College of Physics and
Electronic Information

Inner Mongolia
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The analysis of W+4γ in the 2HDM type-I

Charged Higgs Online workshop

2021-8-31

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on behalf of A. Arhrib, R. Benbrik,
M. Krab, B. Manaut, S. Moretti,
and Q.S. Yan

Based on arXiv:1706.01964,
arXiv:2107.01451

2HDM scalar potential

- With CP-conserving, and a imposed Z_2 symmetry

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

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

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

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

α: mixing angle of neutral scalars

β $\tan\beta \equiv \frac{v_2}{v_1}.$

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

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

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

Theoretical constraints

Perturbativity Unitarity Vacuum stability

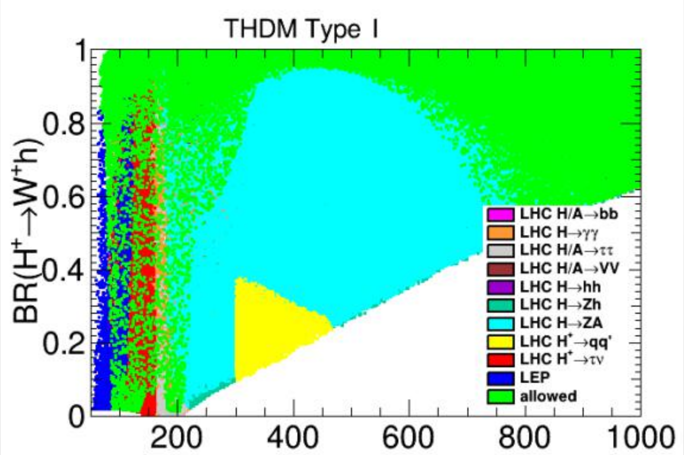
Parameters	Ranges
m_h	[10, 120]
m_H	125
m_A	[10, 500]
$m_{H^\pm}$	[80, 170]
$s_{\beta-\alpha}$	[−1, 1]
$\tan\beta$	[2, 25]
m_{12}^2	$[0,\ m_A^2 s_\beta c_\beta]$
$\lambda_6 = \lambda_7$	0

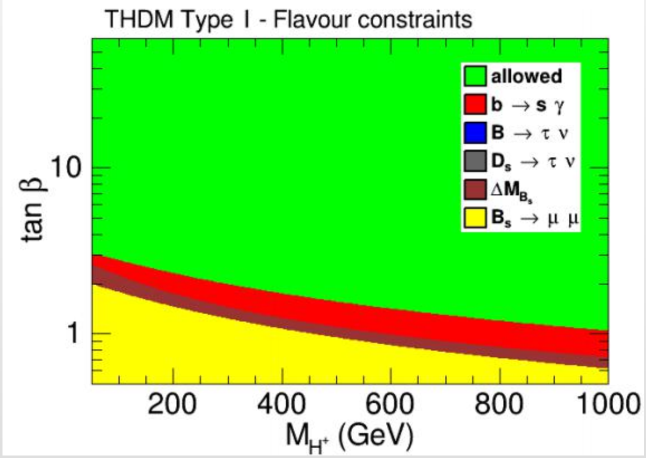
Experimental constraints

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

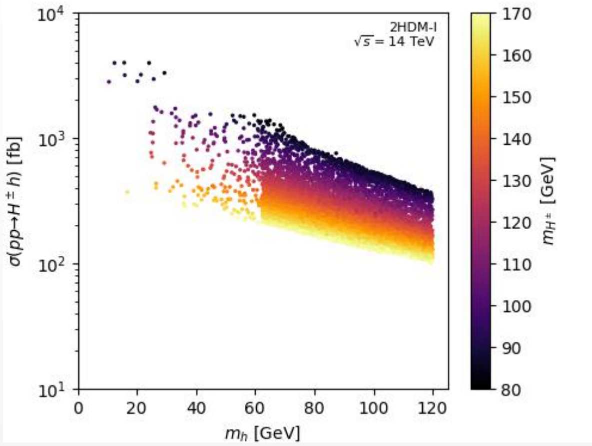
$\sin(\beta-\alpha)\to 0$ → fermiophobic h → $h\to\gamma\gamma$

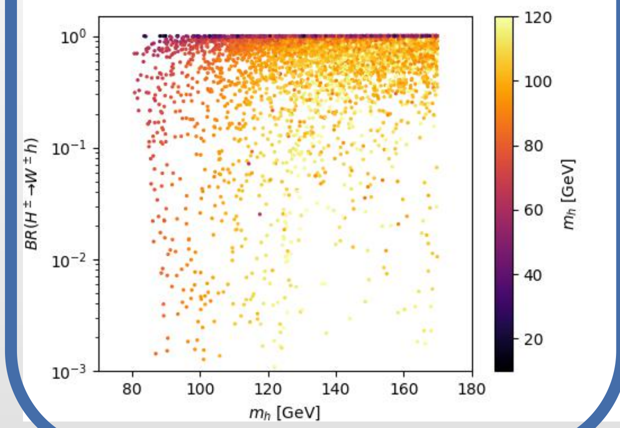
constrain by $H\to W^{\pm}W^{\mp(*)}$ and ZZ^{*}

