College of Physics and
Electronic Information

Inner Mongolia
Normal Unicersity

The analysis of $H^{\pm}h$ process in the 2HDM Type-I

LHC Higgs Working Group WG3 (BSM)

Extended Higgs Sector subgroup meeting

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in collabration with A. Arhrib, R. Benbrik, M. Krab, B. Manaut,
S. Moretti, and Q.S. Yan

2HDM scalar potential

- With CP-conserving, and a imposed Z_2 symmetry

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

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

Three neutral Higgs bosons (h, H, A)

and a $H^\pm$ pair:

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

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

β: $\tan\beta \equiv \frac{v_2}{v_1}$

m_{12}:

2HDM Type-I

Z2-symmetry ⟶ four types

Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

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

ϕ	ξ_ϕ^u	ξ_ϕ^d	ξ_ϕ^ℓ
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

Code with: 2HDMC, HiggsSignals, HiggsBounds, SuperIso ...

Theoretical constraints

Perturbativity

Unitarity

Vacuum stability

Experimental constraints

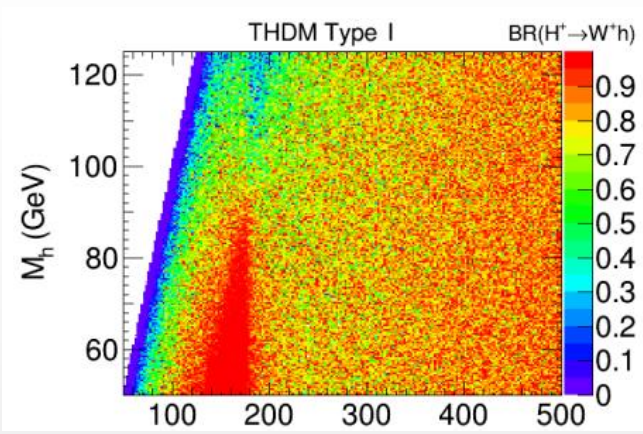
EW oblique parameters S, T, U

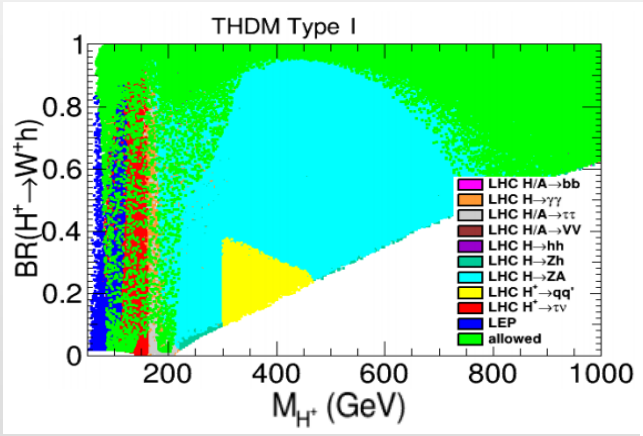
LEP, TeVatron and LHC data

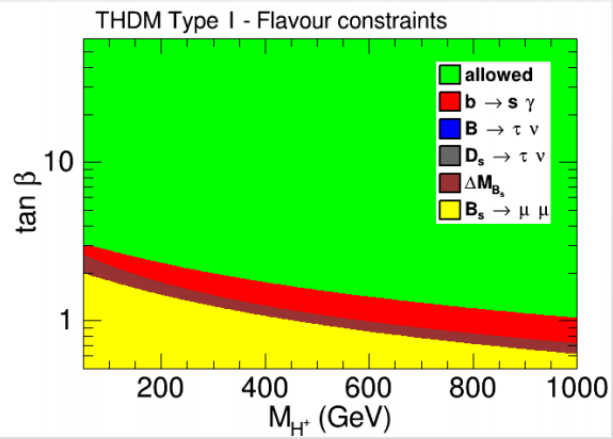
Flavour physics

Still alive

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



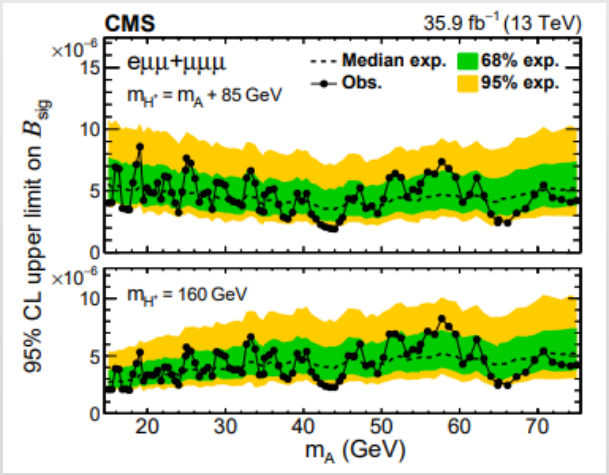




Direct search
for a light $H^\pm$ by

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

no excess



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

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

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

Parameter space scans: production

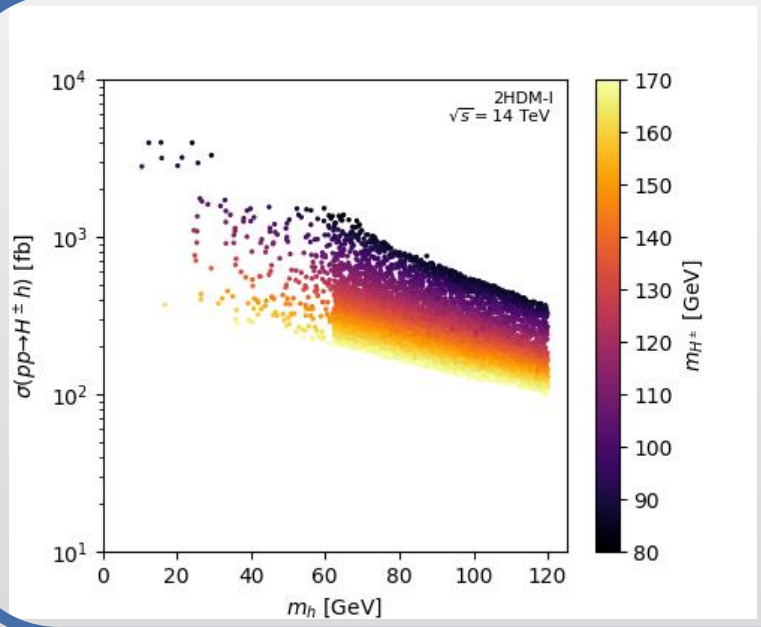
alignment limit: maximise

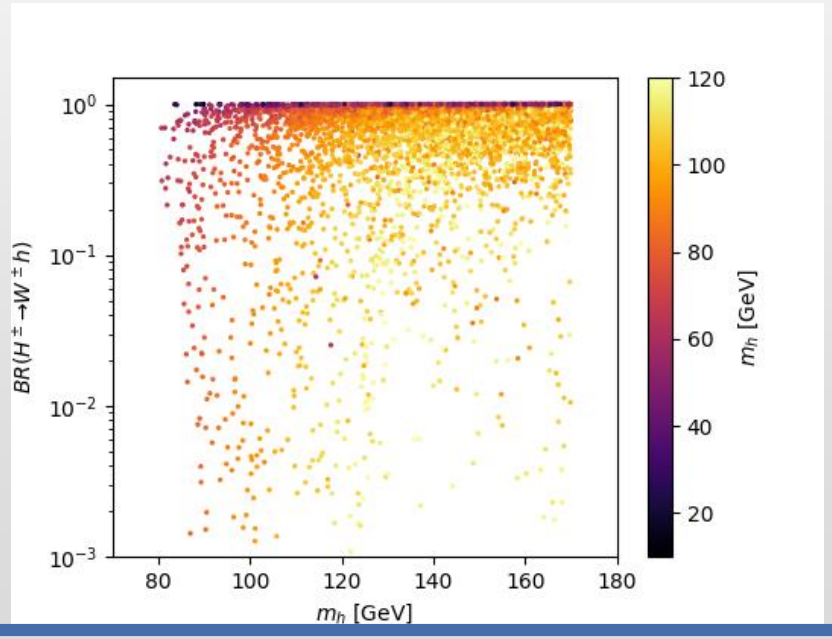
$$g_{hH^{\pm}W^{\mp}} \approx \cos(\beta - \alpha)$$

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

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

with an off-shell W boson





cross section

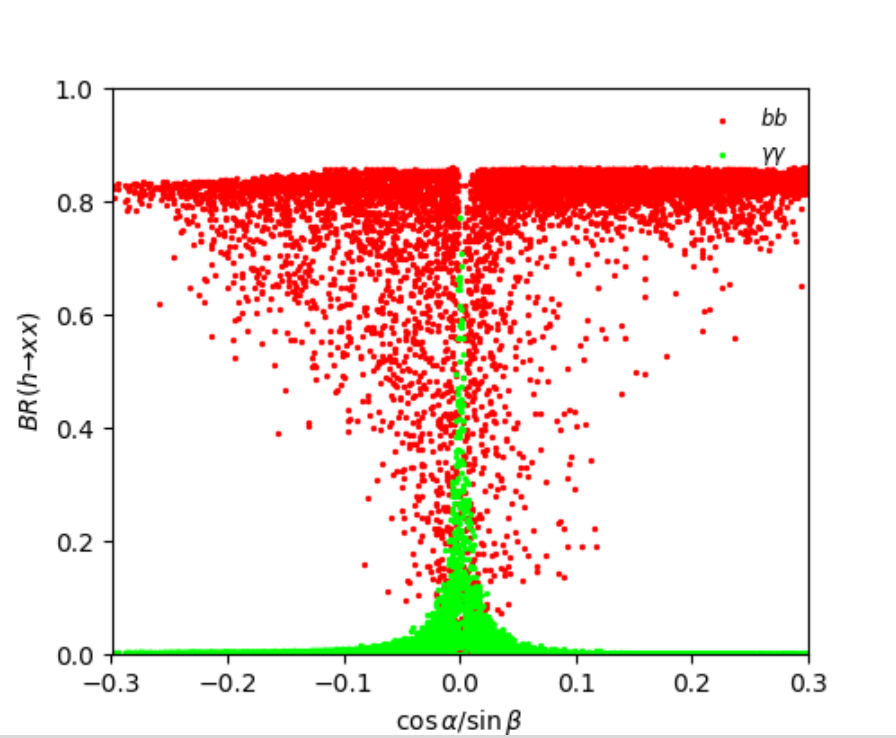
R. Enberg, W. Klemm, S. Moretti, S. Munir, arXiv:1812.08623

