Signatures of the Type-I 2HDM at the LHC

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KIAS, Seoul

Workshop on the Standard Model and beyond, Corfu

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- *2-Higgs-Doublet Models*
- *Type-I:*
  - ➢ *Electroweak production of light scalar-pseudoscalar pairs*
  - ➢ *A (fairly) light charged Higgs boson*
  - ➢ *The promise of multi-photon final states*
  - ➢ *EW vs. QCD production of multiple Higgs bosons at the LHC*
- *Conclusions*

ADDITIONAL HIGGS BOSONS

KOREA INSTITUTE FOR ADVANCED STUDY

Predicted in a minimalistic new physics contender like the 2-Higgs-Doublet Model and in extended frameworks like Supersymmetry and GUTs

Could provide earliest signatures of new physics

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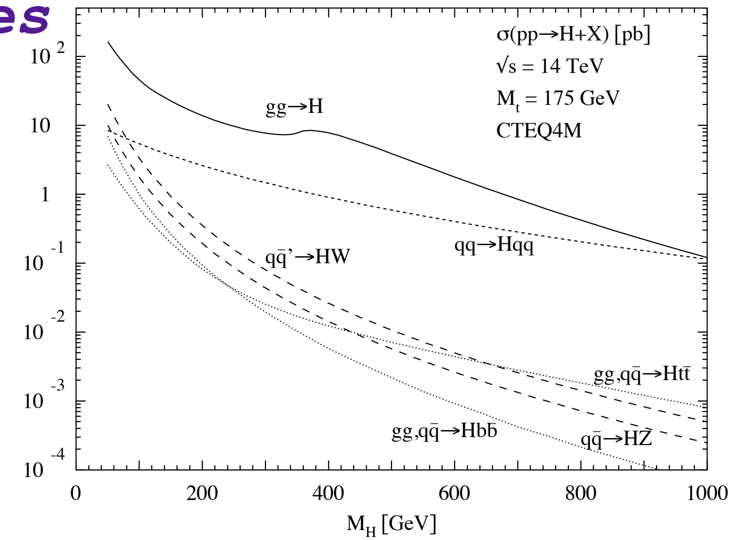
But

- *Masses O(100) GeV:*

Small production cross section - more statistics needed



[A. Djouadi, hep-ph/0503173]

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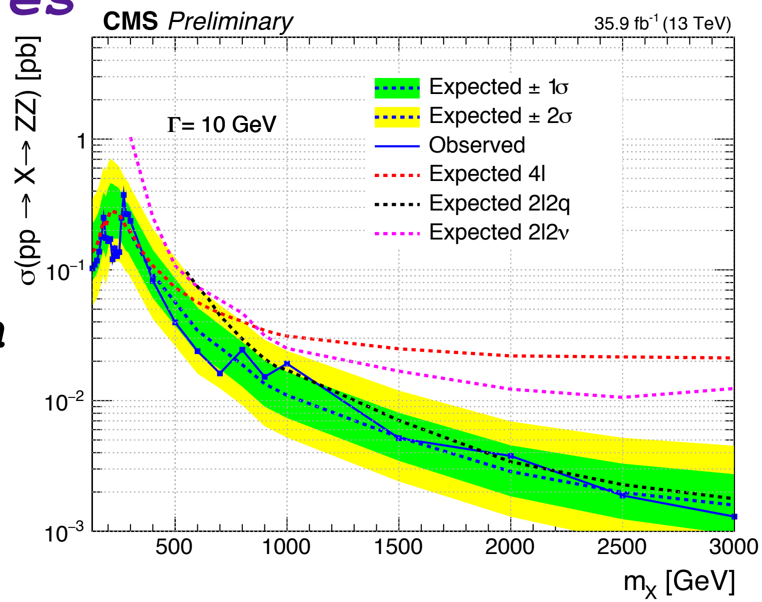

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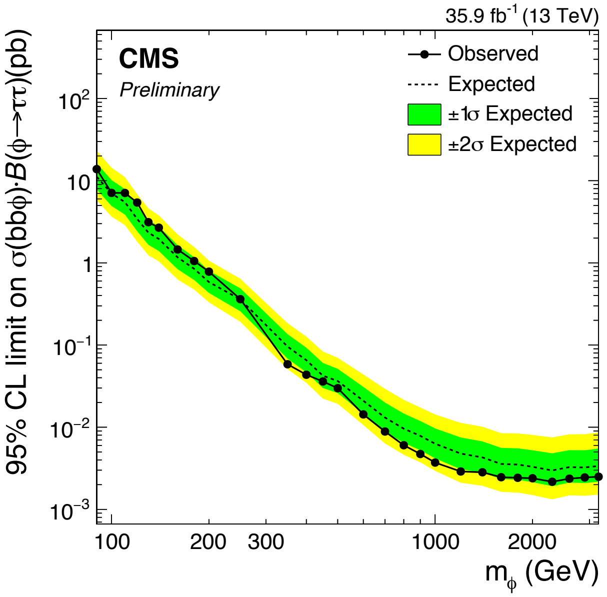

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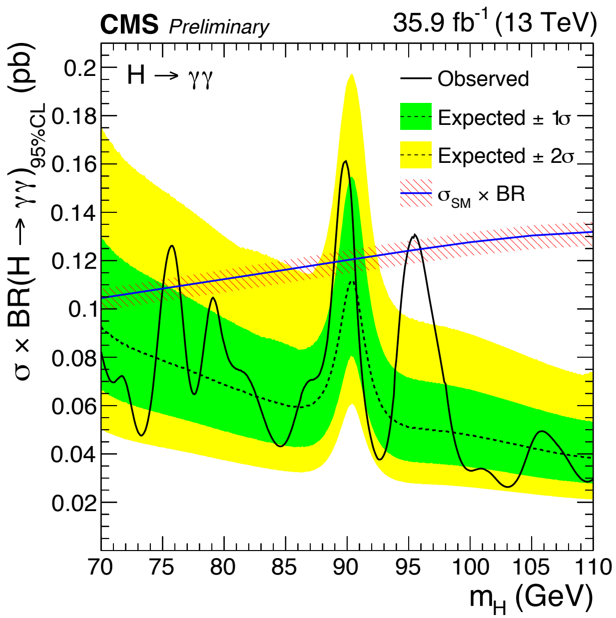
- *Masses O(10) GeV:*

Large SM Backgrounds - improve search strategies



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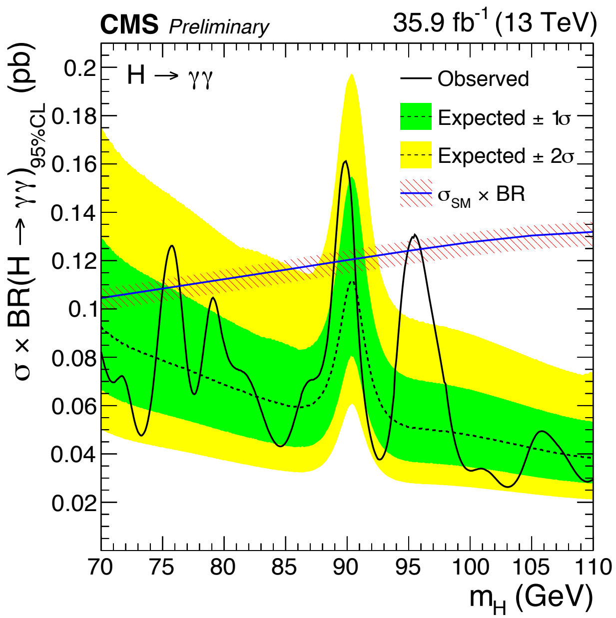

Also (in either case)

decay rates to SM particles may be suppressed

Exploit Higgs-Higgs and Higgs-gauge production

2HDM - SCALAR POTENTIAL

$$\mathcal{V}_{2\mathrm{HDM}} = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - [m_{12}^2\Phi_1^\dagger\Phi_2 + \text{ h.c.}]$$
$$+\tfrac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \tfrac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+\left\{\tfrac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \left[\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)\right]\Phi_1^\dagger\Phi_2 + \text{ h.c.}\right\}.$$