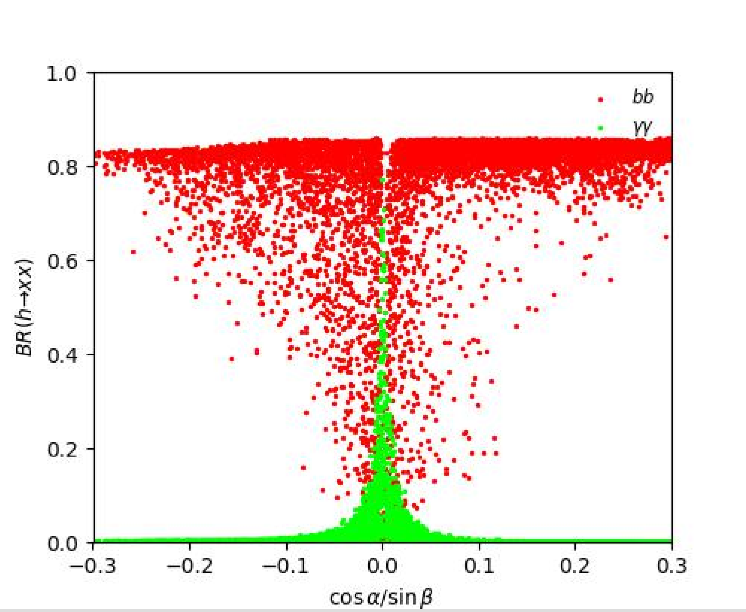
$$pp\to H^{\pm}h\to W^{\pm(*)}hh\to \ell\nu_{\ell}+4\gamma$$

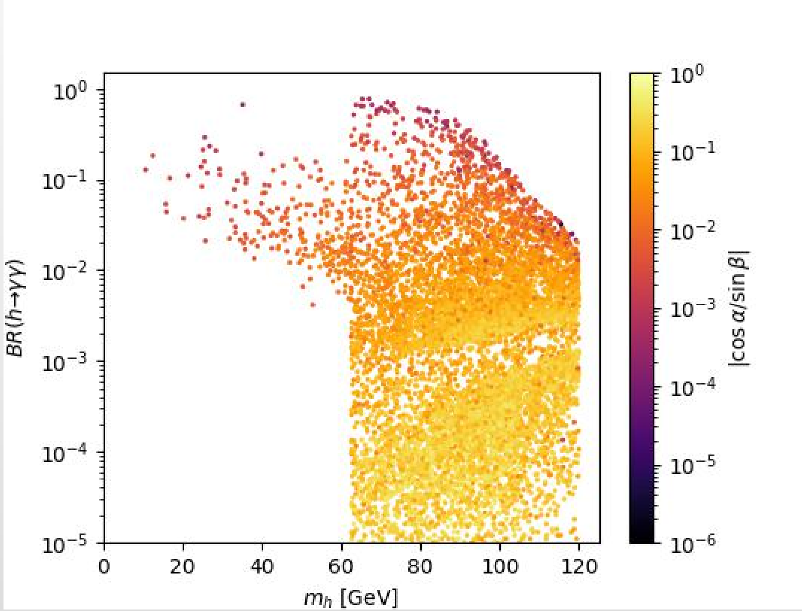
A. G. Akeroyd, M. A. Diaz, and F. J. Pacheco, Phys. Rev. D70, 075002 (2004)

cross section









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

our BPs

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

soft γ from $h \to \gamma\gamma$

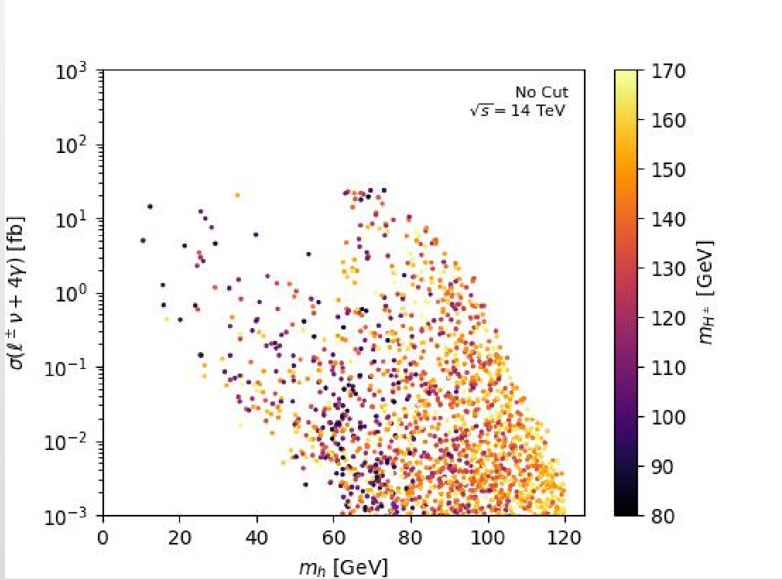
	M_h	M_A	$M_{H^\pm}$	$\sin(\beta-\alpha)$	$\tan\beta$	m_{12}^2	$\sigma_{13}(W+4\gamma)$ [fb]	$\sigma_{14}(W+4\gamma)$ [fb]
BP1	25.57	72.39	111.08	−0.074	13.58	11.97	101.40	112.55
BP2	35.12	111.24	151.44	−0.075	13.32	16.66	167.75	186.20
BP3	45.34	162.07	128.00	−0.136	7.57	80.96	10.76	11.93
BP4	53.59	126.09	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

