



# The analysis of $W+4\gamma$ in the 2HDM type-I

LHC Higgs Working Group WG3  
Extended Higgs Sector subgroup meeting

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Based on arXiv:1706.01964,  
arXiv:2107.01451

# 2HDM scalar potential

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

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

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

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

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

$\alpha$ : mixing angle of neutral scalars

$$\beta \quad \tan \beta \equiv \frac{v_2}{v_1}.$$

# 2HDM Type-I

$Z_2$ -symmetry



four types

Model	$u_B^i$	$d_B^i$	$e_B^i$
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	$\Phi_2$	$\Phi_1$	$\Phi_2$

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

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

Study  $H^\pm + h \rightarrow W + 4\gamma$  final states

# Theoretical constraints

Perturbativity      Unitarity      Vacuum stability

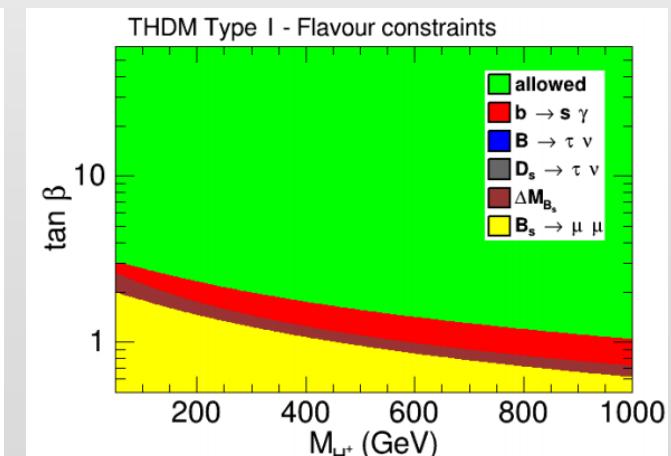
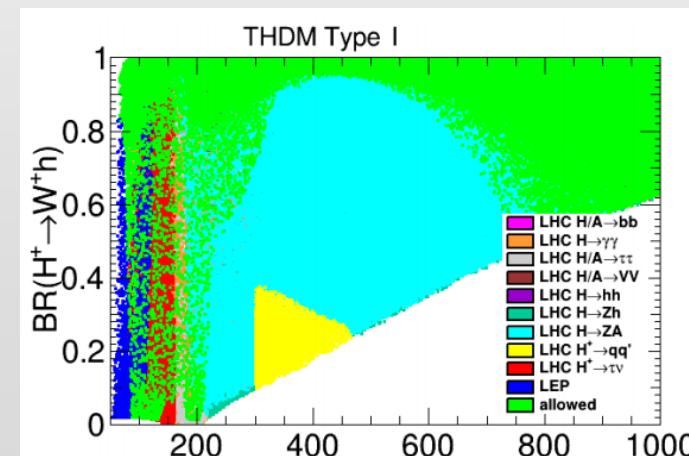
Parameters	Ranges
$m_h$	[10, 120]
$m_H$	125
$m_A$	[10, 500]
$m_{H^\pm}$	[80, 170]
$s_{\beta-\alpha}$	[-1, 1]
$\tan \beta$	[2, 25]
$m_{12}^2$	[0, $m_A^2 s_\beta c_\beta$ ]
$\lambda_6 = \lambda_7$	0

# Experimental constraints

EW oblique parameters S, T, U

LEP, TeVatron and LHC data

Flavour physics



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

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

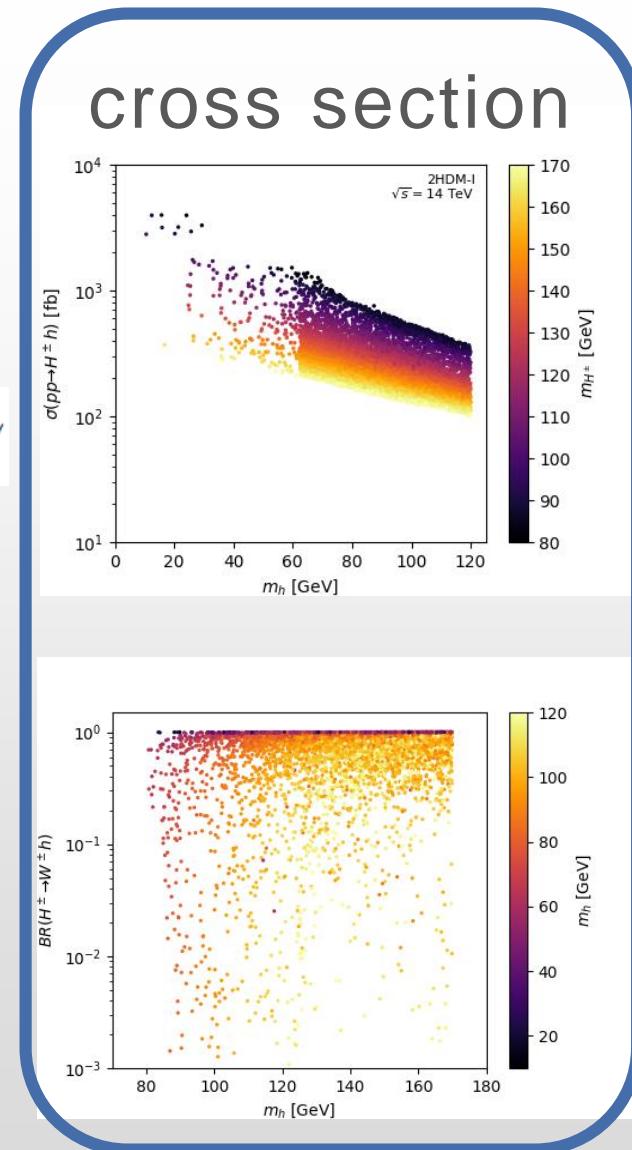
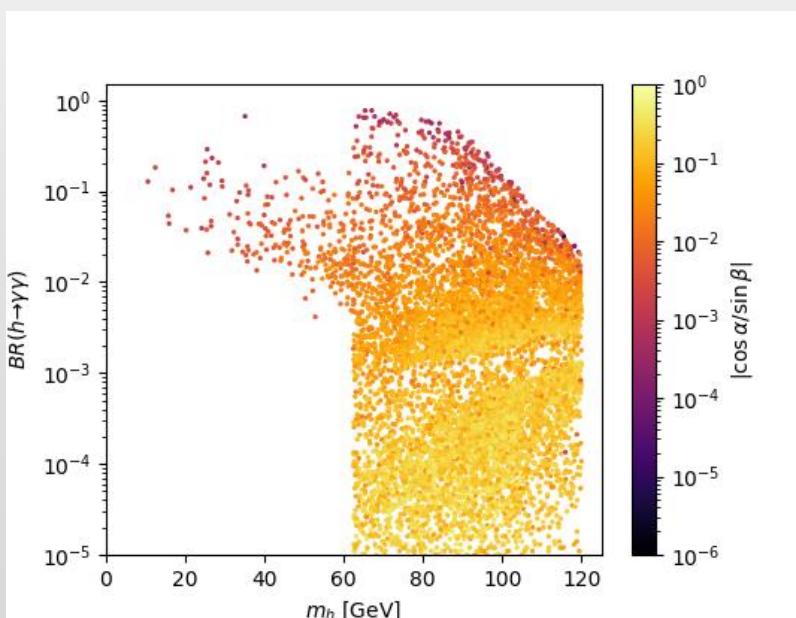
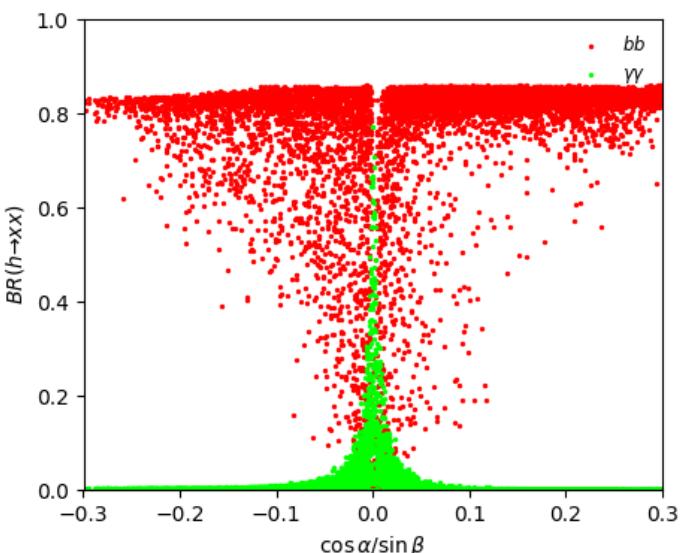
# Parameter space scans