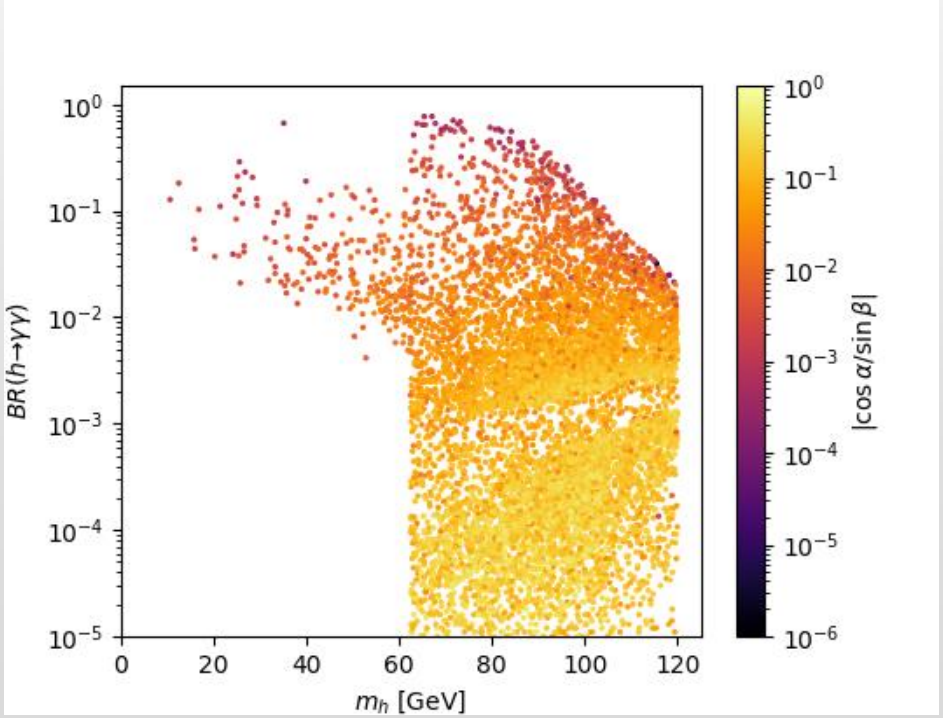
Parameter space scans: decay

$$pp \to H^{\pm} h \to W^{\pm} hh$$

$$\begin{cases} h \to \gamma\gamma \\ h \to b\bar{b} \\ h \to \tau^{+}\tau^{-} \end{cases}$$

fermiophobic h $\sin(\beta - \alpha) \to 0$





[YW, A. Arhrib, R. Benbrik, M. Krab, B. Manaut, S. Moretti, Q.S. Yan J. High Energ. Phys. 2021, 21 (2021)]

First process

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

soft γ from $h \to \gamma\gamma$

	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

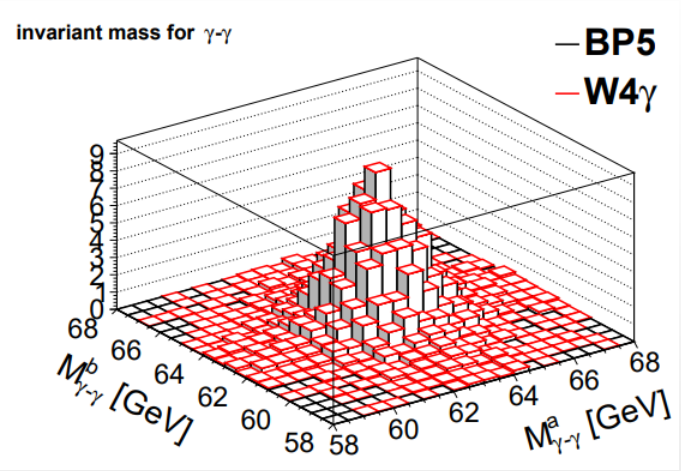
cross sections

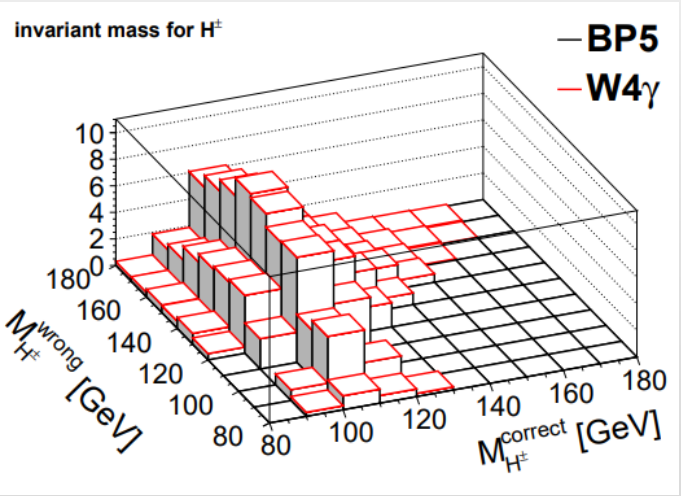
Signal: $pp \to H^{\pm}h \to W^{\pm(*)}hh \to \ell\nu_\ell + 4\gamma$

SM Backgrounds: with fake photons (j->γ)

After selecting l+4γ, 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	2.55×10^{-4}
$W^{\pm} + 1j3\gamma$	0.0282	1.52×10^{-4}
$W^{\pm} + 0j4\gamma$	1.69×10^{-5}	5.71×10^{-6}