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



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

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

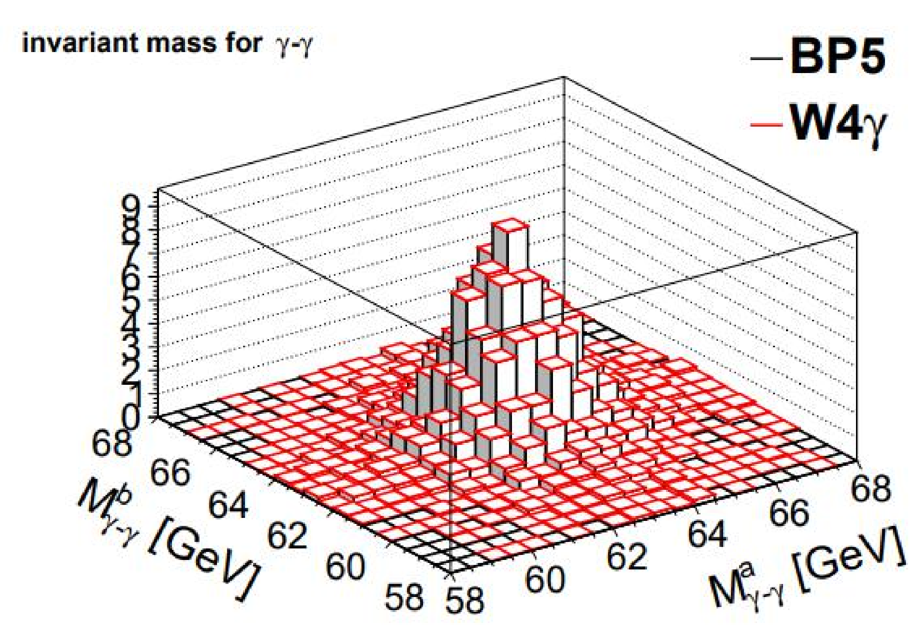
BKG: with faked photons

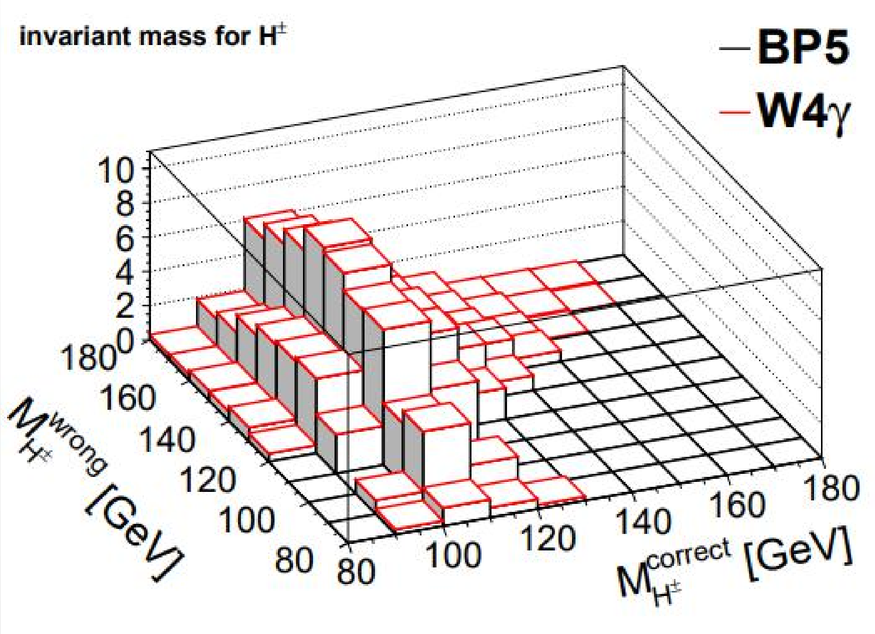
Process	Cross section (fb)
$W^\pm + 4j0\gamma$	145890
$W^\pm + 3j1\gamma$	1730
$W^\pm + 2j2\gamma$	10.2
$W^\pm + 1j3\gamma$	0.0282
$W^\pm + 0j4\gamma$	1.69×10^{-5}

