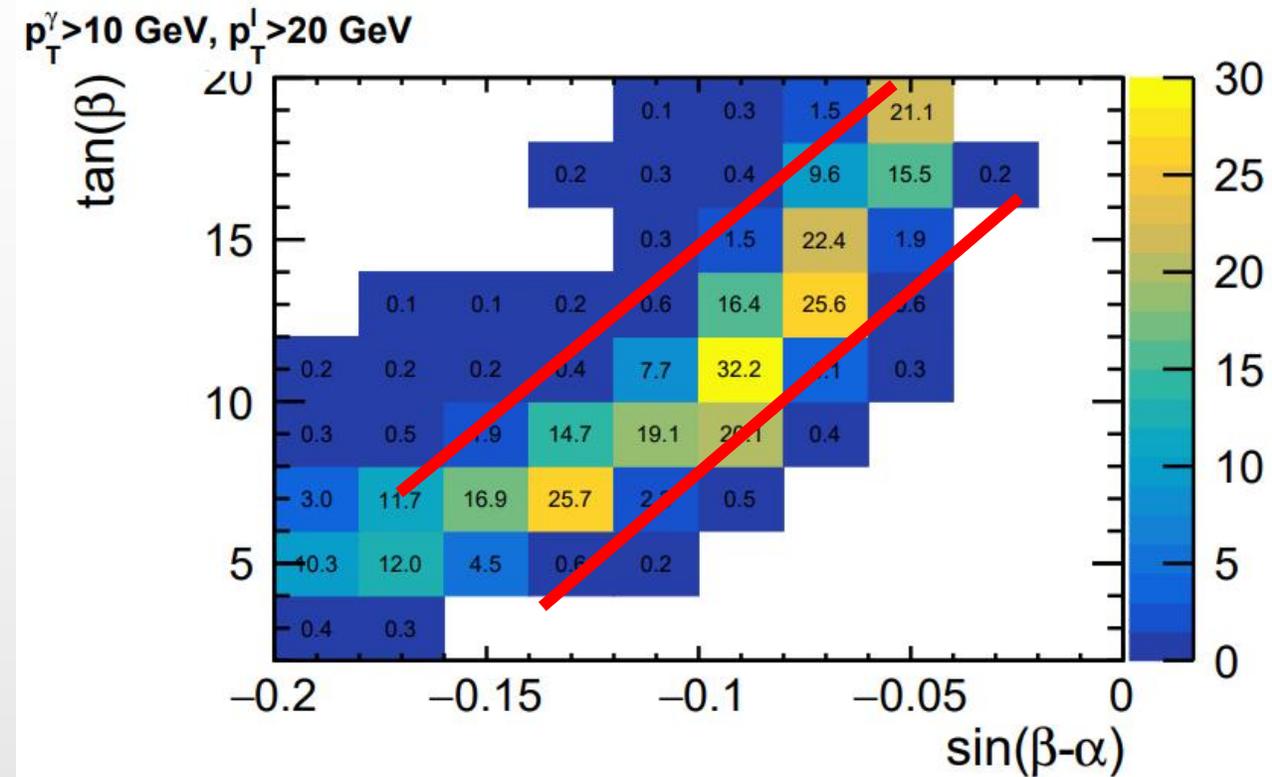
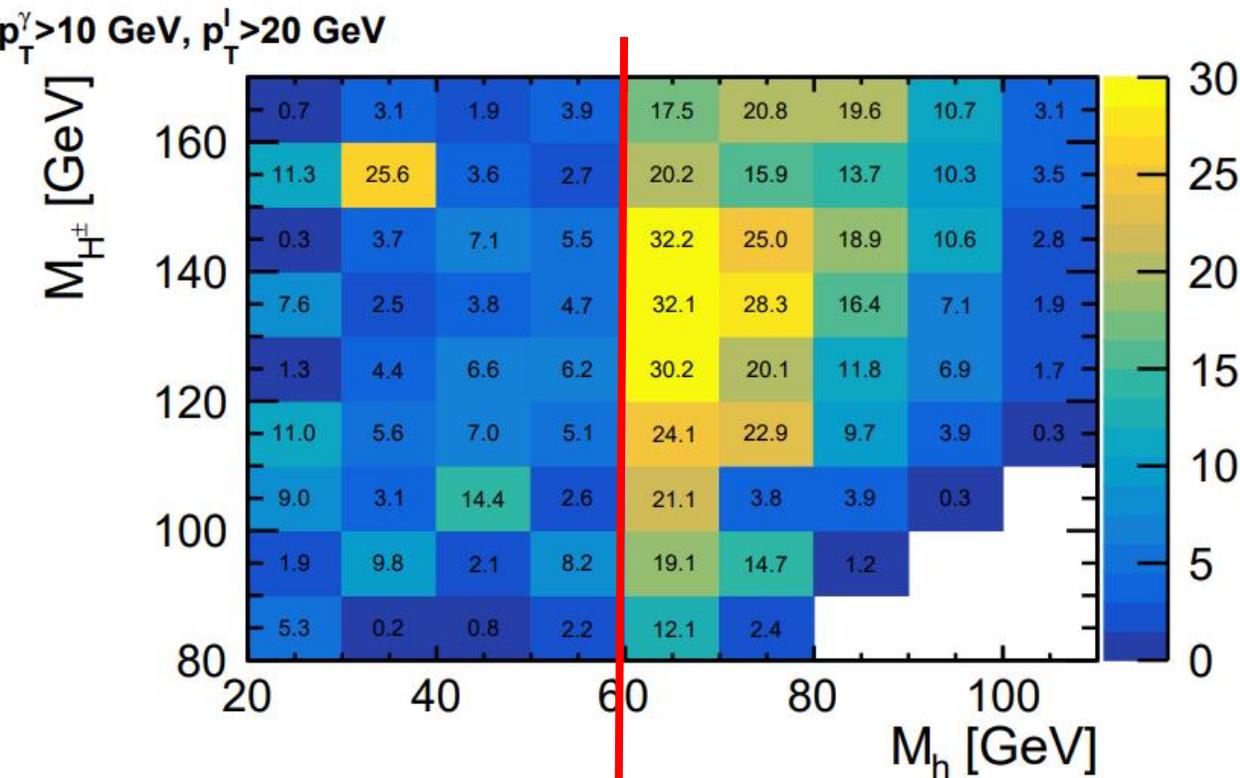
Significance :  $\sigma = \frac{S}{\sqrt{S+B}} \approx \sqrt{S}$