$\sin(\beta - \alpha) \rightarrow 0$   $\rightarrow$  fermiophobic  $h$   $\rightarrow h \rightarrow \gamma\gamma$

constrain by  
 $H \rightarrow W^\pm W^{\mp(*)}$  and  $ZZ^*$

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

A. G. Akeroyd, M. A. Diaz, and F. J. Pacheco, Phys. Rev. D70, 075002 (2004)



# our BPs

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

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

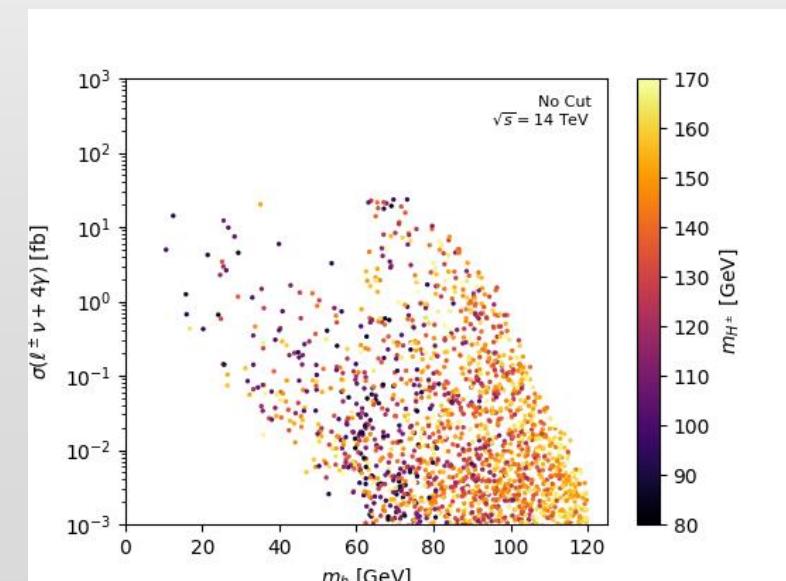
	$M_h$	$M_A$	$M_{H^\pm}$	$\sin(\beta - \alpha)$	$\tan \beta$	$m_{12}^2$	$\sigma_{13}(W + 4\gamma)$ [fb]	$\sigma_{14}(W + 4\gamma)$ [fb]
BP1	25.57	72.39	111.08	-0.074	13.58	11.97	101.40	112.55
BP2	35.12	111.24	151.44	-0.075	13.32	16.66	167.75	186.20
BP3	45.34	162.07	128.00	-0.136	7.57	80.96	10.76	11.93
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

$$H^\pm \rightarrow W^{\pm(*)} h$$



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

# our BPs

	$M_h$	$M_A$	$M_{H^\pm}$	$\sin(\beta - \alpha)$	$\tan \beta$	$m_{12}^2$	$\sigma_{13}(W + 4\gamma)$ [fb]	$\sigma_{14}(W + 4\gamma)$ [fb]
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large signal