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

After selecting lν+4γ

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

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

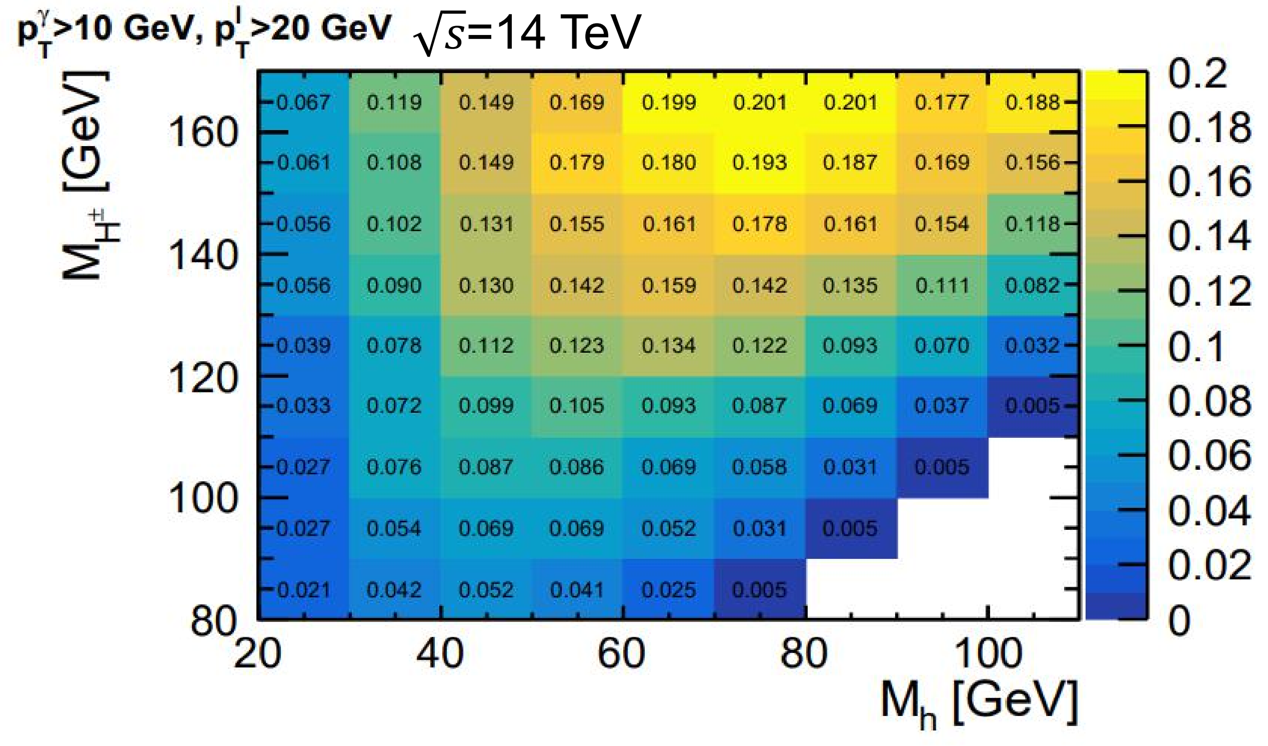
parton level $\sigma(\text{cuts})/\sigma(\text{no cuts})$

p_T^γ >10 GeV, p_T^ℓ >20 GeV

$m_{H^+} \setminus m_h$	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

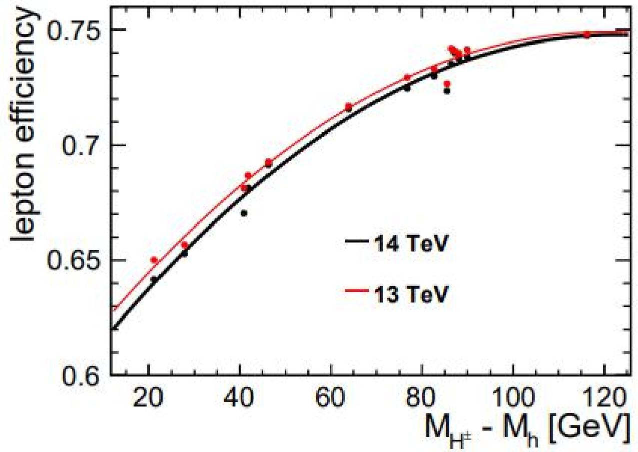
[A. Arhrib, R. Benbrik, R. Enberg, W. Klemm, S. Moretti, S. Munir, Phys.Lett. B774 (2017) 591-598]

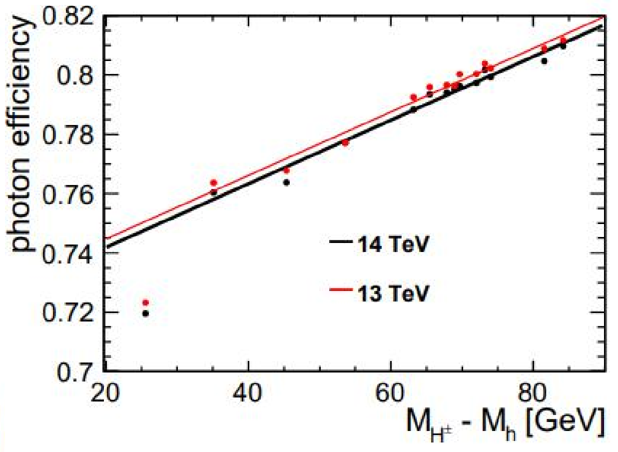
$$\epsilon = \sigma(\text{cuts}) \times \epsilon_{\text{det}}/\sigma(\text{no cuts})$$