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

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

$$\Phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}\,(G^+\cos\beta - H^+\sin\beta) \\ v_1 - h\sin\alpha + H\cos\alpha + \mathrm{i}\,(G\cos\beta - A\sin\beta) \end{pmatrix}$$

$$\Phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}\,(G^+\sin\beta + H^+\cos\beta) \\ v_2 + h\cos\alpha + H\sin\alpha + \mathrm{i}\,(G\sin\beta + A\cos\beta) \end{pmatrix}$$

(α: mixing angle of neutral scalars, $\tan\beta = v_2/v_1$)

The Yukawa Lagrangian for the neutral scalars reads

$$-\mathcal{L}_Y = \overline{Q}_L\widetilde{\Phi}_1\eta_1^U U_R + \overline{Q}_L\Phi_1\eta_1^D D_R + \overline{Q}_L\Phi_1\eta_1^L L_R + \overline{Q}_L\widetilde{\Phi}_2\eta_2^U U_R + \overline{Q}_L\Phi_2\eta_2^D D_R + \overline{Q}_L\Phi_2\eta_2^L L_R$$

$$\Rightarrow\quad M^F = \frac{v}{\sqrt{2}}\left(\eta_1^F\cos\beta + \eta_2^F\sin\beta\right)$$

MINIMAL FLAVOUR VIOLATION

- *To prevent flavour-changing neutral currents, a Z_2 symmetry can be imposed (removes CP-violating $\lambda_{6,7}$)*
- *Z_2-charge assignment ➡ 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

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$\phi_1 \to -\phi_1$

Model	u_R^i	d_R^i	e_R^i
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$\xi_f^h = \cos\alpha/\sin\beta$

$\xi_f^H = \sin\alpha/\sin\beta$

$$\cos\alpha = \sin\beta\sin(\beta-\alpha) + \cos\beta\cos(\beta-\alpha)$$

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

A LIGHT SCALAR-PSEUDOSCALAR PAIR

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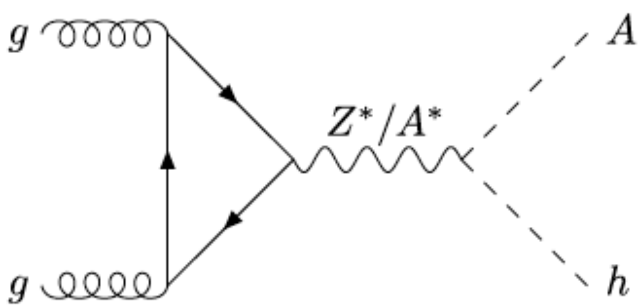
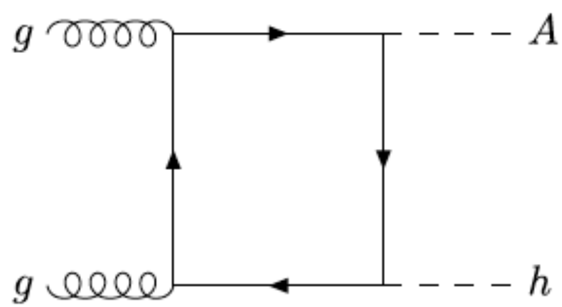
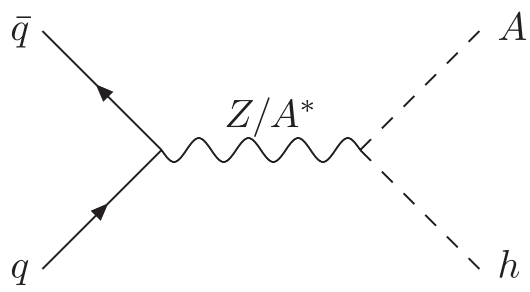
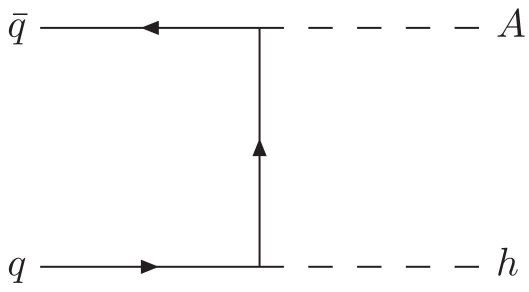
Landau-Yang theorem forbids the contribution of a resonant Z boson to the QCD production of a hA pair





but not to EW production: enhanced cross sections?





NUMERICAL ANALYSIS

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Numerically scanning of the parameter space (trading λ_{1-5} for the physical Higgs boson masses as input parameters), with the following constraints imposed:

m_H = 125 GeV

m_h (GeV)	$10 - 80$
m_A (GeV)	$10 - (M_Z - m_h)$
$m_{H^\pm}$ (GeV)	$90 - 500$
$\sin(\beta - \alpha)$	$-1 - 1$
m_{12}^2 (GeV^2)	$0 - m_A^2 \sin\beta\cos\beta$
$\tan\beta$	2, 25

Code: 2HDMC [D. Eriksson, J. Rathsman, O. Stal, 0902.0851]

- ***Unitarity, perturbativity and vacuum stability***
- ***Oblique parameters S, T and U***
- ***Flavour physics***

NUMERICAL ANALYSIS

SuperIso Manual [F. Mahmoudi, 0808.3144]

- ***Flavour physics***

$$
\begin{array}{rcl}
2.63 \leq & \mathrm{BR}(B \to X_s \gamma) \times 10^4 & \leq 4.23 \\
0.71 < & \mathrm{BR}(B_u \to \tau \nu_\tau) \times 10^4 & < 2.57 \\
1.3 < & \mathrm{BR}(B_s \to \mu^+ \mu^-) \times 10^9 & < 4.5 \\
-1.7 \times 10^{-2} < & \Delta_0(B \to K^* \gamma) & < 8.9 \times 10^{-2} \\
0.56 < & R_{\tau \nu_\tau} & < 2.70 \\
2.9 \times 10^{-3} < & \mathrm{BR}(B \to D^0 \tau \nu_\tau) & < 14.2 \times 10^{-3} \\
0.151 < & \xi_{D\ell\nu} & < 0.681 \\
 & \mathrm{BR}(B_d \to \mu^+ \mu^-) & < 1.1 \times 10^{-9} \\
0.6257 < & \dfrac{\mathrm{BR}(K \to \mu\nu)}{\mathrm{BR}(\pi \to \mu\nu)} & < 0.6459 \\
0.985 < & R_{\ell 23} & < 1.013 \\
4.7 \times 10^{-2} < & \mathrm{BR}(D_s \to \tau \nu_\tau) & < 6.1 \times 10^{-2} \\
4.9 \times 10^{-3} < & \mathrm{BR}(D_s \to \mu \nu_\mu) & < 6.7 \times 10^{-3} \\
3.0 \times 10^{-4} < & \mathrm{BR}(D \to \mu \nu_\mu) & < 4.6 \times 10^{-4} \\
-2.4 \times 10^{-10} < & \delta a_\mu & < 5.0 \times 10^{-9}
\end{array}
$$

NUMERICAL ANALYSIS

[F. Mahmoudi, O. Stal [0907.1791]]