BPs	1	2	3	4	5	6	7	8	9	10	11	12	13	14
$\sigma_{13\text{TeV}}$	12.1	23.7	6.7	9.4	27.4	32.6	29.2	25.2	23.9	20.8	20.2	20.3	19.9	19.9
$\sigma_{14\text{TeV}}$	12.5	24.4	7.0	9.8	28.4	33.9	30.3	26.2	24.8	21.8	21.1	21.0	20.8	20.8



# Scan for $(M_h, M_{H^\pm}), (\sin(\beta - \alpha), \tan\beta)$

$$m_h = \frac{1}{2} M_H = 62.5 \text{ GeV}$$



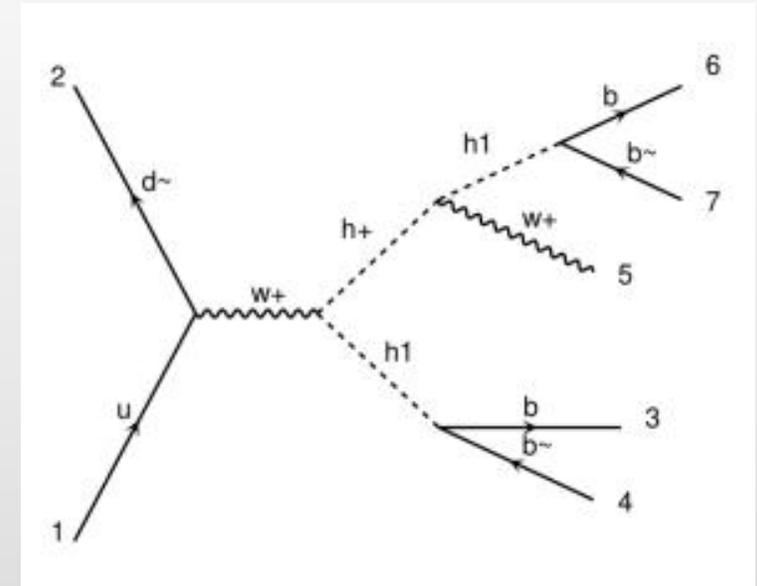
# Second process $pp \rightarrow H^\pm h \rightarrow W^{\pm*} hh \rightarrow l^\pm \nu + 4b$

all BPs:  $m_H=125$  GeV,  $m_{H^\pm} < m_t$ , with

off-shell W boson: soft leptons

light Higgs mass: soft b-jets

$\sigma$ (fb)	$M_h$	$M_H$	$M_A$	$M_{H^\pm}$	$\sin(\beta - \alpha)$	$\tan\beta$	$m_{12}$	$\sigma(W^{\pm*} + 4b)$ (fb)
BP1	65.11	125.00	112.07	88.51	-0.061	51.14	82.33	807.69
BP2	69.88	125.00	108.31	85.50	-0.059	41.90	113.63	675.55
BP3	69.12	125.00	106.14	90.62	-0.092	40.63	115.73	664.89
BP4	64.39	125.00	107.74	107.61	-0.059	45.03	90.47	521.93
BP5	65.20	125.00	104.30	106.02	-0.064	57.64	73.50	525.88
BP6	68.65	125.00	114.53	115.66	-0.098	48.67	96.16	397.13



off-shell W boson

## Event Generation:

Simulate with MG5 + Pythia + Delphes (ATLAS card):

Signal  $pp \rightarrow H^\pm h \rightarrow W^{\pm*} hh \rightarrow l^\pm \nu + 4b$

BKG:  $tt/W + 4b/W + 2b2j/W + 4j/Ztb$

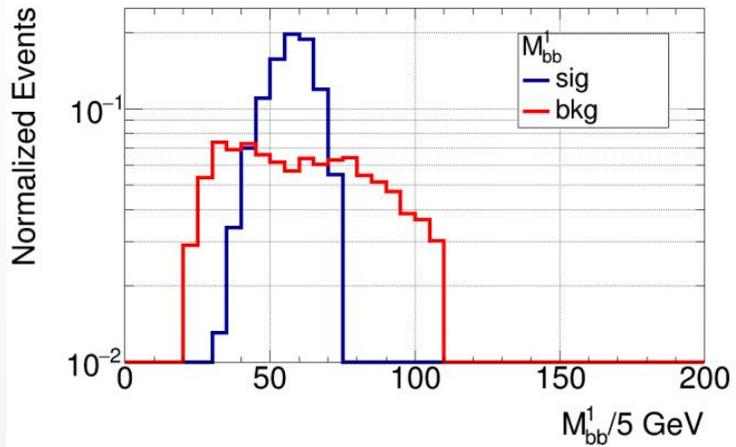
$\sigma$ (fb)	BP1	BP2	BP3	BP4	BP5	BP6	$t\bar{t}_{l\nu jjbb}$	$wbbbb$	$wjjbb$	$wjjjj$	$ztb_{zjjbb}$
LACs	32.59	20.93	26.22	31.94	31.38	26.40	85625	9.45	13474	789960	0.143
TACs	5.39	2.71	4.34	8.31	8.00	7.89	54975	1.48	2940	127545	$9.3 \times 10^{-2}$