cross sections

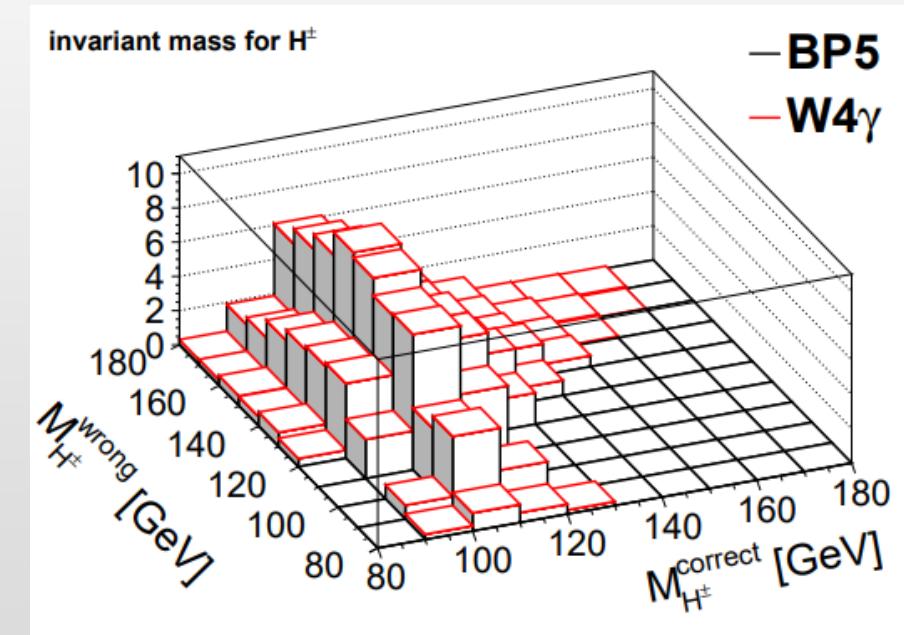
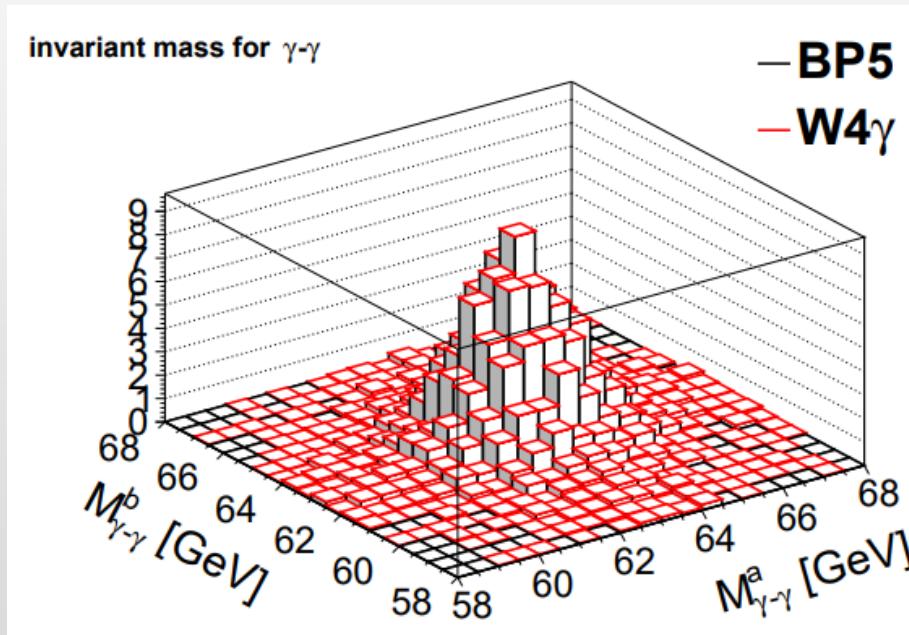
BKG: with faked photons

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

# Event generation and simulation

MadGraph5\_aMC@NLO + Pythia + Delphes (ATLAS card) for 13 TeV and 14 TeV

$$|\eta(l, j, \gamma)| < 2.5, \quad p_T(j, \gamma, l) > 10 \text{ GeV}, \quad \Delta R(l, j, \gamma) > 0.5, \quad \text{MET} > 5 \text{ GeV}$$



# Event generation and simulation

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	$1.52 \times 10^{-4}$
$W^\pm + 0j4\gamma$	$1.69 \times 10^{-5}$	$5.71 \times 10^{-6}$

After selecting  $l\nu+4\gamma$   
Background Free

Cross section (fb)	MG	After selection
BP1	2.09	0.42
BP2	7.43	1.89
BP3	0.57	0.15
BP4	1.17	0.29
BP5	9.49	2.57
BP6	12.48	3.65
BP7	10.42	2.90
BP8	8.09	2.18
BP9	7.31	1.98
BP10	4.72	1.47
BP11	4.65	1.39
BP12	4.59	1.39
BP13	4.36	1.34
BP14	4.23	1.34

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

# Efficiency

in Backup, also find plots for  $p_T^\gamma > 10$  GeV,  $p_T^l > 20$  GeV,  $\sqrt{s}=13/14$  TeV

parton level  $\sigma(\text{cuts})/\sigma(\text{no cuts})$

plots for  $p_T^\gamma > 20$  GeV,  $p_T^l > 10$  GeV,  $\sqrt{s}=13/14$  TeV

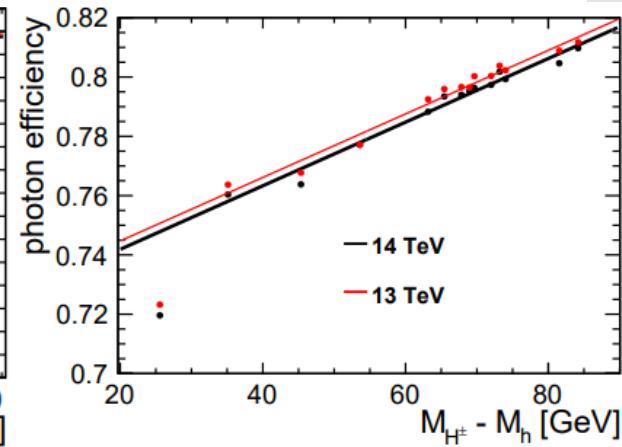
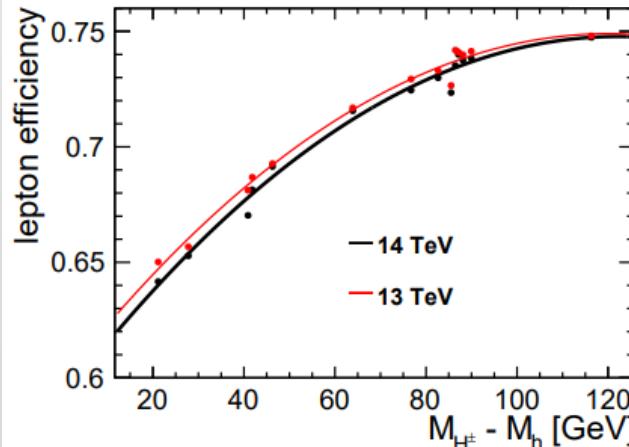
$p_T^\gamma > 10$  GeV,  $p_T^l > 20$  GeV