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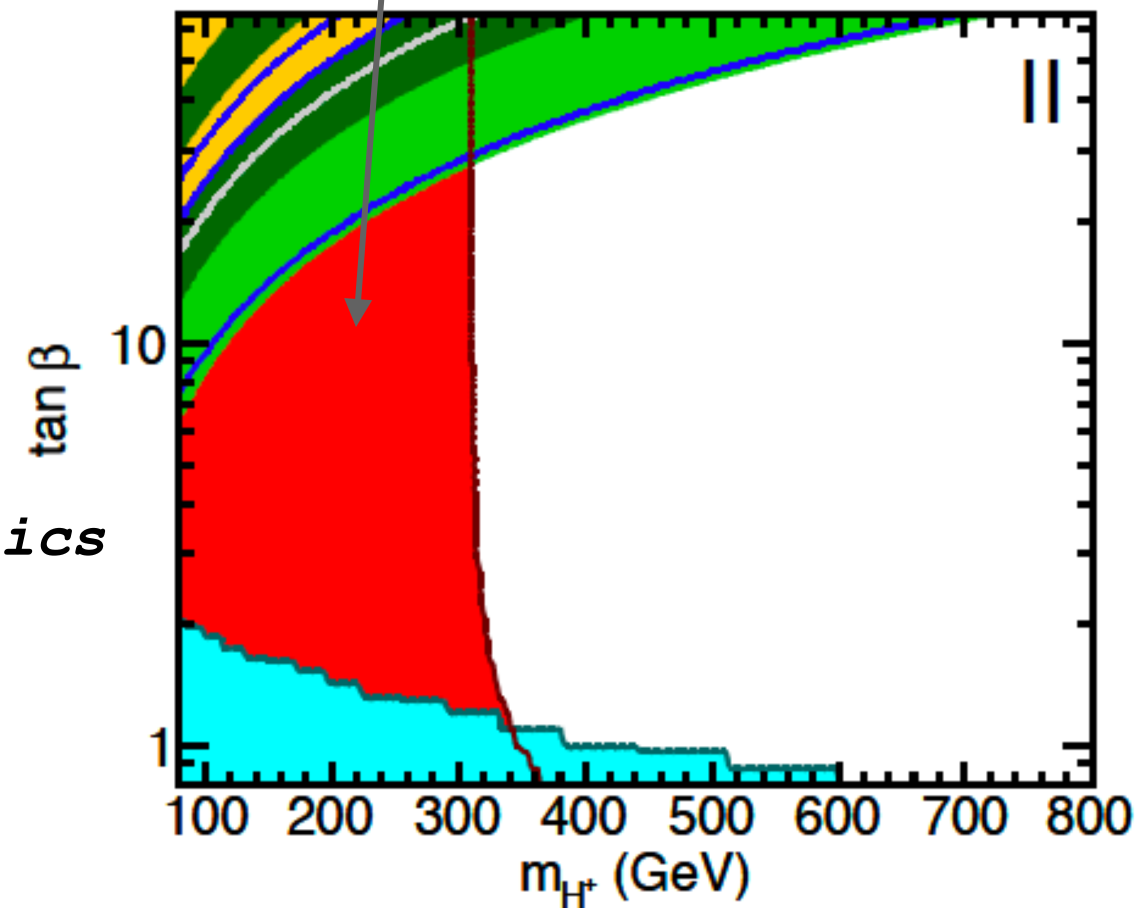


NUMERICAL ANALYSIS

[A. Arbey, F. Mahmoudi, O. Stal, T. Stefaniak, [1706.07414]

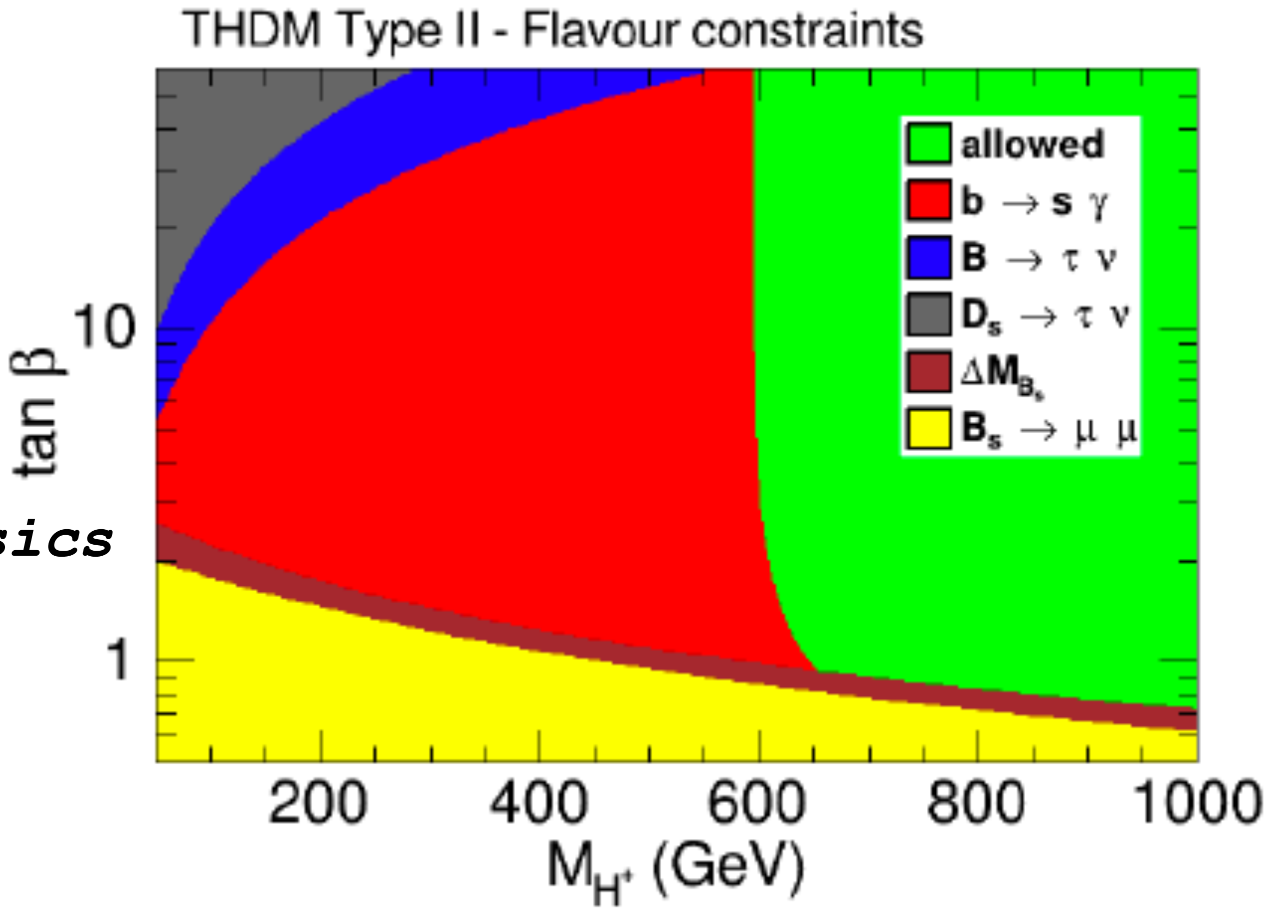
HFLAV Coll., 1612.07233]

$$3.32 - 0.15 \leq \quad \mathrm{BR}(B \to X_s\gamma) \times 10^4 \quad \leq 3.32 + 0.15$$

$$1.06 \pm 0.19 \leq \quad \mathrm{BR}(B_u \to \tau^\pm\nu_\tau) \times 10^4 \quad \leq 1.06 + 0.19$$

LHCb Coll., 1703.05747]

$$3.0 - 0.85 \leq \quad \mathrm{BR}(B_s \to \mu^+\mu^-) \times 10^9 \quad \leq 3.0 + 0.85$$