detector level

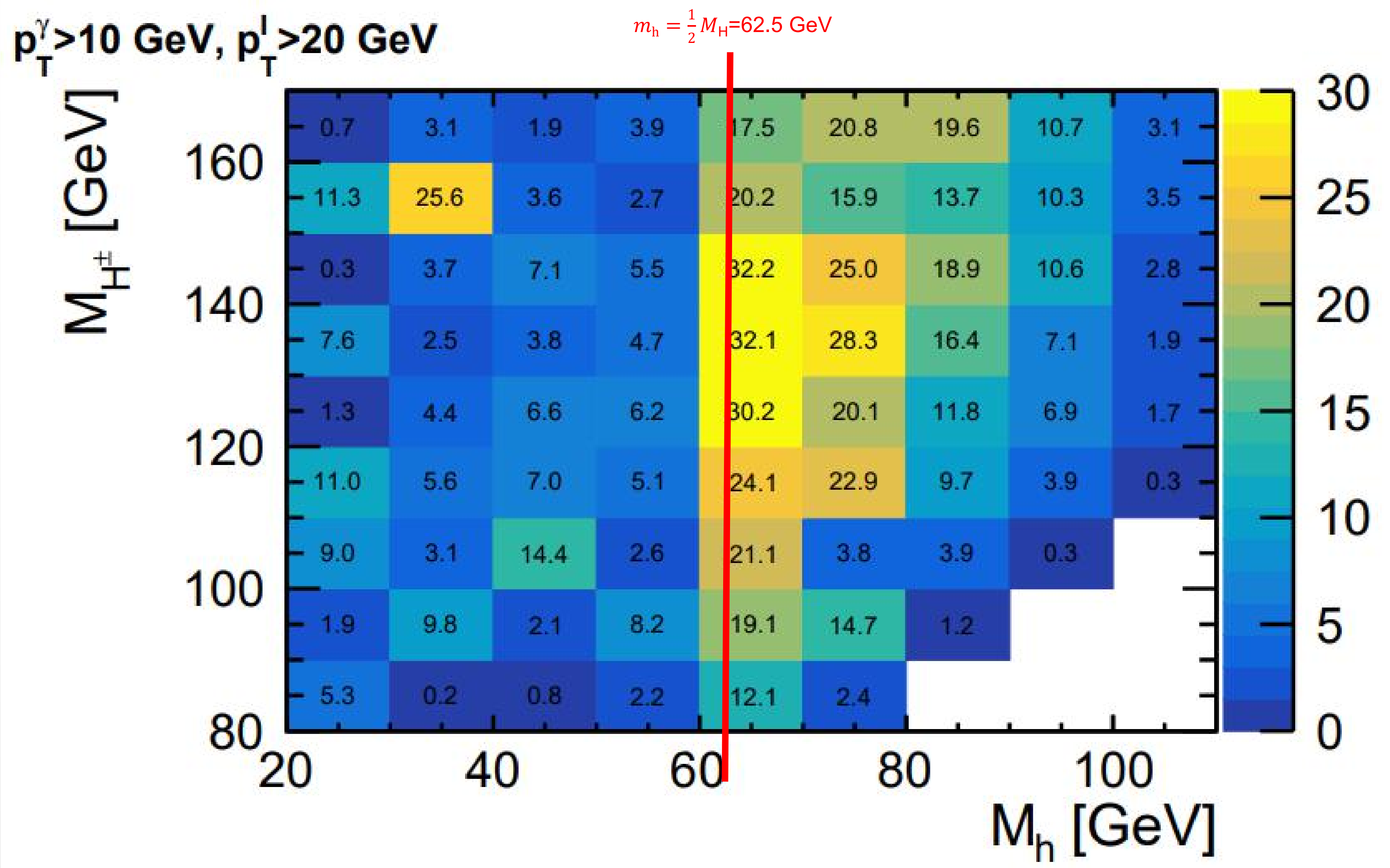
$$\epsilon_{\text{det}} = 10^{-3\, n_j} \times \epsilon_\ell \times \epsilon_\gamma^{4-n_j}$$