$m_{H^\pm} \setminus m_h$	20	30	40	50	60	70	80	90	100
80	0.04	0.08	0.10	0.08	0.05	<0.01	/	/	/
90	0.05	0.10	0.13	0.13	0.10	0.06	<0.01	/	/
100	0.05	0.14	0.16	0.16	0.13	0.11	0.06	<0.01	/
110	0.06	0.13	0.18	0.19	0.17	0.16	0.13	0.07	<0.01
120	0.07	0.14	0.20	0.22	0.24	0.22	0.17	0.13	0.06
130	0.10	0.16	0.23	0.25	0.28	0.25	0.24	0.20	0.15
140	0.10	0.18	0.23	0.27	0.28	0.31	0.28	0.27	0.21
150	0.11	0.19	0.26	0.31	0.31	0.33	0.32	0.29	0.27
160	0.12	0.21	0.26	0.29	0.34	0.34	0.34	0.30	0.32

[A. Arhrib, R. Benbrik, R. Enberg, W. Klemm, S. Moretti, S. Munir, Phys.Lett. B774 (2017) 591-598]

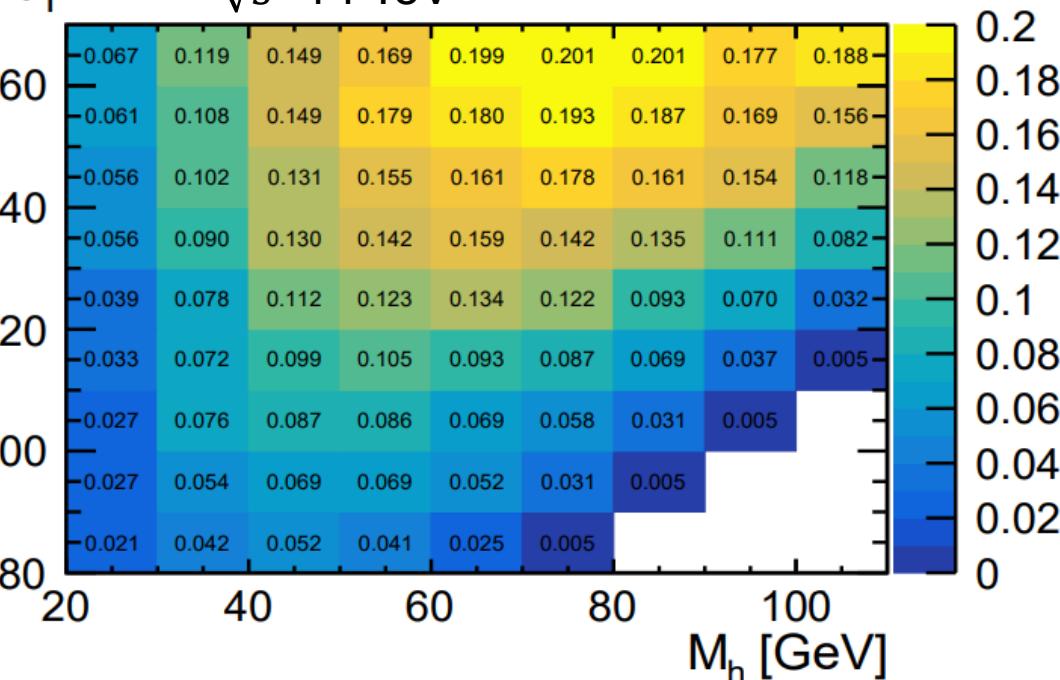
detector level

$$\epsilon_{\text{det}} = 10^{-3} n_j \times \epsilon_\ell \times \epsilon_\gamma^{4-n_j}$$