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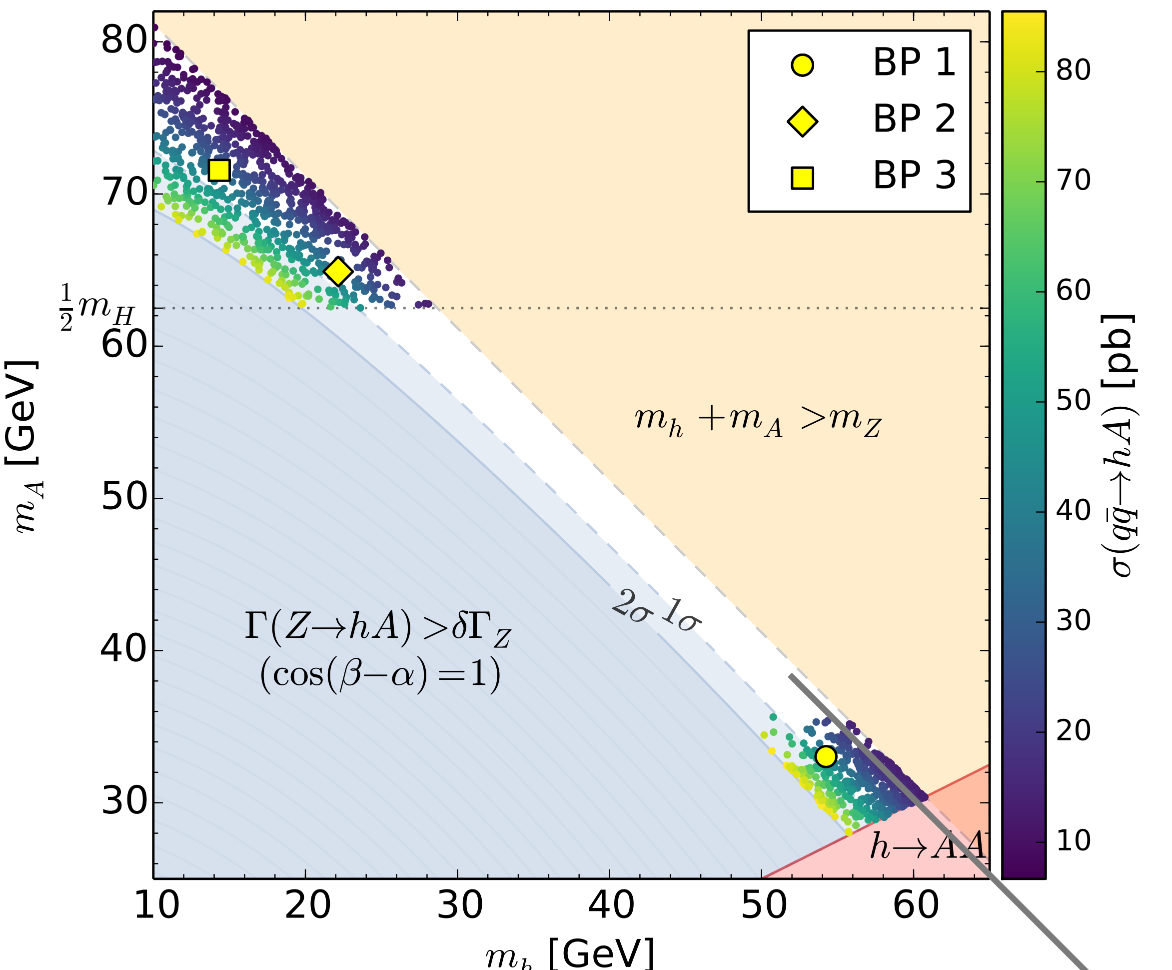
(Code: 2HDMC [D. Eriksson, J. Rathsman, O. Stal, 0902.0851])

- *Unitarity, perturbativity and vacuum stability*
- *Oblique parameters S, T and U*
- *Flavour physics*
- *LEP, TeVatron and LHC results for*
  - *Additional Higgs bosons (HiggsBounds)*
  - *Measured Higgs signal strengths (HiggsSignals)*

$m_h + m_A < m_Z$ IN TYPE-I 2HDM



m_h (GeV)	$10 - 2M_Z/3$
m_A (GeV)	$m_h/2 - (M_Z - m_h)$
$m_{H^\pm}$ (GeV)	$90 - 150$
$\sin(\beta - \alpha)$	$-0.25 - 0$
m_{12}^2 (GeV^2)	$0 - m_A^2 \sin\beta\cos\beta)$
$\tan\beta$	$(-0.95 - -1.1)/\sin(\beta - \alpha)$

$\Gamma_Z = 2.4952 \pm 0.0023$ GeV

[R. Enberg, W. Klemm, S. Moretti, SM, 1605.02498]

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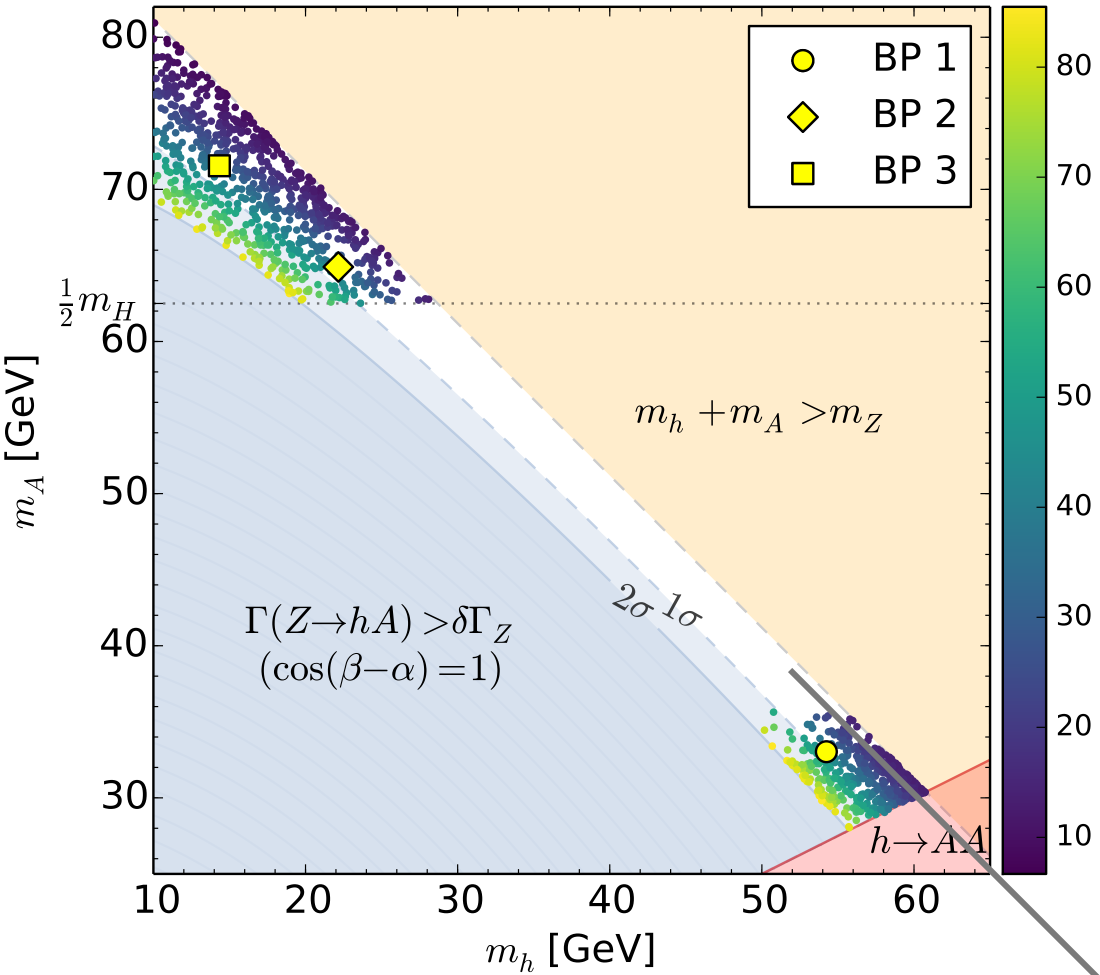

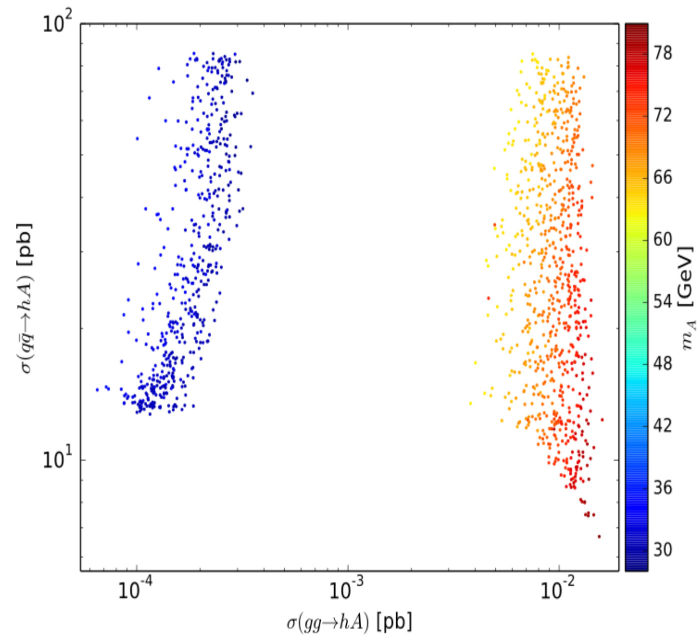

EW production cross section up to four orders of magnitude larger!