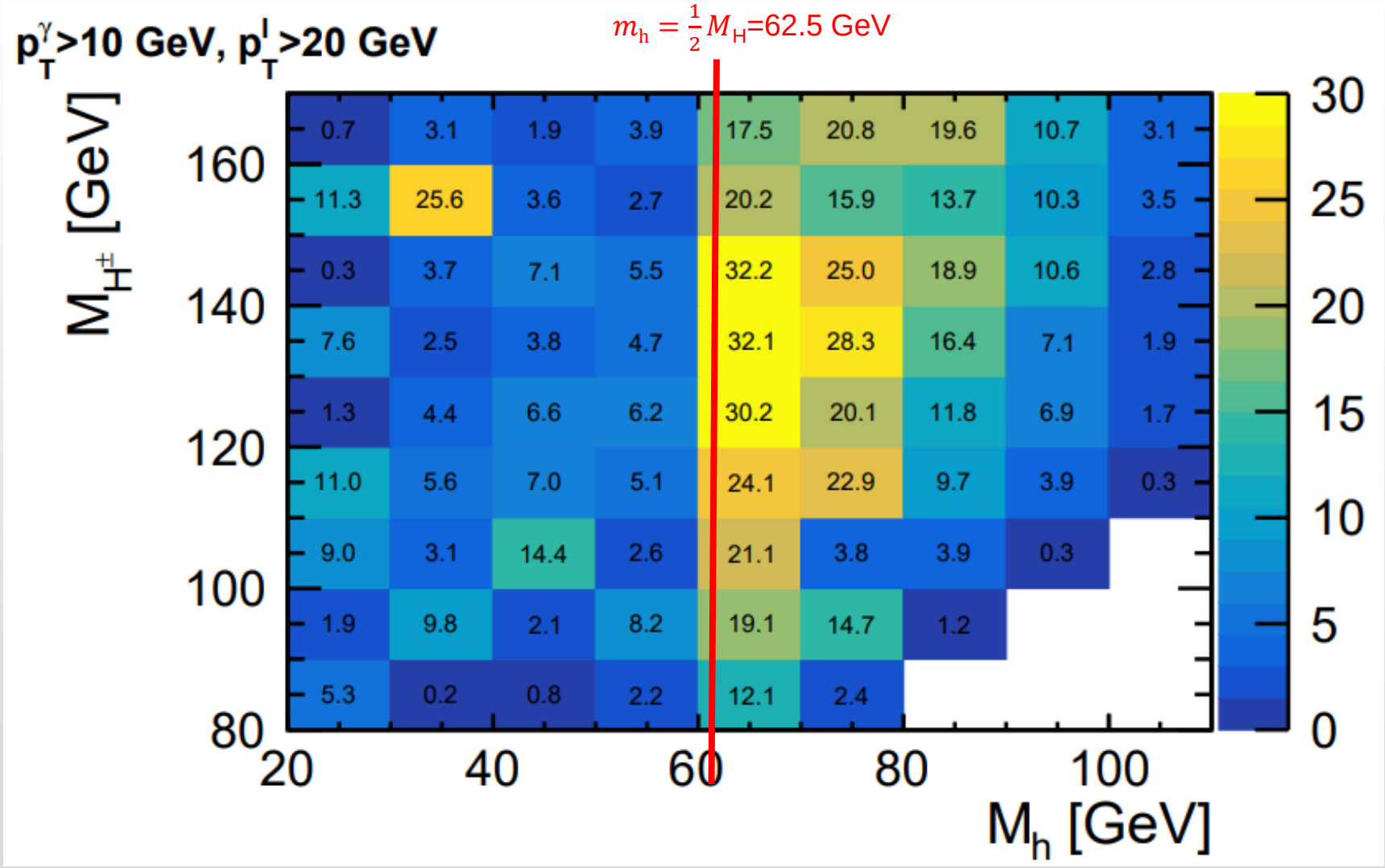


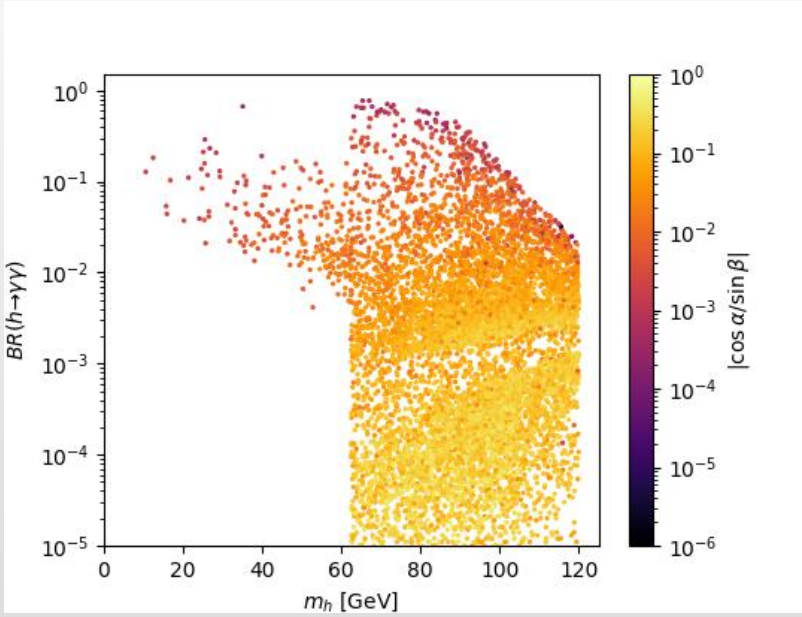
Significance : above 10 $\sigma = \frac{S}{\sqrt{S+B}} \approx \sqrt{S}$

BPs	1	2	3	4	5	6	7	8	9	10	11	12	13	14
σ_{13TeV}	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
σ_{14TeV}	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