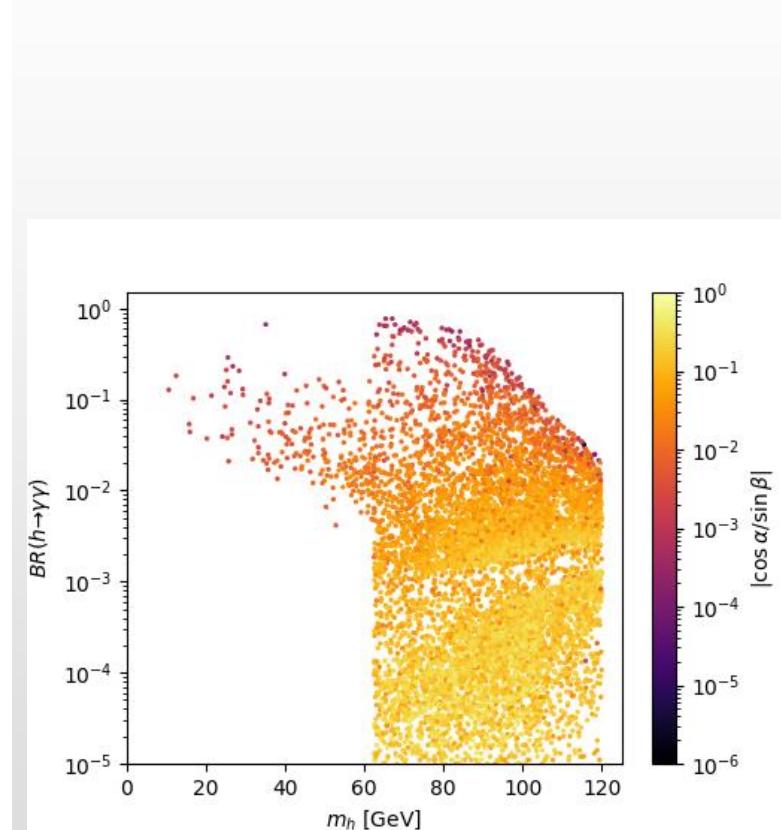
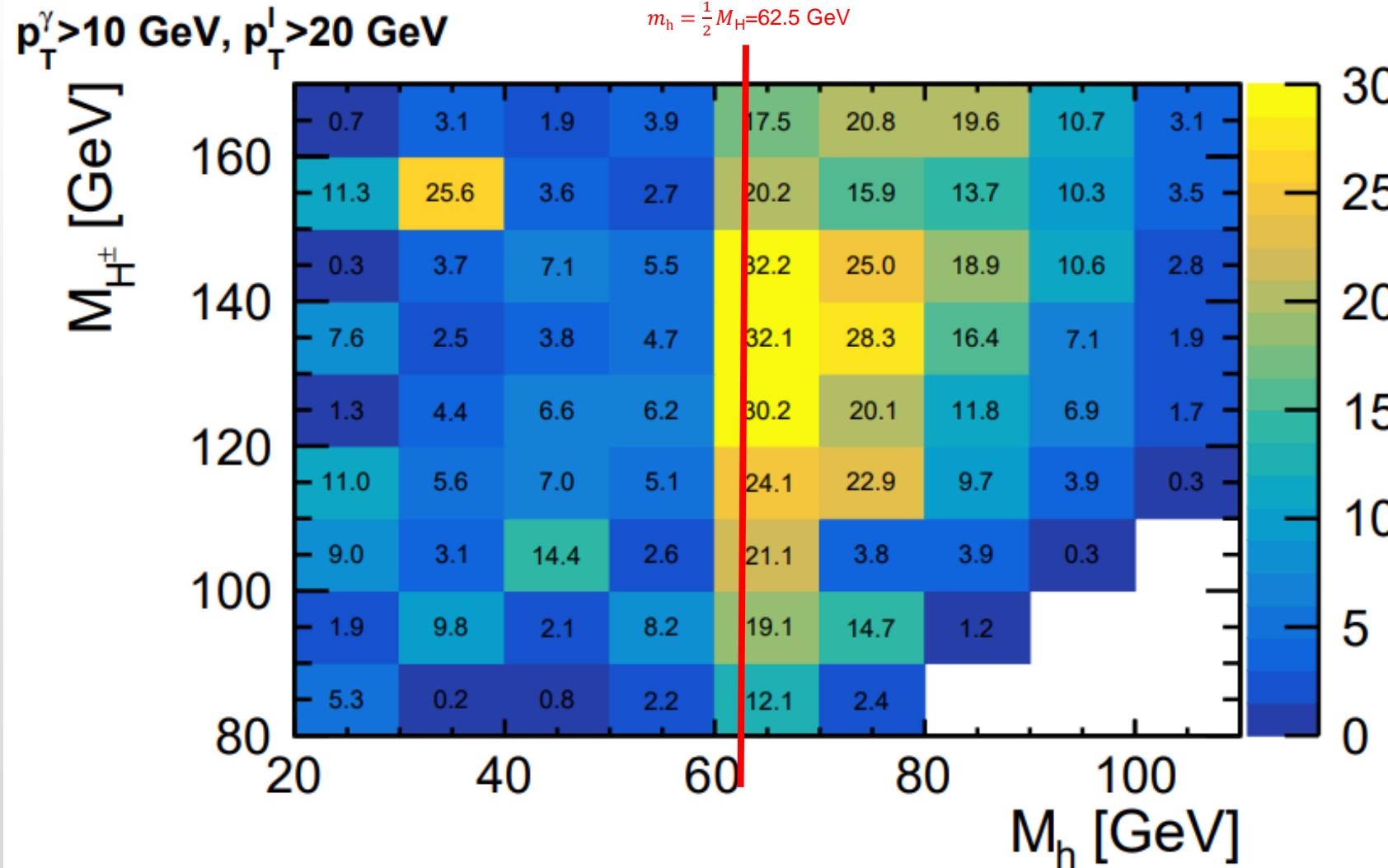
$$\epsilon = \sigma(\text{cuts}) \times \epsilon_{\text{det}} / \sigma(\text{no cuts})$$

$p_T^\gamma > 10$  GeV,  $p_T^l > 20$  GeV,  $\sqrt{s}=14$  TeV

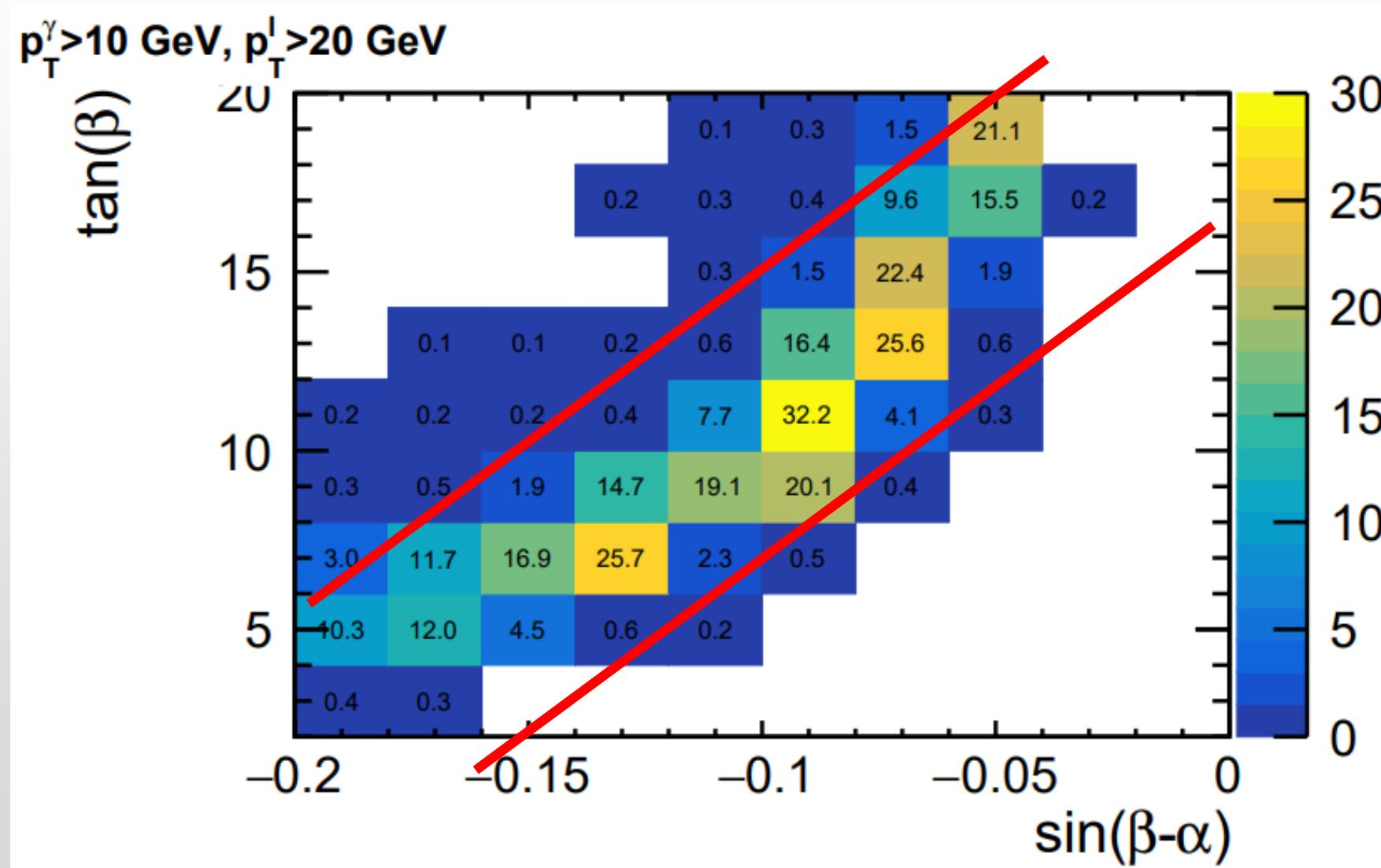


[YW, A. Arhrib, R. Benbrik, M. Krab, B. Manaut, S. Moretti, Q.S. Yan 2107.01451]