LACs :  $|\eta(\ell, j)| < 2.5, p_T(j, \ell) > 10 \text{ GeV}, \Delta R(\ell\ell/jj) > 0.4, \text{MET} > 5 \text{ GeV},$

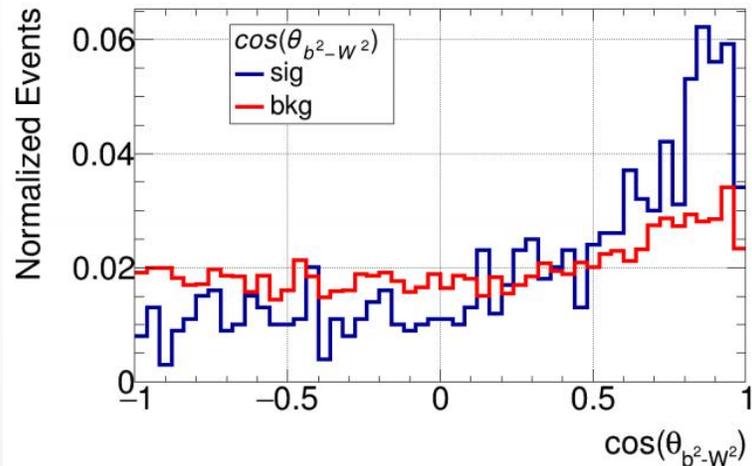
TACs :  $|\eta(\ell, j)| < 2.5, p_T(j, \ell) > 20 \text{ GeV}, \Delta R(\ell\ell/jj) > 0.5, \text{MET} > 5 \text{ GeV}.$