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DOMINANT SEARCH CHANNELS

KOREA INSTITUTE FOR ADVANCED STUDY (KIAS)

	[GeV]				[GeV²]		[pb]	
BP	m_h	m_A	$m_{H^\pm}$	$\sin(\beta-\alpha)$	m_{12}^2	$\tan\beta$	$\sigma(q\bar{q})$	$\sigma(gg)$
1	54.2	33.0	95.9	-0.12	118.3	9.1	41.2	1.5×10^{-4}
2	22.2	64.9	101.5	-0.05	10.6	22.1	34.4	7.2×10^{-3}
3	14.3	71.6	107.2	-0.06	2.9	16.3	31.6	1.1×10^{-2}

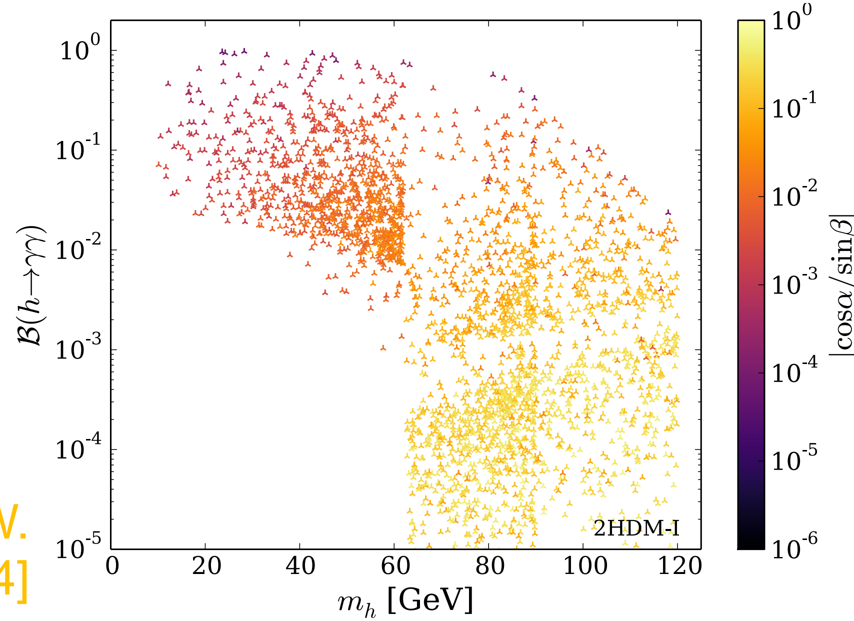
	BR($h\to\ldots$) [%]				BR($A\to\ldots$) [%]		
BP	Z^*A	$b\bar{b}$	$\gamma\gamma$	$\tau\tau$	Z^*h	$b\bar{b}$	$\tau\tau$
1	**94**	5	<1	<1	0	**86**	7
2	0	**83**	3	7	**86**	12	1
3	0	**60**	**24**	7	**90**	8	1

$\sin(\beta-\alpha)\to0$ ➡ "Alignment limit" ➡ maximal hAZ coupling;

nearly fermiophobic h

"For $m_A>m_h$, $Z^*\gamma\gamma\gamma\gamma$ could be an important signature"

[A. Arhrib, R. Benbrik, R. Enberg, W. Klemm, S. Moretti, SM, 1706.01964]



LIGHT FERMIOPHOBIC HIGGS BOSON

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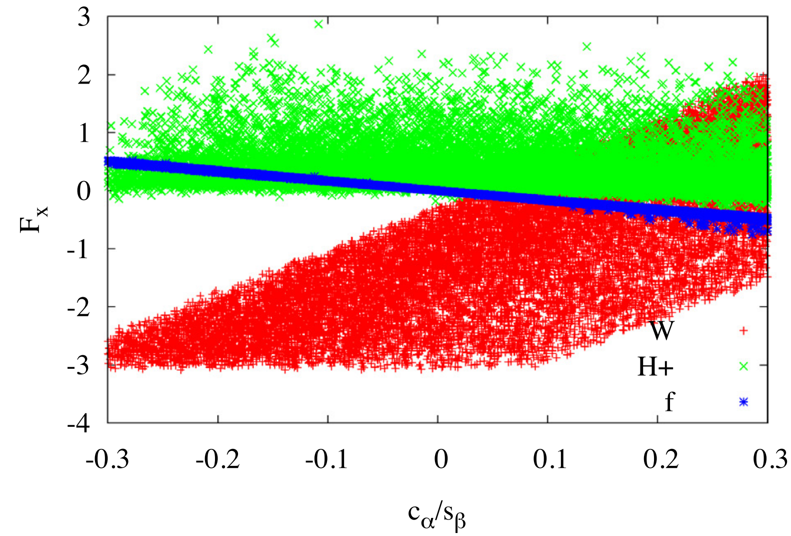
$$F_f = \sum_i \frac{-2}{\tau_f^2} N_f Q_f^2 \xi_f^h (\tau_f + (\tau_f - 1) I(\tau_f)),$$

$$F_{H^\pm} = \frac{g_{hH^\pm H^\mp}}{\tau_{H^\pm}^2} \frac{m_W^2}{m_{H^\pm}^2} (\tau_{H^\pm} - I(\tau_{H^\pm})),$$

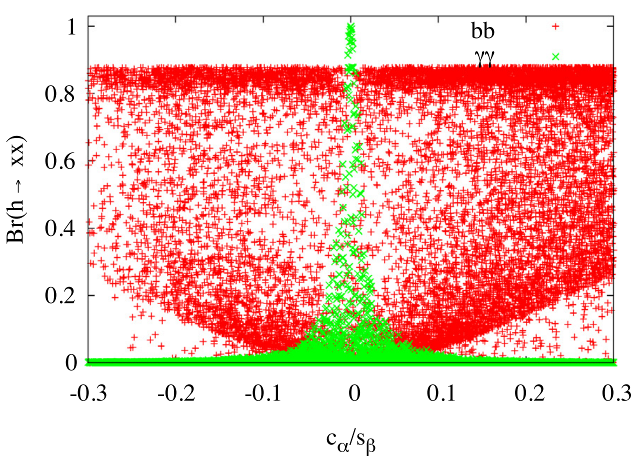
$$F_W = \frac{\sin(\beta-\alpha)}{\tau_W^2} (2\tau_W^2 + 3\tau_W + 3(2\tau_W - 1) I(\tau_W))$$