# predicted significances for $(M_h, M_{H^\pm})$



# **predicted significances for $(\sin(\beta - \alpha), \tan\beta)$**



# Conclusions

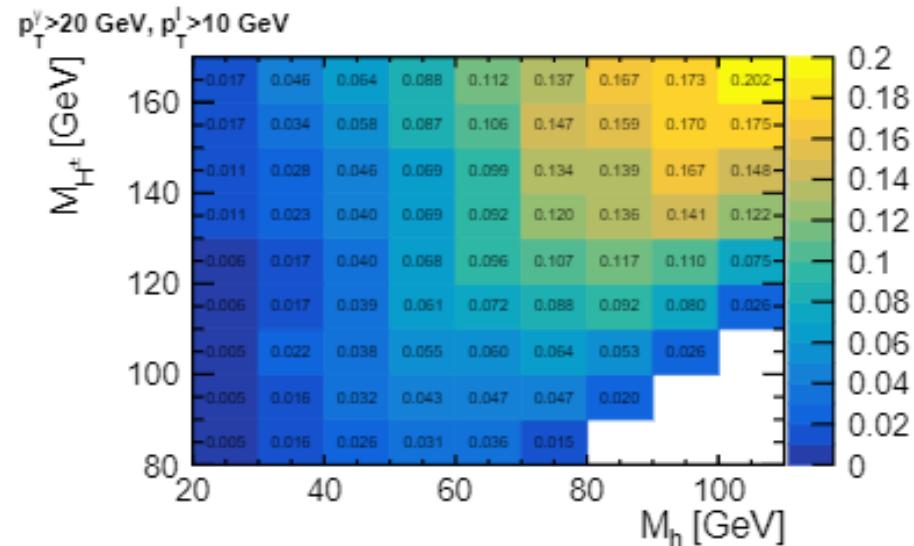
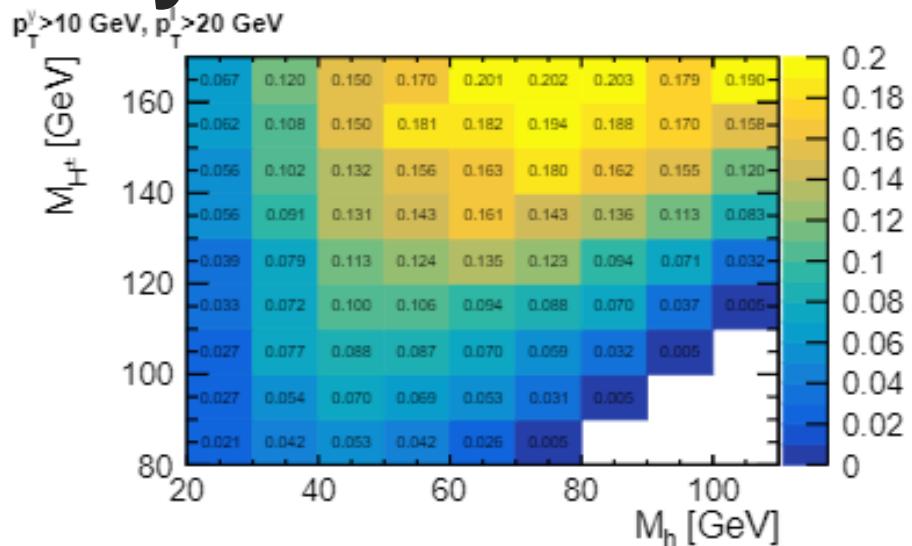
- A charged Higgs is always predicted in the multi Higgs doublet model.
- Always hard to detected, owing to reduced couplings to the SM.
- In the 2HDM Type-I, there are  $W+4\gamma$  final states by  $H^\pm+h$  production with a clear signature. **fermophobic light h**.
- Our analysis has been a detector level study exploiting full MC event generation.
- In presence of background generated by both real and fake photons, , the signal is essentially background free.
- We provided estimates for the detector efficiency and associated heat maps which can expedite an estimate of the signal significance.