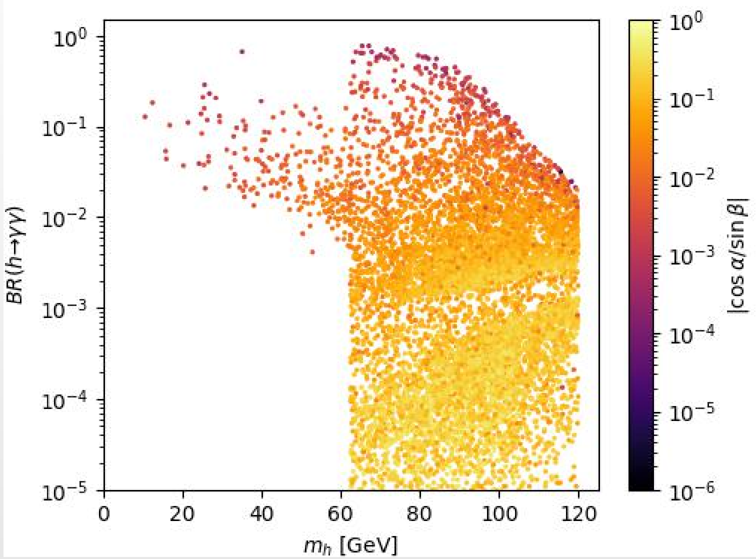




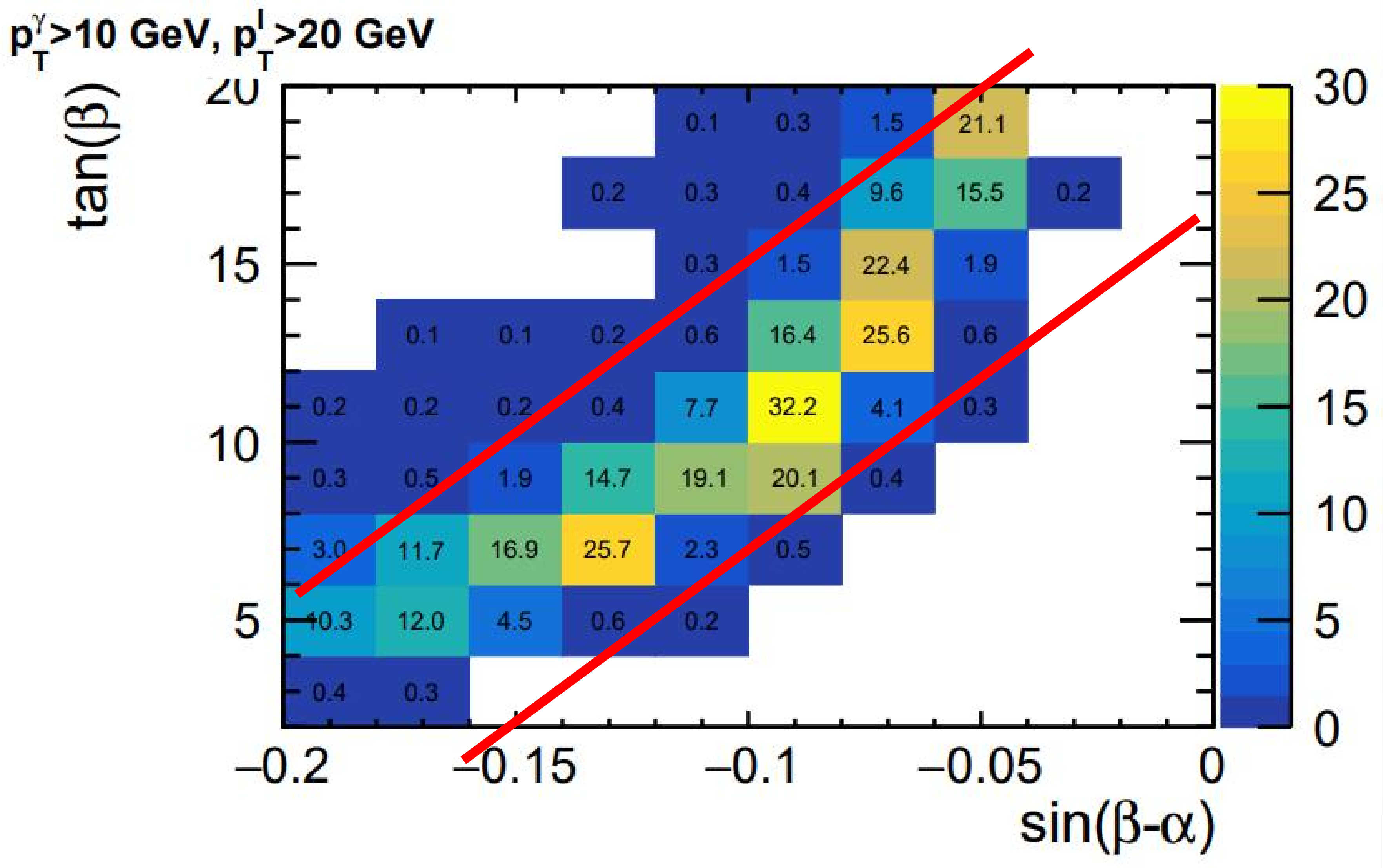
[YW, A. Arhrib, R. Benbrik, M. Krab, B. Manaut, S. Moretti, Q.S. Yan 2107.01451]

predicted significances for (Mh, MH±)