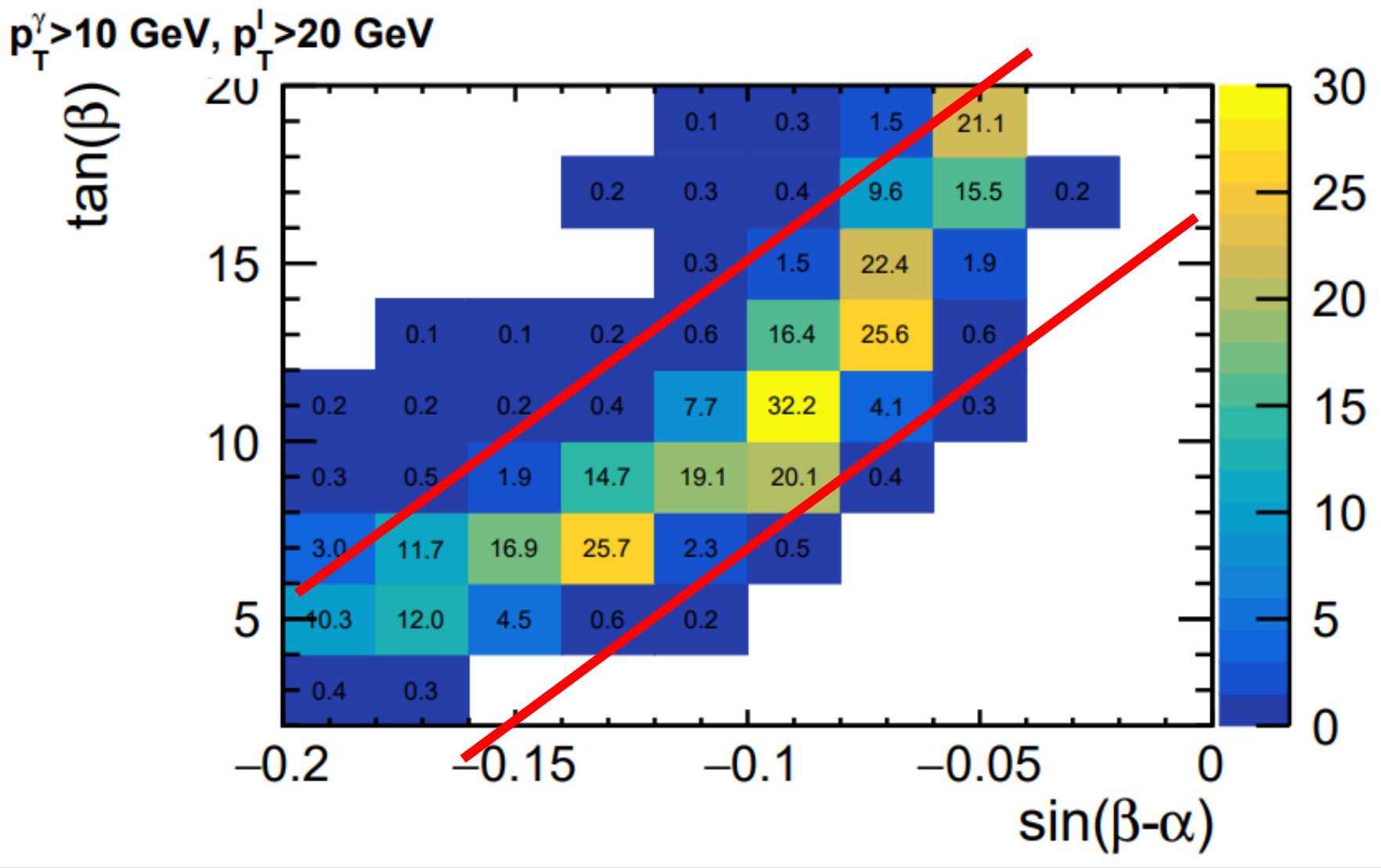
Simulate with MadGraph5_aMC@NLO + Pythia + Delphes (ATLAS card) for 13 TeV and 14 TeV

Scan for (Mh, MH±), the maximun significances





Scan for (sin(β − α), tanβ), the maximun significances



[ZhenLi, A. Arhrib, R. Benbrik, M. Krab, B. Manaut, S. Moretti, Q.S. Yan, YW ,arXiv:2211:xxxxx]

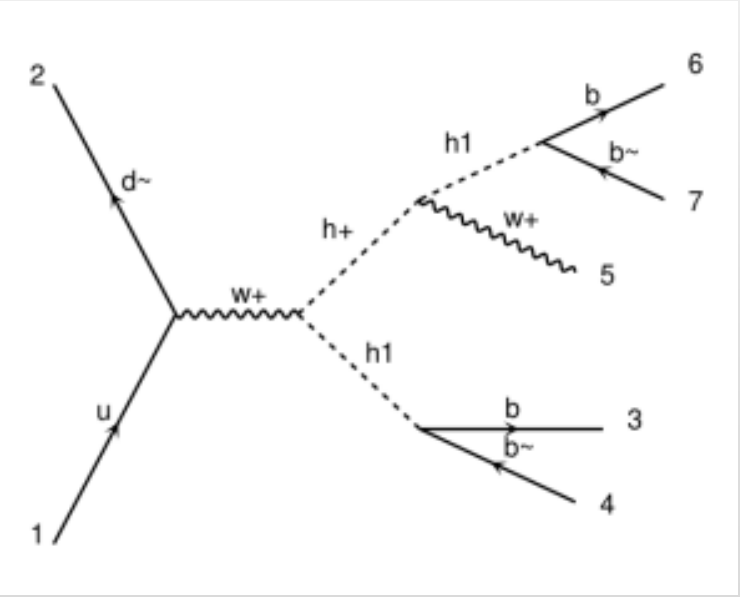
Second process $pp \to H^{\pm} h \to W^{\pm *} hh \to l^{\pm} \nu + 4b$