# kinematic cuts:

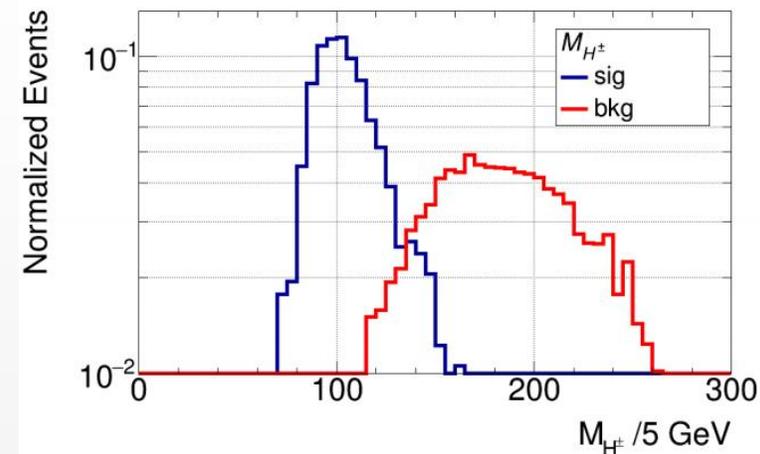
e.g.: light Higgs mass



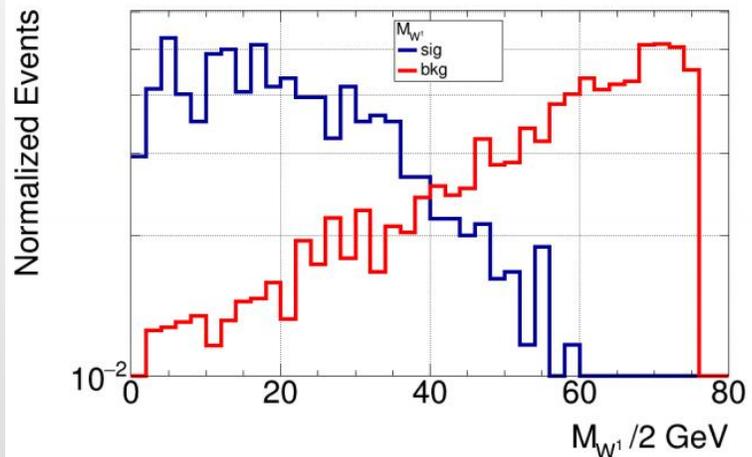
HT



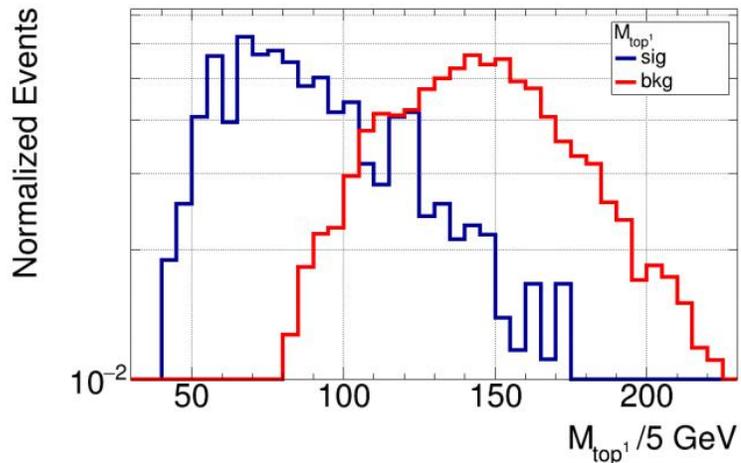
charged Higgs mass



W boson mass



top quark mass



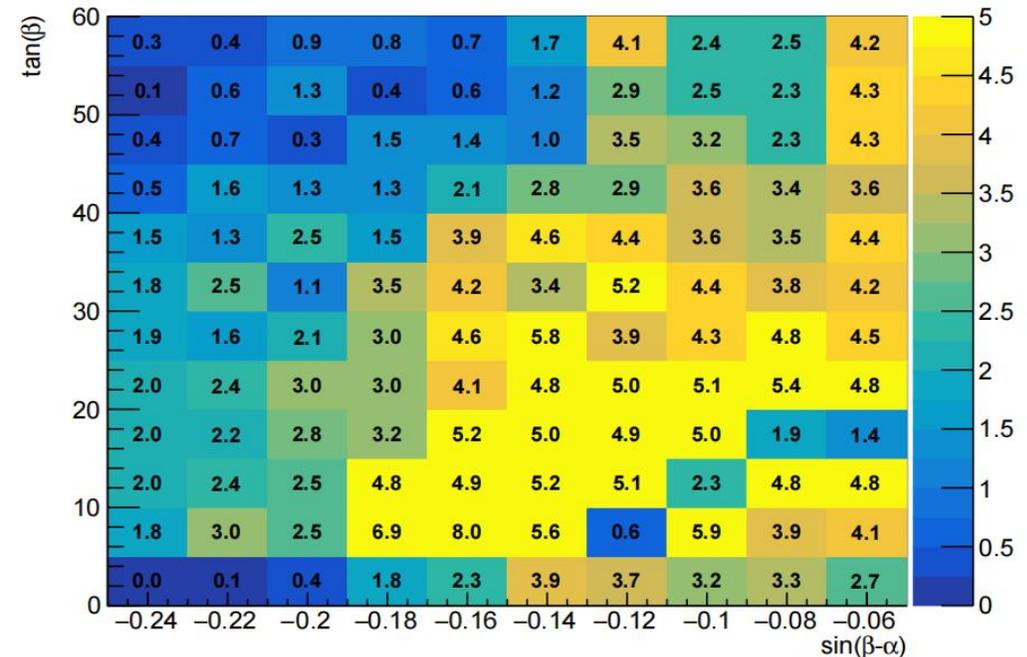
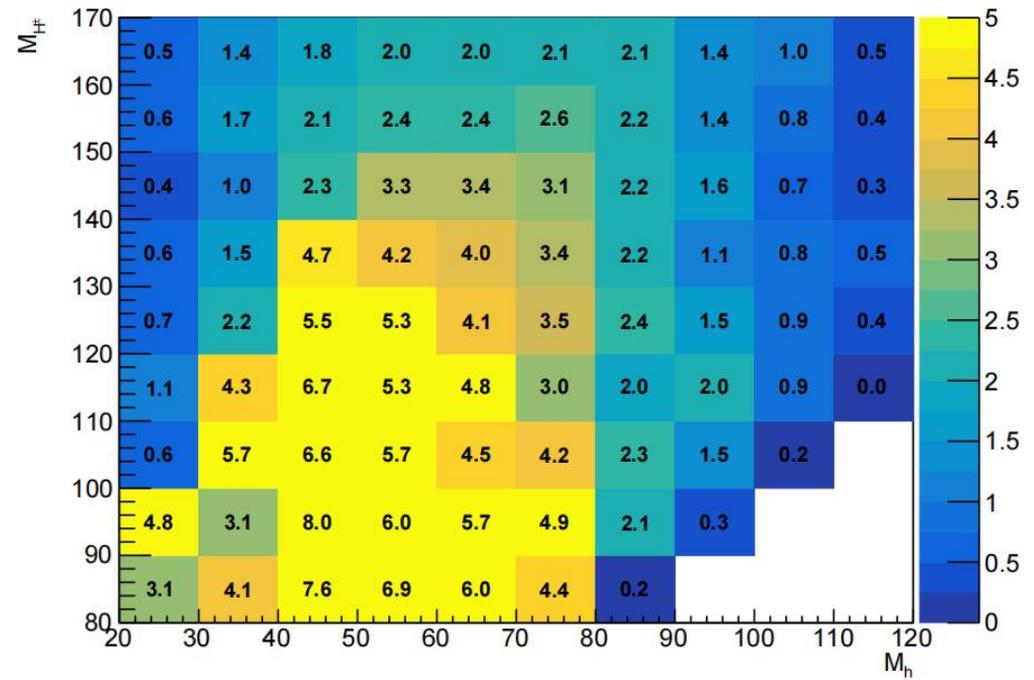
BDT variables

BSM invariant masses	$M_{bb}^1$	$M_{bb}^2$	$M_{H^\pm}$	$M_{H^\pm} - M_h$
BSM angles	$\cos(\theta_{b^1-b^2})$	$\cos(\theta_{b^3-b^4})$	$\cos(\theta_{h-h})$	
SM invariant masses	$M_{W^1}$	$M_{top^1}$	$M_{t\bar{t}}$	
SM angles	$\cos(\theta_{b^2-W^2})$			
Other variables	$M_{4b}$	$HT$		