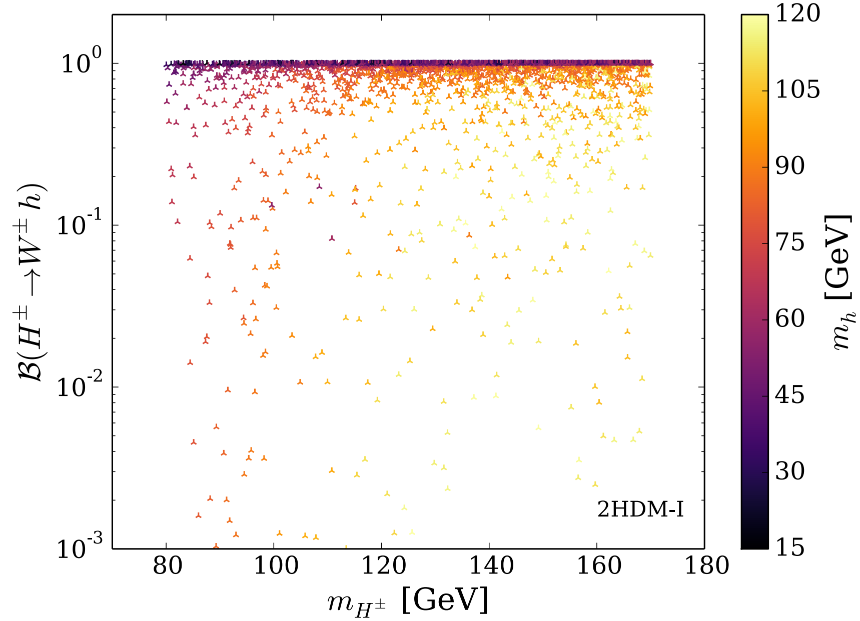


$\sin(\beta-\alpha) \to 0$

➡ "Alignment limit" ➡ maximal hAZ and hH⁺W⁻ couplings

$$\cos\alpha = \sin\beta \sin(\beta-\alpha) + \cos\beta \cos(\beta-\alpha)$$





DISCOVERY POTENTIAL

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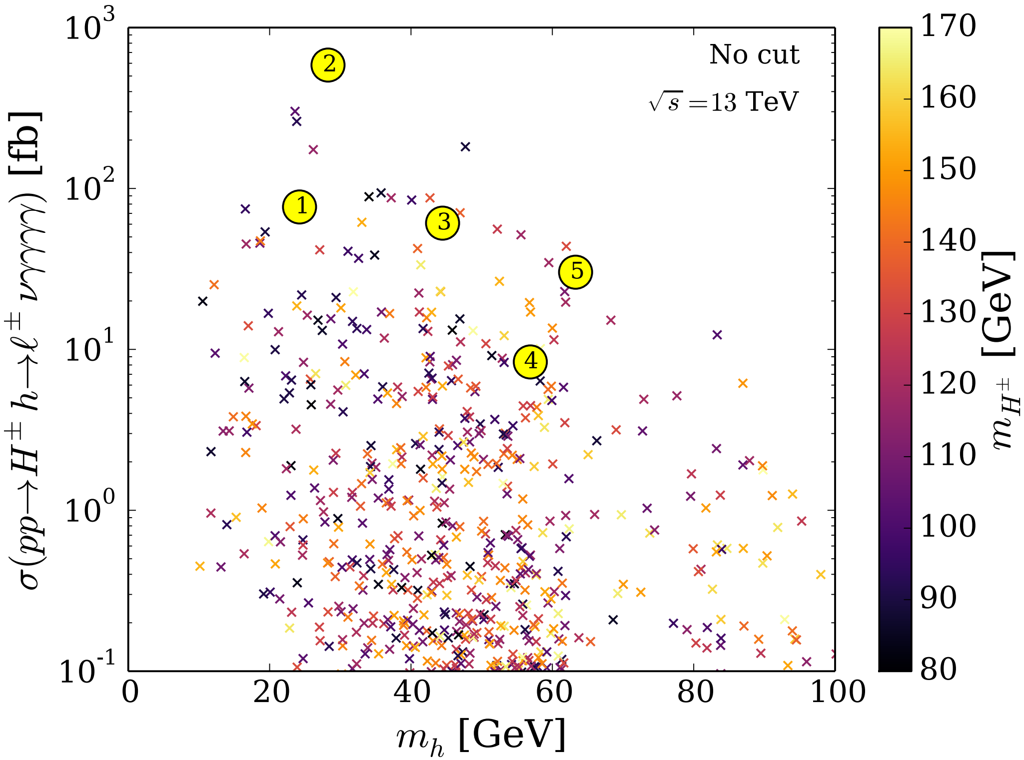
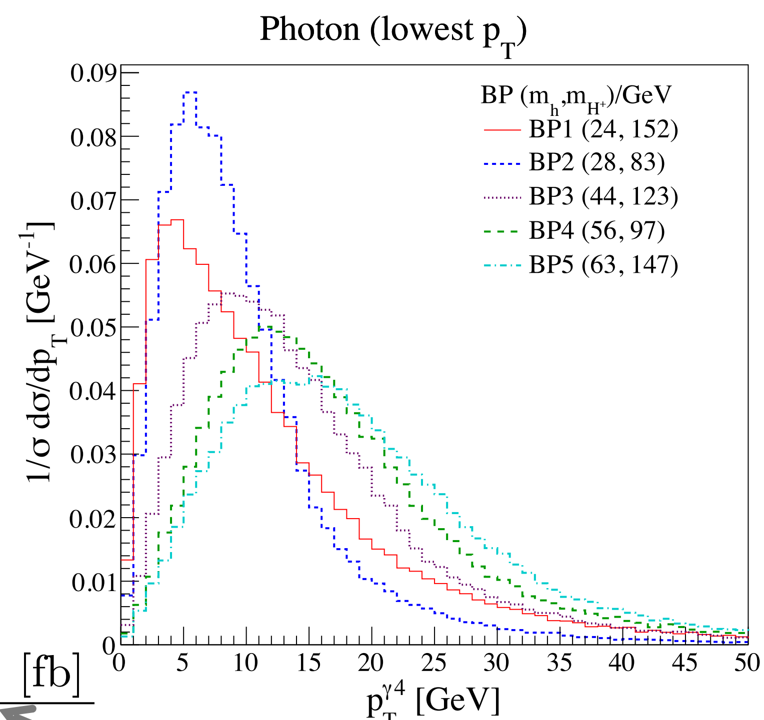
MadGraph5_aMC@NLO

$q = u, d, s, c, b$

$$\sigma(qq' \to H^+h) \times BR(H^\pm \to W^\pm h) \times BR(h \to \gamma\gamma)^2 \times BR(W^\pm \to \ell^\pm \nu)$$



[A. Arrhib, R. Benbrik, R. Enberg, W. Klemm, S. Moretti, SM, 1706.01964]



BP	m_h	m_{H+}	m_A	$\sin_{\beta-\alpha}$	m_{12}^2	$\tan\beta$	$\sigma(W+4\gamma)$ [fb]
1	24.2	152.2	111.1	-0.048	19.0	20.9	359
2	28.3	83.7	109.1	-0.050	31.3	20.2	2740
3	44.5	123.1	119.9	-0.090	30.8	10.9	285
4	56.9	97.0	120.3	-0.174	243.9	5.9	39
5	63.3	148.0	129.2	-0.049	173.1	20.7	141

Vanishing background

DISCOVERY POTENTIAL

$q = u, d, s, c, b$

$$\sigma(qq' \to H^+h) \times BR(H^\pm \to W^\pm h) \times BR(h \to \gamma\gamma)^2 \times BR(W^\pm \to \ell^\pm \nu)$$

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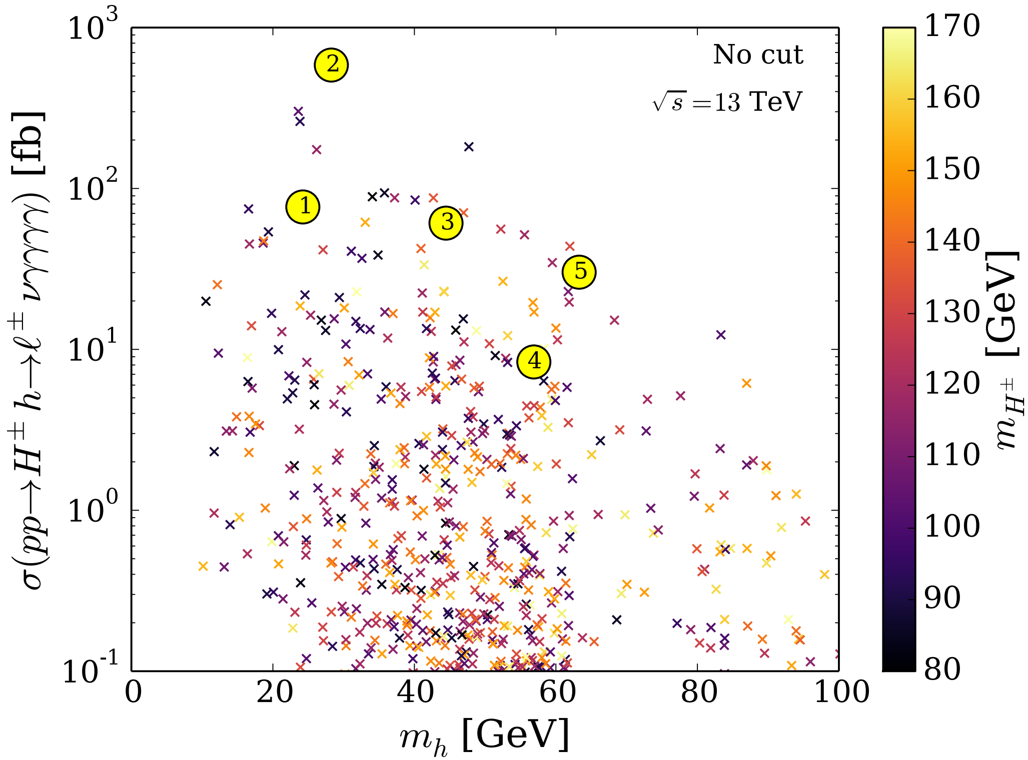