**Thank you for your attention!**

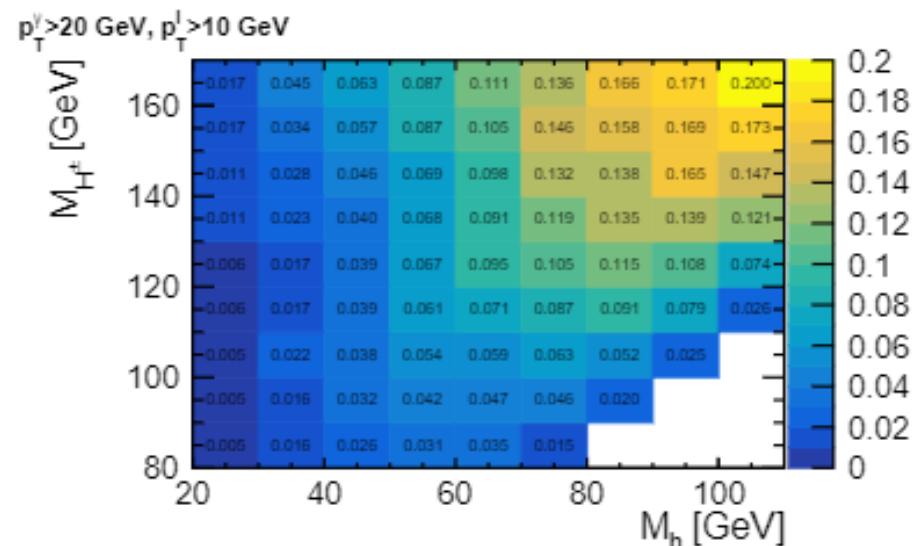
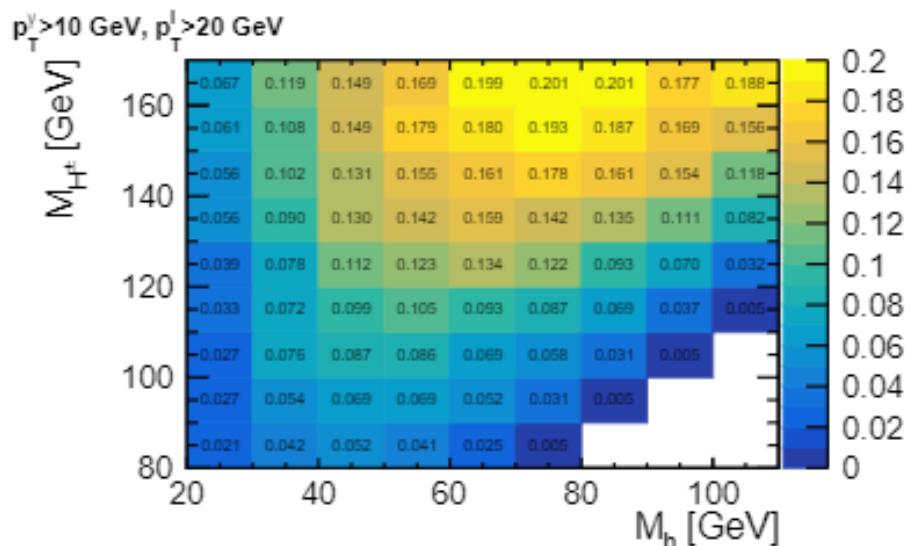
# Backup

# Efficiency

13 TeV

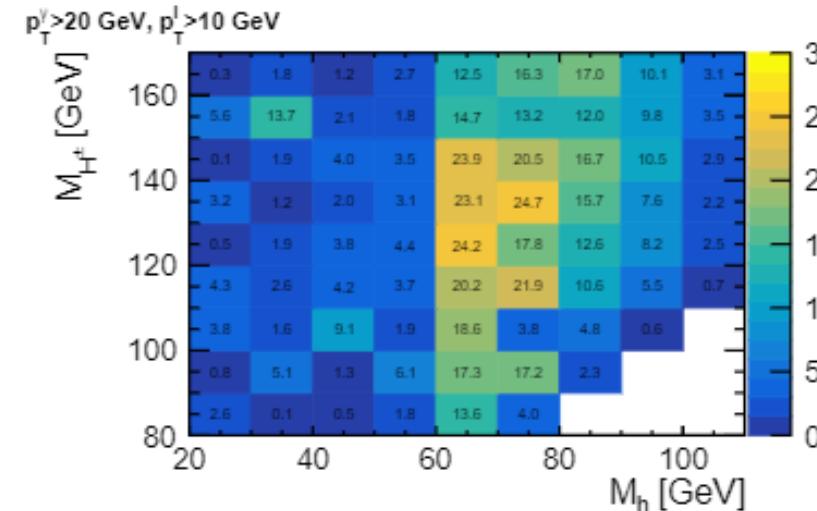
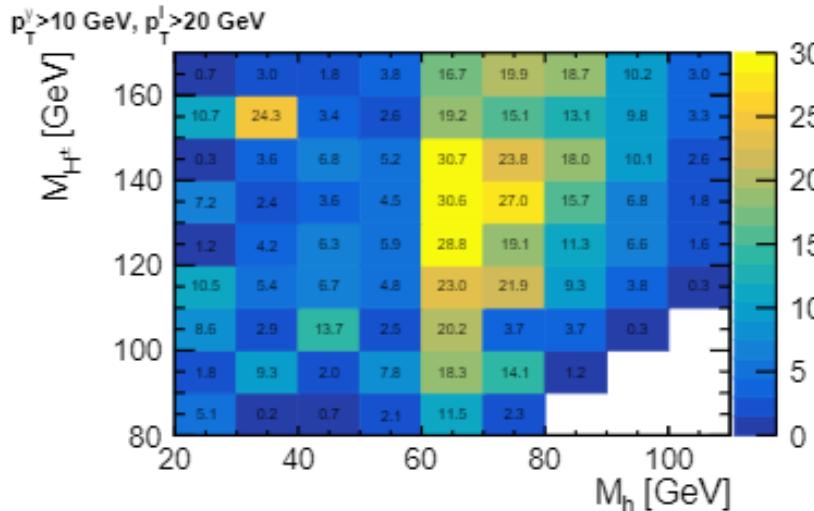


14 TeV

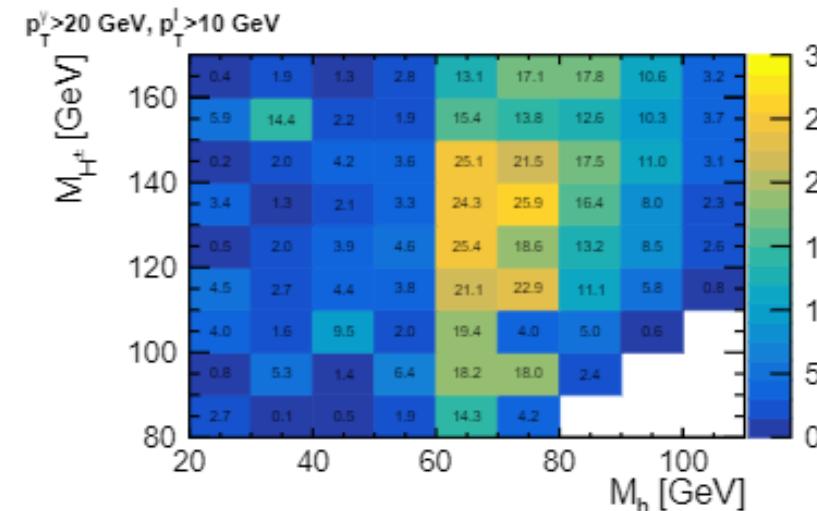
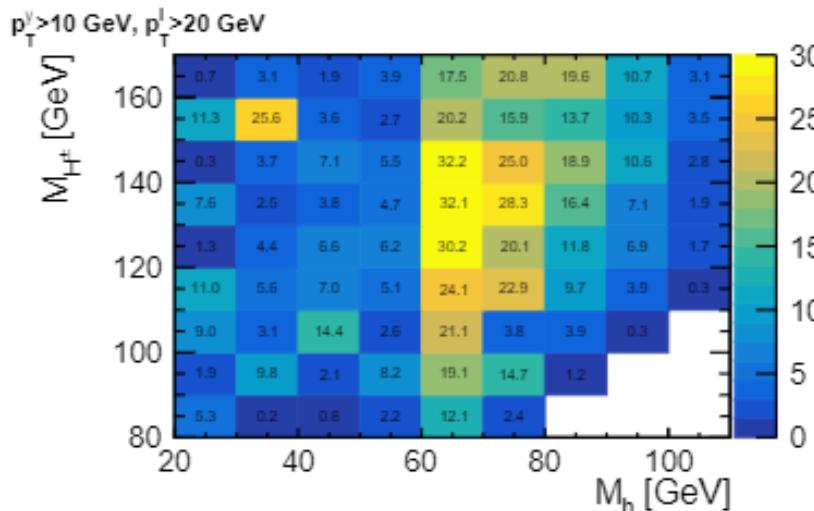