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

an off-shell W boson: soft leptons

light Higgs mass: soft b-jets

parameters	M_h	M_H	M_A	$M_{H^\pm}$	$\sin(\beta-\alpha)$	$\tan\beta$	m_{12}^2	$\sigma(W+4b)$ (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



Event Generation:

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

$|\eta(l,j)| < 2.5,\ p_T(j,l) > 10\ \text{GeV},\ \text{R(ll/jj)} > 0.4,\ \text{MET} > 5\ \text{GeV},\ \text{(PC1)}$

$|\eta(l,j)| < 2.5,\ p_T(j,l) > 20\ \text{GeV},\ \text{R(ll/jj)} > 0.5,\ \text{MET} > 5\ \text{GeV},\ \text{(PC2)}$

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

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

σ (parton cut) (fb)	BP1	BP2	BP3	BP4	BP5	BP6	$t\bar{t}_{l\nu jjbb}$	$wbbbb$	$wjjbb$	$wjjjj$	ztb_{zjjbb}
parton-cut 1	32.50	20.92	26.26	32.17	31.51	26.52	85680	10	13480	647170	-
parton-cut 2	5.376	2.71	4.36	8.34	8.04	7.89	54980	1.48	2940	127550	9.3×10^{-2}

Event Selection:

three categories: 4b0j, 3b1j, 2b2j

TABLE IV. Cross section of signal for BPs

BPs	BP1	BP2	BP3	BP4	BP5	BP6
PC1 4b0j	1.646	0.993	1.389	1.554	1.507	1.473
PC1 3b1j	5.395	3.127	4.412	5.197	5.005	4.763
PC1 2b2j	8.30	4.703	6.648	8.020	7.748	7.221
PC2 4b0j	0.153	0.070	0.122	0.317	0.300	0.313
PC2 3b1j	0.470	0.212	0.384	1.013	0.948	0.994
PC2 2b2j	0.573	0.260	0.468	1.281	1.206	1.255

TABLE V. Cross section of background

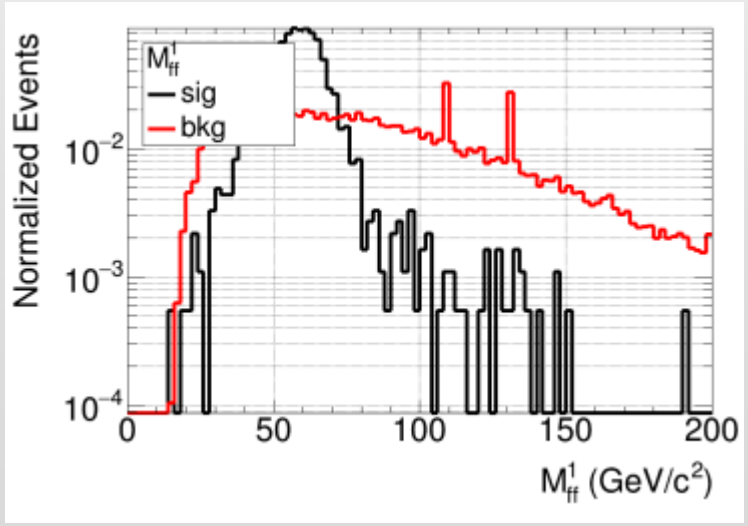
	$t\bar{t}_{lvjjbb}$	$wbbbb$	$wjjbb$	$wjjjj$	ztb_{zjjbb}
PC1 4b0j (fb)	572.96	-	36.69	-	-
PC1 3b1j (fb)	5229.5	-	354.22	-	-
PC1 1b2j (fb)	29600.6	-	2350.03	-	-
PC2 4b0j (fb)	98.84	8.6×10^{-2}	4.54	6.96	9.53×10^{-3}
PC2 3b1j (fb)	1658.4	2.61×10^{-1}	56.92	89.81	2.56×10^{-2}
PC2 1b2j (fb)	14704.8	3.34×10^{-1}	522.13	939.82	3.02×10^{-2}

kinematic cuts:

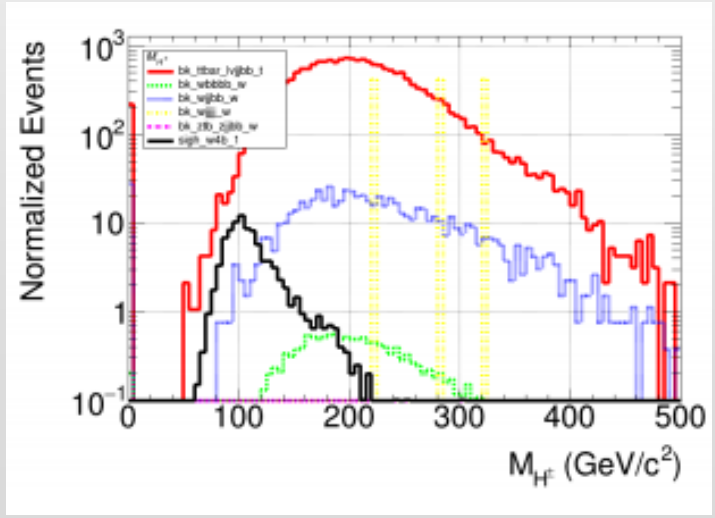
signal invariant mass	$M_1^{b\bar{b}}$	$M_2^{b\bar{b}}$	$M^{H^\pm}$			
top invariant mass	M^{W_1}	M^{W_2}	M^{t_1}	M^{t_2}		
top angle	$\cos W_2$	$\cos W_2$	$\cos(top_1)$	$\cos(top_2)$		
visible invariant mass	$M^{H^\pm h}$	$P_T^{H^\pm h}$	M^{jjjj}			
visible angle	HT	$\cos(vis)$	M^{tt}	$\cos(tt)$		
jet angle	$\cos(\theta_{b_1-b_2})$	$\cos(\theta_{b_2-b_3})$	$\cos(\theta_{b_2-b_4})$	$\cos(\theta_{b_1-b_3})$	$\cos(\theta_{b_3-b_4})$	$\cos(\theta_{b_1-b_4})$
jet-w boson	$\cos(\theta_{b_1-w_1})$	$\cos(\theta_{b_2-w_2})$	$\cos(\theta_{b_1-w_2})$	$\cos(\theta_{b_2-w_1})$		