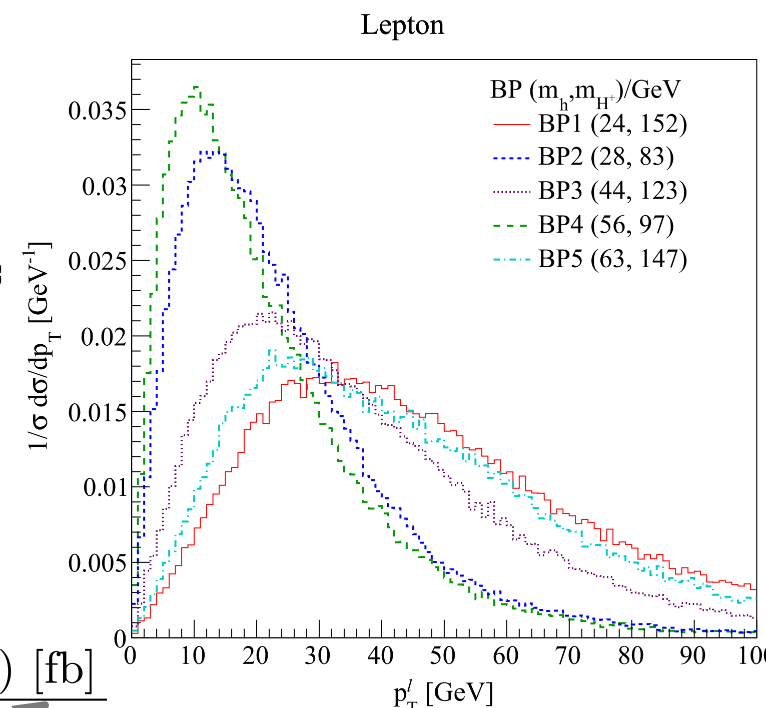

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Vanishing background

CUT EFFICIENCIES

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

$m_{H^+} \backslash m_h$	20	30	40	50	60	70	80	90	100
80	<0.01	0.03	0.05	0.06	0.07	0.03			
90	0.01	0.03	0.06	0.08	0.09	0.09	0.04		
100	<0.01	0.04	0.07	0.10	0.11	0.12	0.11	0.05	
110	<0.01	0.03	0.07	0.11	0.13	0.16	0.17	0.15	0.05
120	<0.01	0.03	0.07	0.12	0.17	0.19	0.21	0.20	0.14
130	0.02	0.04	0.07	0.12	0.16	0.21	0.24	0.25	0.22
140	0.02	0.05	0.08	0.12	0.17	0.23	0.24	0.29	0.26
150	0.03	0.06	0.10	0.15	0.18	0.25	0.27	0.29	0.30
160	0.03	0.08	0.11	0.15	0.19	0.23	0.28	0.29	0.34

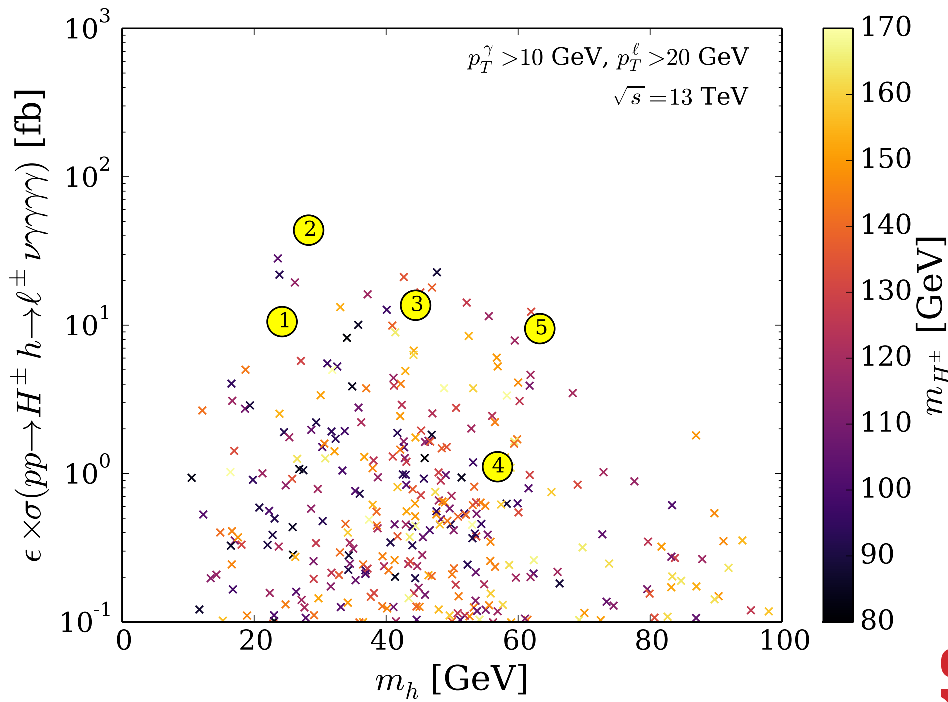
$$\sqrt{s} = 13 \text{ TeV}$$

$$|\eta| < 2.5$$

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.4$$

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

$m_{H^+} \backslash m_h$	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



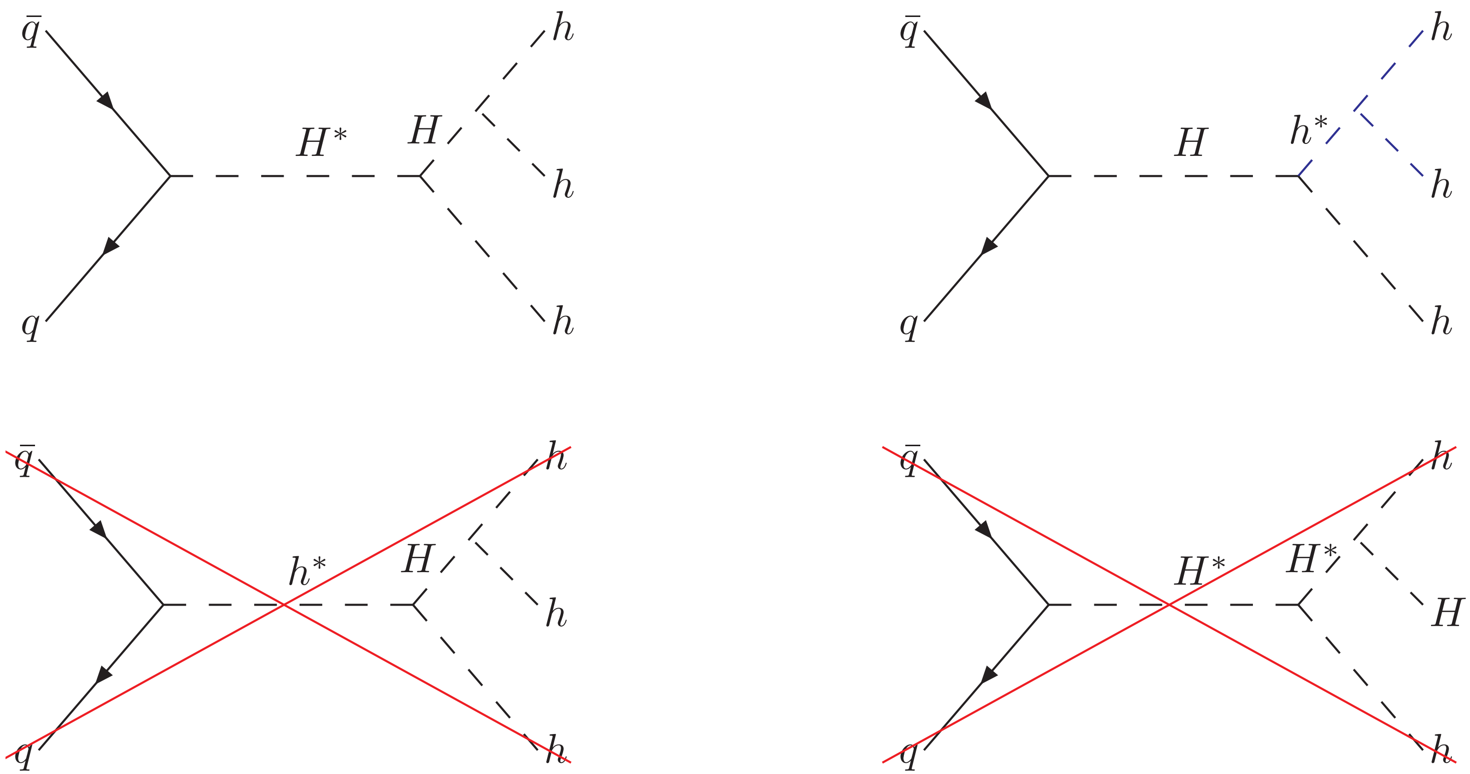
Cross section can still reach a few tens of fb