# Scan for $(M_h, M_{H^\pm})$ $(\sin(\beta-\alpha), \tan\beta)$

Significance :  $\sigma = \frac{S}{\sqrt{S+B}}$

	TACs		
	2b2j	3b1j	4b0j
BP1	0.45	1.60	3.28
BP2	0.27	1.30	2.45
BP3	0.51	1.90	3.3
BP4	0.73	2.97	5.44
BP5	0.71	2.42	4.91
BP6	0.70	2.37	4.79



# Third process

$$H \rightarrow hh \rightarrow 4\tau \rightarrow \tau_i \tau_j l^+ l^+ / \tau_i \tau_j l^- l^-$$

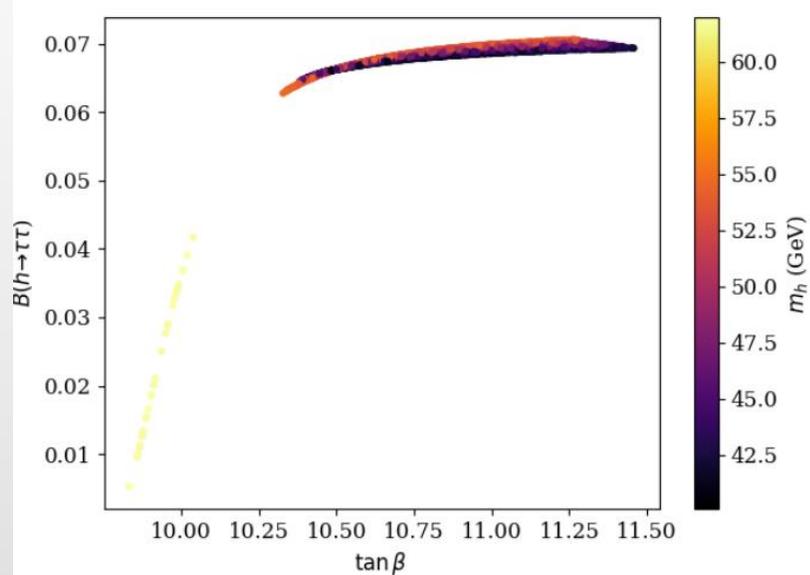
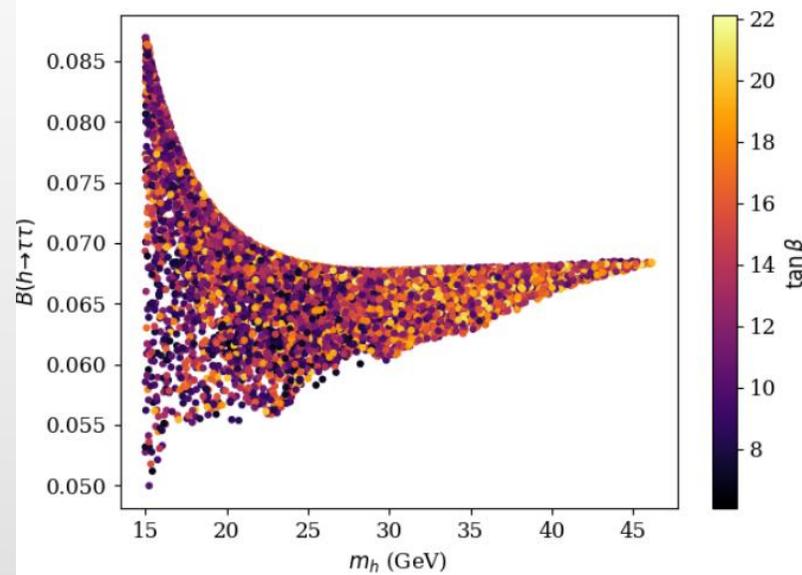
pre-selection