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



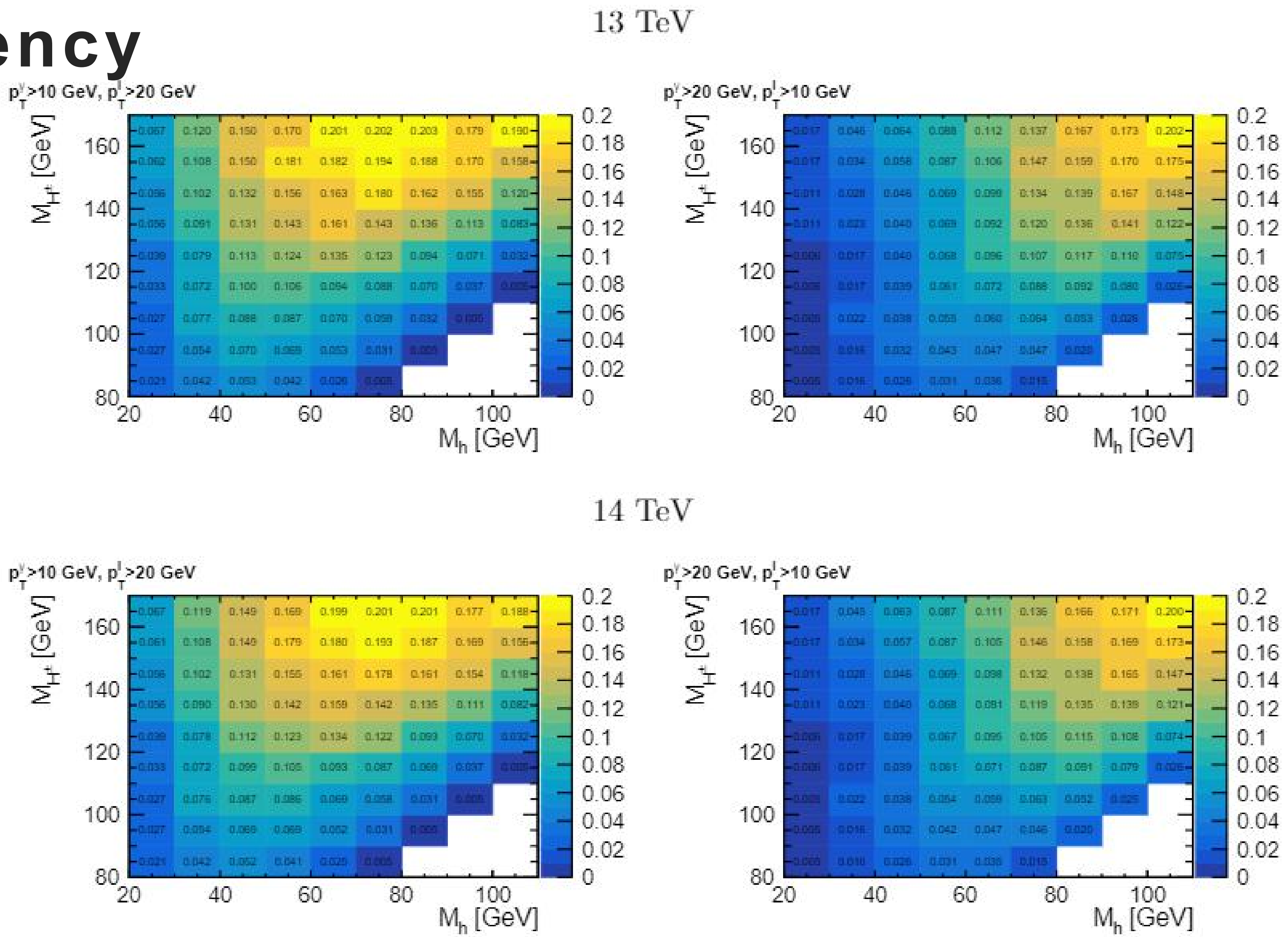
Conclusions

- 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+4γ final states by $H^{\pm}$+h production with a clear signature with a fermiophobic 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.

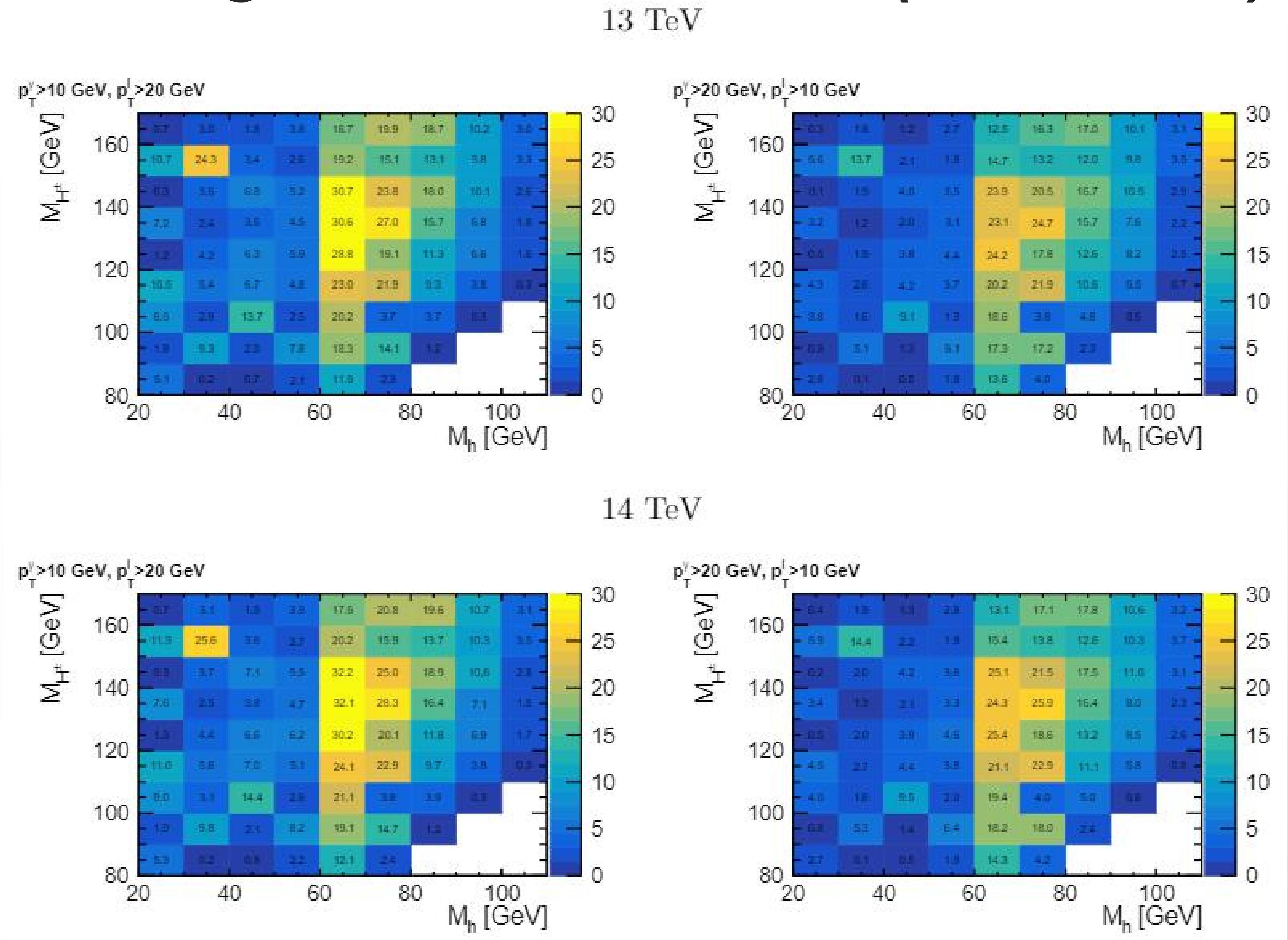
Thank you for your attention!