e.g.:

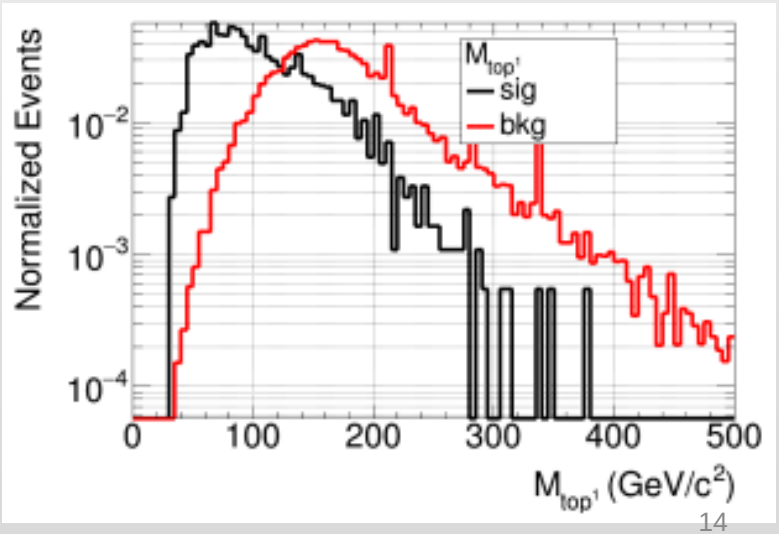
light Higgs mass



charged Higgs mass



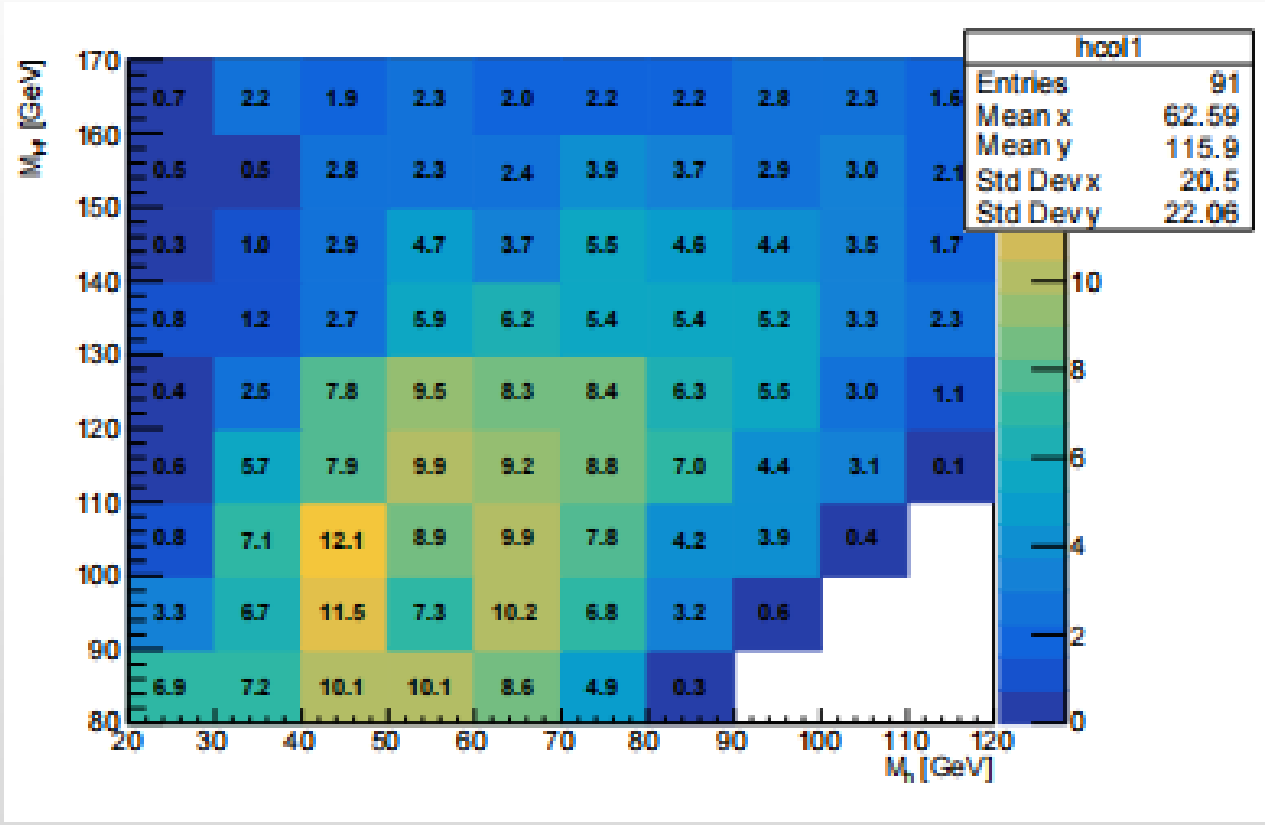
top quark mass



Scan for (Mh, MH±), the maximun significances

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

	$p_T(b,j,l) = 10$ GeV			$p_T(b,j,l) = 20$ GeV		
	2b2j	3b1j	4b0j	2b2j	3b1j	4b0j
BP1	6.16	10.97	18.77	0.69	2.31	3.7
BP2	3.9	7.11	14.71	0.31	1.14	2.08
BP3	5.0	9.25	17.29	0.53	1.92	3.38
BP4	3.79	7.17	7.9	0.86	1.34	5.23
BP5	3.84	7.15	9.49	0.84	2.72	5.14
BP6	3.05	6.04	9.21	0.83	2.71	4.97



[ZhenLi, A. Arhrib, R. Benbrik, M. Krab, B. Manaut, S. Moretti, Q.S. Yan, YW ,arXiv:2212:xxxxx]

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

2τ2b final states

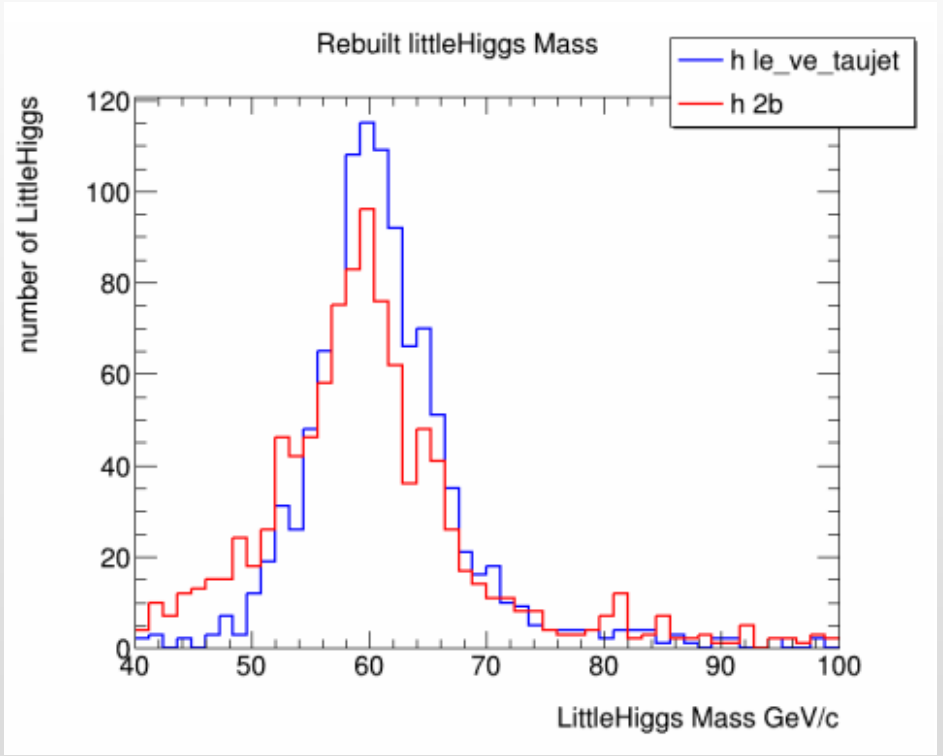
Similar with 4b

with same sign leptons observable

main background is still ttbar

parameters	M_h	M_H	M_A	$M_H^{\pm}$	$\sin(\beta-\alpha)$	$\tan\beta$	M_{12}^2	$\sigma_h^h(W+2b2\tau)$
BP1	65.11	125.00	112.07	88.51	-0.06	51.14	82.33	69.51
BP2	69.88	125.00	108.31	85.50	-0.06	41.90	113.63	58.84
BP3	69.12	125.00	106.14	90.62	-0.09	40.63	115.73	57.81