# predicted significances for $(M_h, M_{H^\pm})$

13 TeV

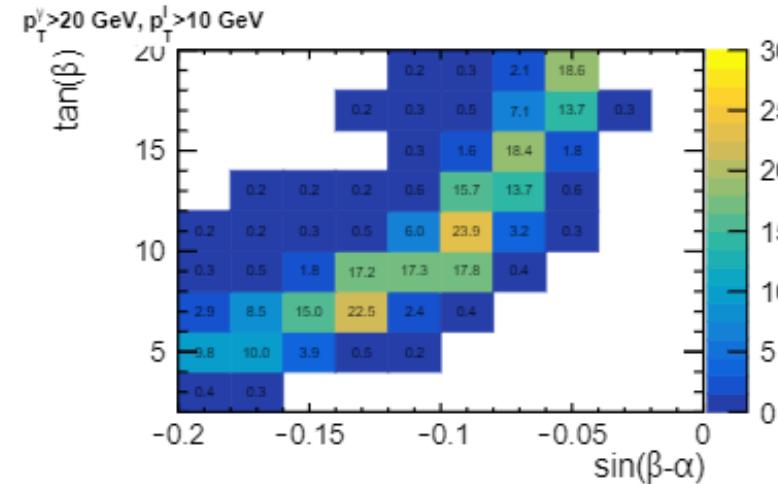
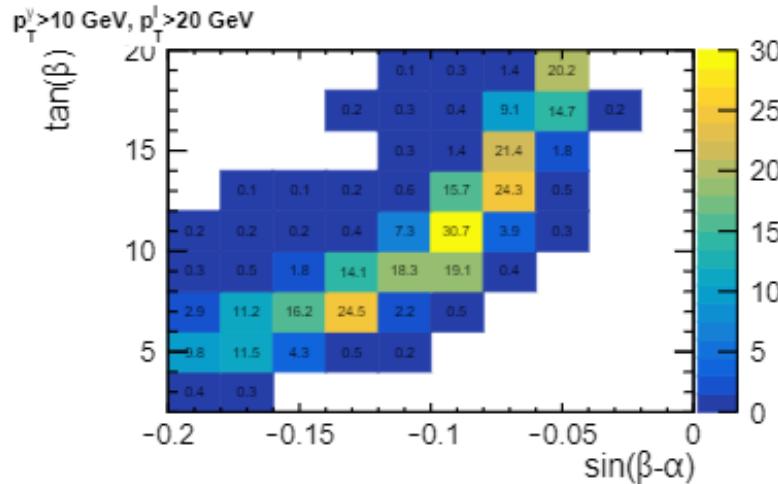


14 TeV

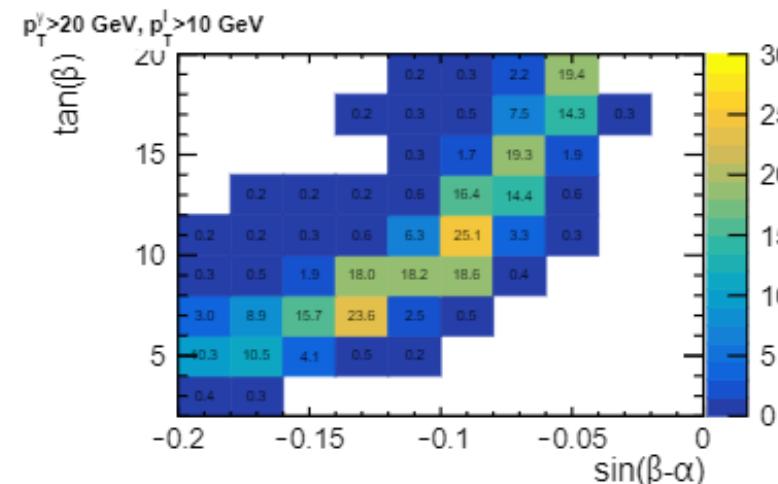
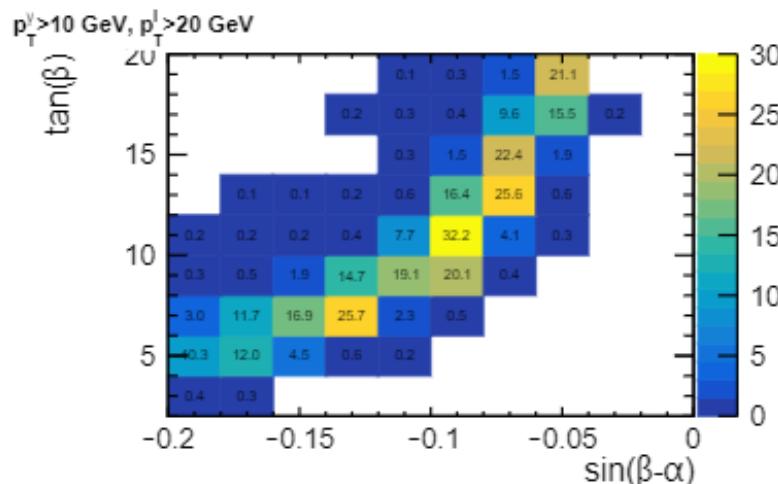


# predicted significances for $(\sin(\beta - \alpha), \tan\beta)$

13 TeV



14 TeV



# charged Higgs production and decay

- production:

- $gb \rightarrow H^-$  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)