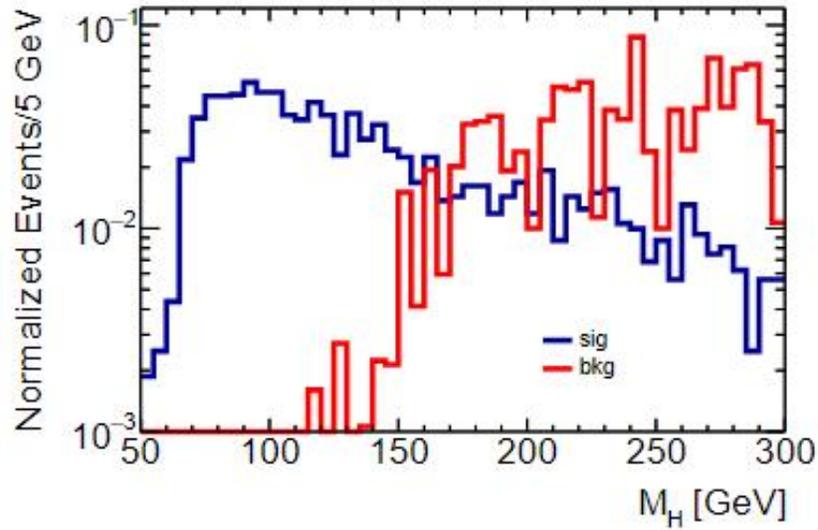
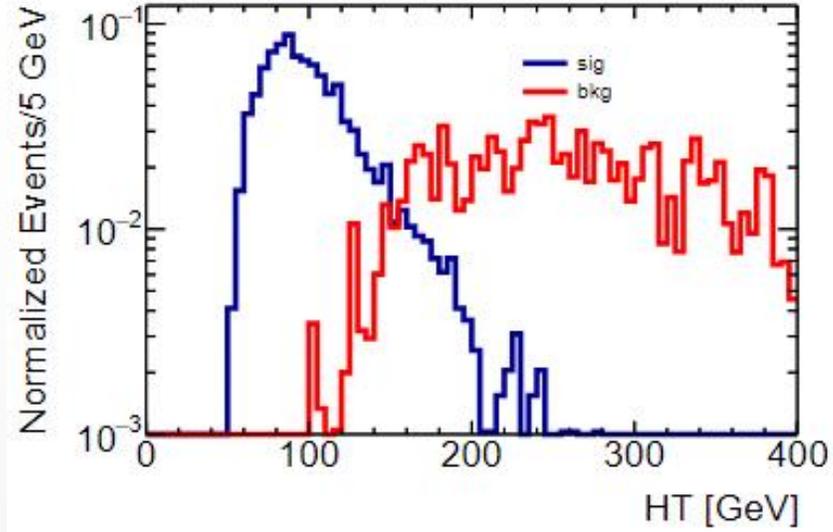
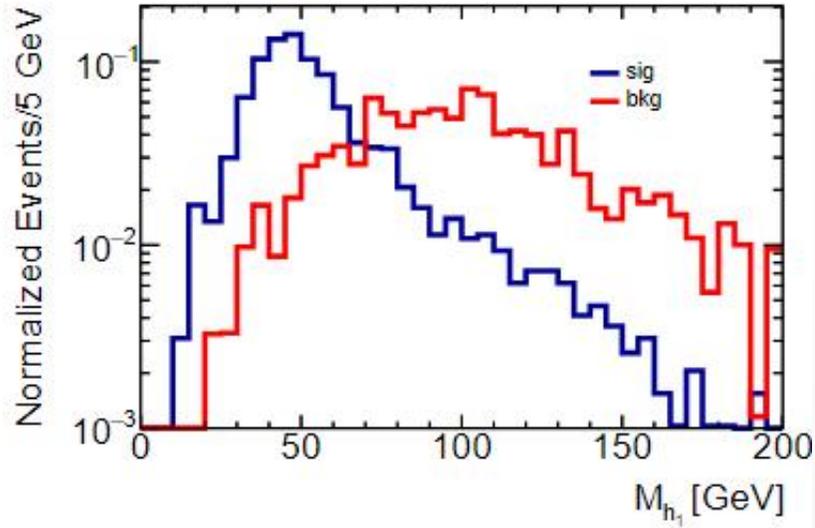
2 $\tau$ 2l final states, PT>10 GeV

same sign leptons

	$bk_{t\bar{t}}^t$	$bk_{wtb}^w$	$bk_{wwjj}^w$	$bk_{zjj}^z$	$bk_{zz}^z$
cross-section(MG):fb	16060	518.3	1053	317600	18.885

	$m_h$	$\sin(\beta - \alpha)$	$\tan\beta$	$\sigma_{4\tau,14TeV}(pb)$
BP1	19.04	-0.12	8.06	2.53
BP2	21.8	-0.162	6.35	3.29
BP3	25.11	-0.16	5.82	2.18
BP4	28.00	-0.17	5.612	2.72
BP5	32.14	-0.15	6.36	4.006
BP6	36.02	-0.107	9.72	3.31
BP7	44.00	-0.188	5.10	2.43
BP8	46.88	-0.0944	10.29	4.74
BP9	47.30	-0.10	9.92	3.88
BP10	50.98	-0.13	7.57	2.81
BP11	55.10	-0.149	6.449	2.65
BP12	58.16	-0.11	8.91	1.80





	$m_h$	$\sin(\beta - \alpha)$	$\tan\beta$	$\sigma_{4\tau, 14TeV}(pb)$	significance(MVA)
BP1	19.04	-0.12	8.06	2.53	7.24
BP2	21.8	-0.162	6.35	3.29	7.5
BP3	25.11	-0.16	5.82	2.18	6.27
BP4	28.00	-0.17	5.612	2.72	6.94
BP5	32.14	-0.15	6.36	4.006	8.77
BP6	36.02	-0.107	9.72	3.31	7.39
BP7	44.00	-0.188	5.10	2.43	7.49
BP8	46.88	-0.0944	10.29	4.74	13.46
BP9	47.30	-0.10	9.92	3.88	12.1
BP10	50.98	-0.13	7.57	2.81	11.14
BP11	55.10	-0.149	6.449	2.65	11.31
BP12	58.16	-0.11	8.91	1.80	11.46

# Conclusions

- A charged Higgs is always predicted in the multi Higgs doublet model.
- Always hard to detected, owing to reduced couplings to the SM.
- In the 2HDM Type-I, there are  $W+4\gamma$ ,  $W+4b$ , final states by  $H^\pm+h$  production with off-shell  $W/h$ .
- Our analysis has been a detector level study exploiting full MC event generation.
- We provide analysis for  $W+4\gamma$ ,  $W+4b$  signals, which would be helpful for experiments.
- We also discuss the  $H\rightarrow hh\rightarrow 4\tau$  process.