parameters	M_h	M_H	M_A	$M_H^{\pm}$	$\sin(\beta-\alpha)$	$\tan\beta$	M_{12}^2	$\sigma_h^h(W+4b)$
BP4	64.39	125.00	107.74	107.61	-0.06	45.03	90.47	44.83
BP5	65.20	125.00	104.30	106.02	-0.06	57.64	73.50	45.27
BP6	68.65	125.00	114.53	115.66	-0.09	48.67	96.16	34.49

preliminary results



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+4γ, W+4b, W+2b2τ final states by $H^{\pm}$+h production with approximated fermiophobic.
- Our analysis has been a detector level study exploiting full MC event generation.
- We provide analysis for W+4γ, W+4b, W+2b2τ signals, which would be helpful for experiments.

Thank you for your attention!

Backup

charged Higgs production and decay

- production:
  - $gb \to tH^-$ and $gg \to t\bar{b}H^-$
  - $gg \to W^+H^-$ and $b\bar{b} \to W^+H^-$
  - $gg \to H^+H^-$ and $\bar{q}q \to H^+H^-$
  - $\bar{q}q' \to H^+\phi$
  - $\bar{s}c, \bar{b}c \to H^+$
  - $t \to bH^+$
- decay
  - $H^+ \to \bar{b}c, \bar{s}c, \bar{b}t, \tau^+\nu$ Fermionic decay
  - $H^+ \to W^+\gamma, W^+Z$ Bosonic decay
  - $H^+ \to W^+\phi$

parameter scan

- B-physics with SuperIso v4.1:

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