Backup

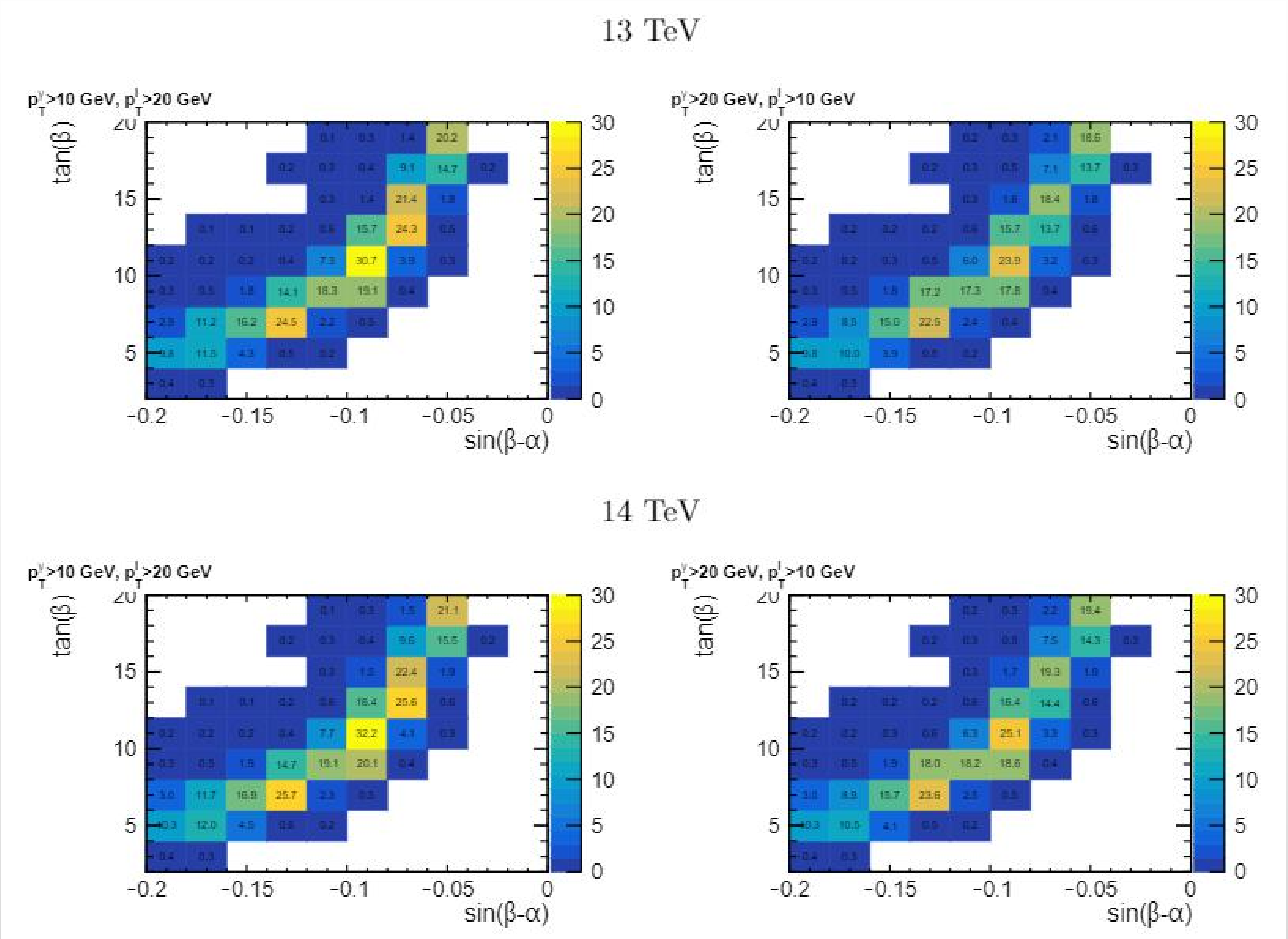
Efficiency


13 TeV
p_T^γ>10 GeV, p_T^l>20 GeV
p_T^γ>20 GeV, p_T^l>10 GeV
$M_{H^\pm}$ [GeV]
M_h [GeV]
14 TeV
p_T^γ>10 GeV, p_T^l>20 GeV
p_T^γ>20 GeV, p_T^l>10 GeV
$M_{H^\pm}$ [GeV]
M_h [GeV]

predicted significances for (Mh, MH±)



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



charged Higgs production and decay

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

main experiment exclusions

LEP

- (ee)->(h1)Z->bb Z,
- (ee)->(h3 h1)->4b,
- (ee)->(h1 h3)->4b,
- (ee)->(h1 ->h3 h3)h3 ->6b,
- (ee)->(h1->h3 h3)Z->4b Z,
- (ee)->(h3->b b)(h1 ->ττ).

LHC

- t->(H1 +)b->tau ν b,
- (p p)-> H (125) -> h1 h1 -> b b τ τ,
- t->(H1 +)b ->τ ν b,
- (p p)->H (125) -> h3 h3 -> b b τ τ,