**Thank you for your attention!**

# Backup

# charged Higgs production and decay

- production:

- $gb \rightarrow tH^-$  and  $gg \rightarrow t\bar{b}H^-$
- $gg \rightarrow W^+H^-$  and  $b\bar{b} \rightarrow W^+H^-$
- $gg \rightarrow H^+H^-$  and  $\bar{q}q \rightarrow H^+H^-$
- $\bar{q}q' \rightarrow H^+\phi$
- $\bar{s}c, \bar{b}c \rightarrow H^+$
- $t \rightarrow bH^+$

- decay

- $H^+ \rightarrow \bar{b}c, \bar{s}c, \bar{b}t, \tau^+\nu$  Fermionic decay
- $H^+ \rightarrow W^+\gamma, W^+Z$  Bosonic decay
- $H^+ \rightarrow W^+\phi$

# parameter scan

- B-physics with SuperIso v4.1:

Observable	Experimental result	SM prediction
$\text{BR}(B \rightarrow X_s \gamma)$	$(3.32 \pm 0.15) \times 10^{-4}$ [10]	$(3.34 \pm 0.22) \times 10^{-4}$
$\text{BR}(B_s \rightarrow \mu^+ \mu^-)$	$(3.0 \pm 0.6 \pm 0.25) \times 10^{-9}$ [11]	$(3.54 \pm 0.27) \times 10^{-9}$
$\text{BR}(B_d \rightarrow \tau \nu)$	$(1.06 \pm 0.19) \times 10^{-4}$ [10]	$(0.82 \pm 0.29) \times 10^{-4}$

- EW

$$S = 0.05 \pm 0.11, \quad T = 0.09 \pm 0.13, \quad U = 0.01 \pm 0.11.$$

- Collider: exclusions from nil searches for Higgs boson companions, via HiggsBounds-5.9.0, and measurements of the SM-like Higgs boson properties, via HiggsSignals-2.6.0 (for which we have enforced a best fit at 95.5% CL)

## Event Selection:

three categories: 4b0j, 3b1j, 2b2j

BPs	BP1	BP2	BP3	BP4	BP5	BP6	$t\bar{t}_{\ell\nu jjbb}$	$wbbbb$	$wjjbb$	$wjjjj$	$ztb_{zjjbb}$
LACs 4b0j	1.39	0.86	1.16	1.78	1.74	1.67	572.64	0.42	36.69	108.34	0.022
LACs 3b1j	5.18	3.03	4.20	6.34	6.18	5.72	5226.43	1.51	354.22	699.25	0.054
LACs 2b2j	8.28	4.71	6.64	10.22	9.83	9.03	29583.0	2.67	2316.04	6480.41	0.073
TACs 4b0j	0.15	0.08	0.13	0.31	0.31	0.34	98.96	$8.6 \times 10^{-2}$	4.54	6.96	$9.53 \times 10^{-3}$
TACs 3b1j	0.47	0.21	0.38	1.01	0.95	0.99	1658.4	$2.61 \times 10^{-1}$	56.92	89.81	$2.56 \times 10^{-2}$
TACs 2b2j	0.57	0.26	0.47	1.28	1.21	1.26	14704.8	$3.34 \times 10^{-1}$	522.13	939.82	$3.02 \times 10^{-2}$

# Third process $H^\pm h \rightarrow l^\pm \nu + 2\tau + 2b \rightarrow l^\pm \nu + l^\pm \nu \nu + \tau_j b \bar{b}$

Same BPs as W+4b

2 $\tau$ 2b final states

same sign leptons

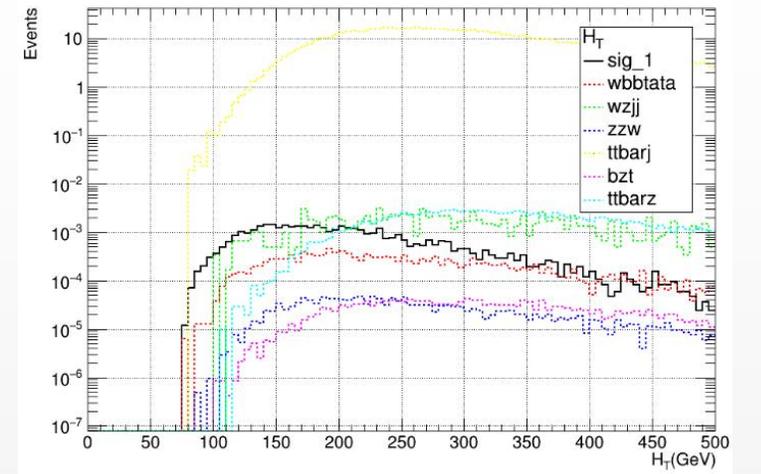
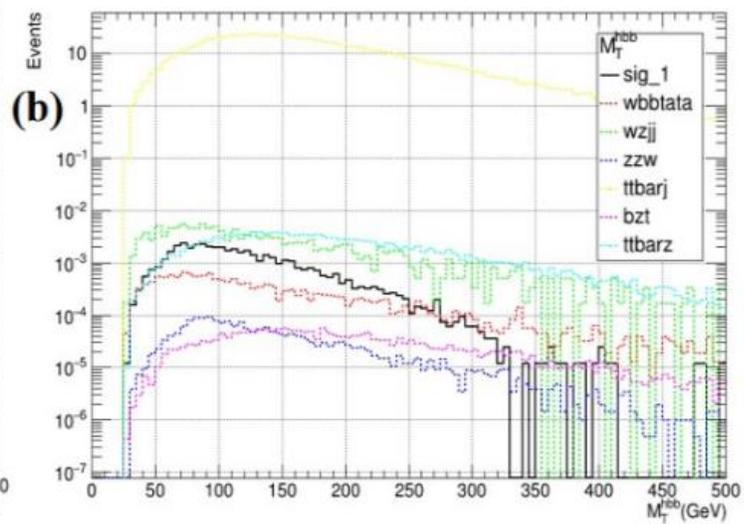
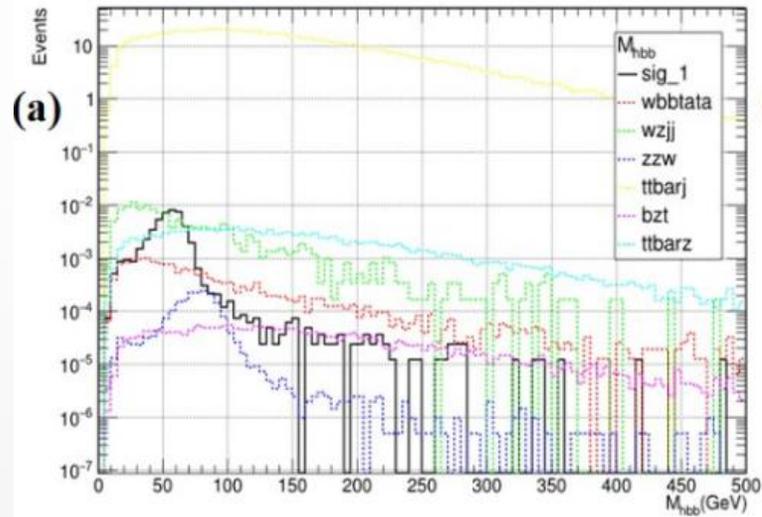
main background is still ttbar

(parton cut) (fb)	$wbb\tau\tau$	$wzjj$	$zzw$	$t\bar{t}j$	$bzt$	$t\bar{t}z$
$\sigma$	0.60	0.32	77.94	0.02	20007	0.49

e.g.: light Higgs mass

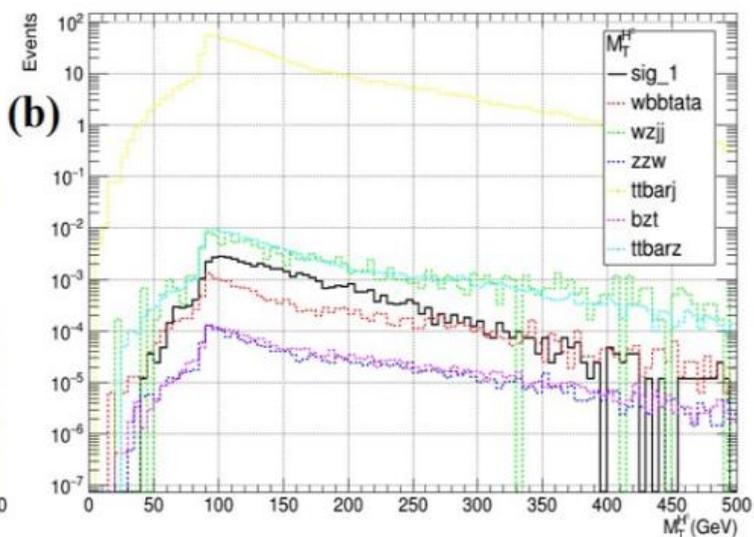
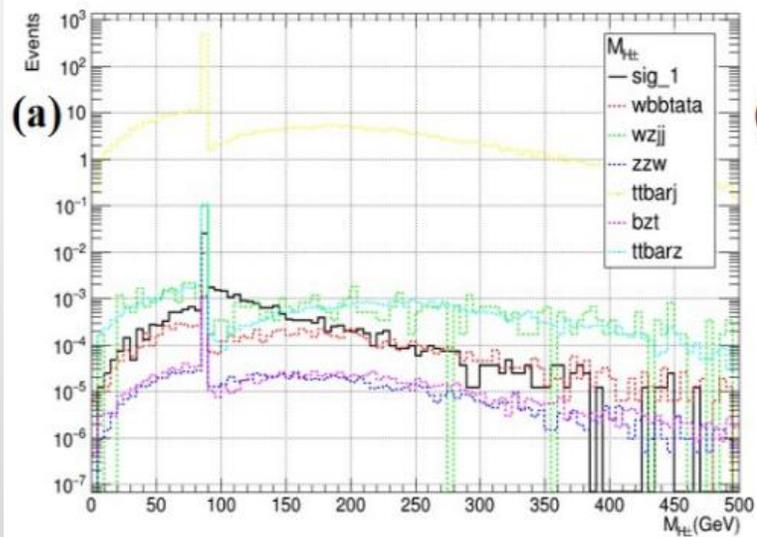
light Higgs MT

HT



charged Higgs Mass

charged Higgs MT





$\int Ldt = 300 fb^{-1}$	$sig_{w2b2\tau}^1$	$bk_{wbb\tau\tau}^w$	$bk_{wzjj}^w$	$bk_{zzw}^w$	$bk_{ttbarj}^t$	$bk_{bzt}^w$	$bk_{ttbar_z}^t$	significance
Theoretical cross section	0.595	0.315	77.94	0.024	20007	0.021	0.489	-
cross section after pre-selection	0.0172	0.007	0.066	0.0009	88.156	0.0010	0.0911	0.0317
Detector event number	5.159	2.363	19.856	0.273	26446.7	0.305	27.341	0.0317
Tow positive lepton	1.521	0.775	5.225	0.090	97.534	0.145	1.648	0.1471
$M_{bb} \in [10,110]$	1.460	0.512	4.379	0.084	60.021	0.049	0.690	0.1781
$M_{H^\pm} \in [85,200]$	1.414	0.399	2.687	0.062	52.518	0.036	0.411	0.1864
$M_T^{H^\pm} \in [85,200]$	1.192	0.335	1.592	0.048	30.011	0.030	0.308	0.2060
$HT \in [90,220]$	0.917	0.172	0.746	0.024	7.503	0.013	0.070	0.2985
$M_T^{bb} \in [45,130]$	0.821	0.147	0.498	0.022	0.0	0.011	0.065	0.6565