[A. Arhrib, R. Benbrik, R. Enberg, W. Klemm, S. Moretti, SM, 1706.01964]

MULTI-HIGGS (EW) PRODUCTION

Electroweak production of all possible 2-body and 3-body Higgs-Higgs/gauge states in the Type-I 2HDM

- ***Can it dominate over QCD production?***
- ***Which Higgs-Higgs and Higgs-gauge couplings can be potentially probed at the LHC?***



2-BODY FINAL STATES

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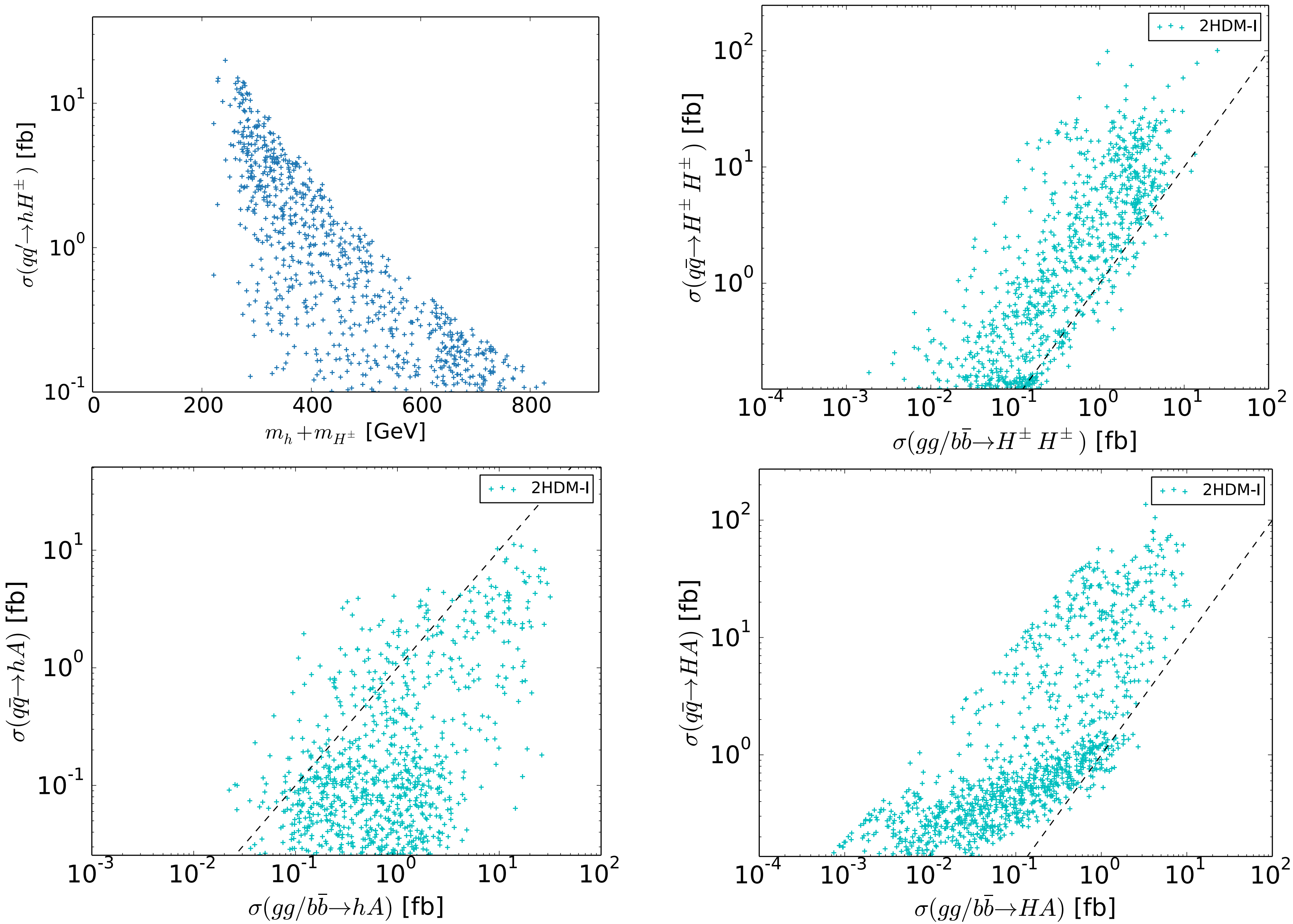
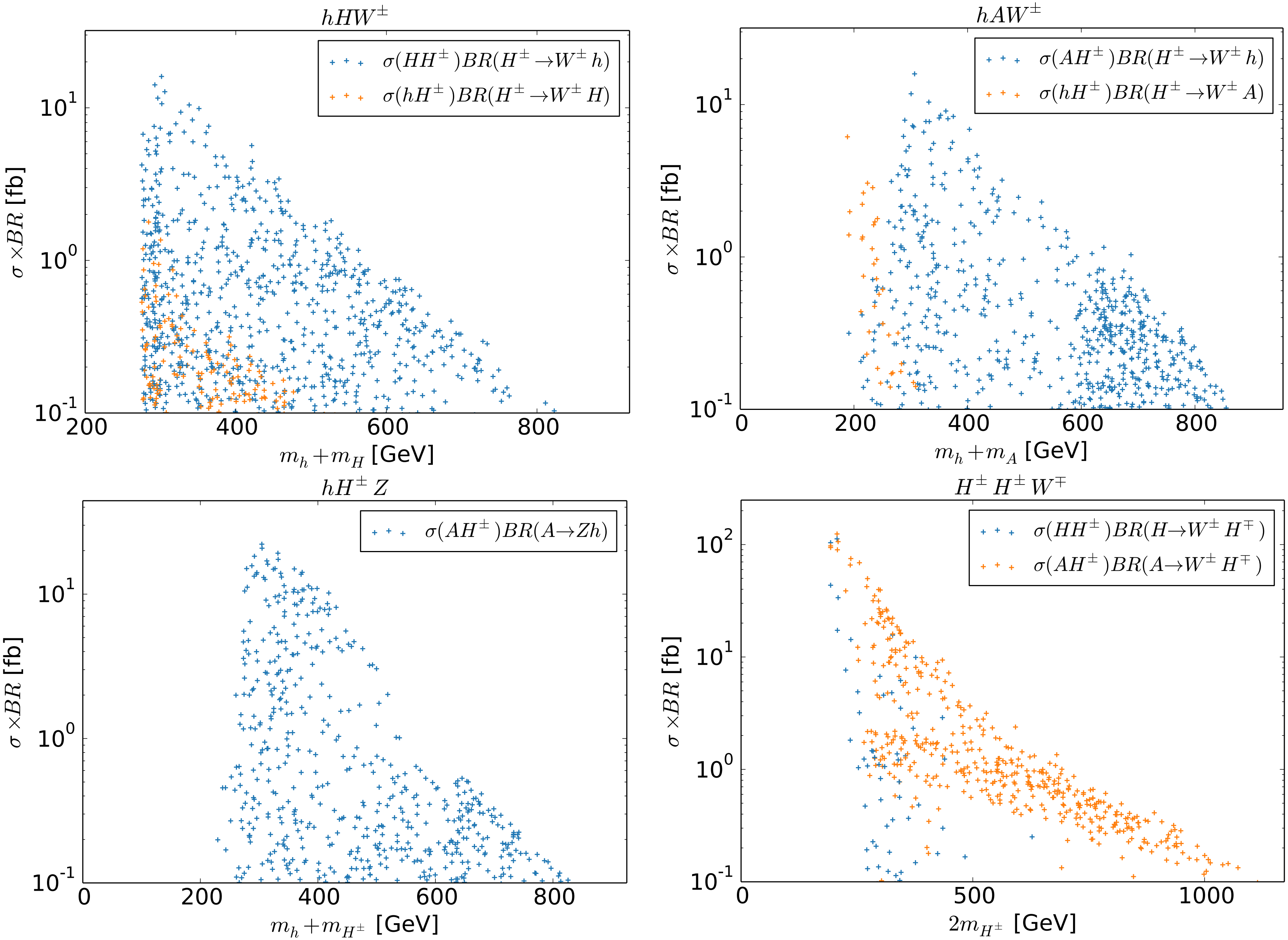
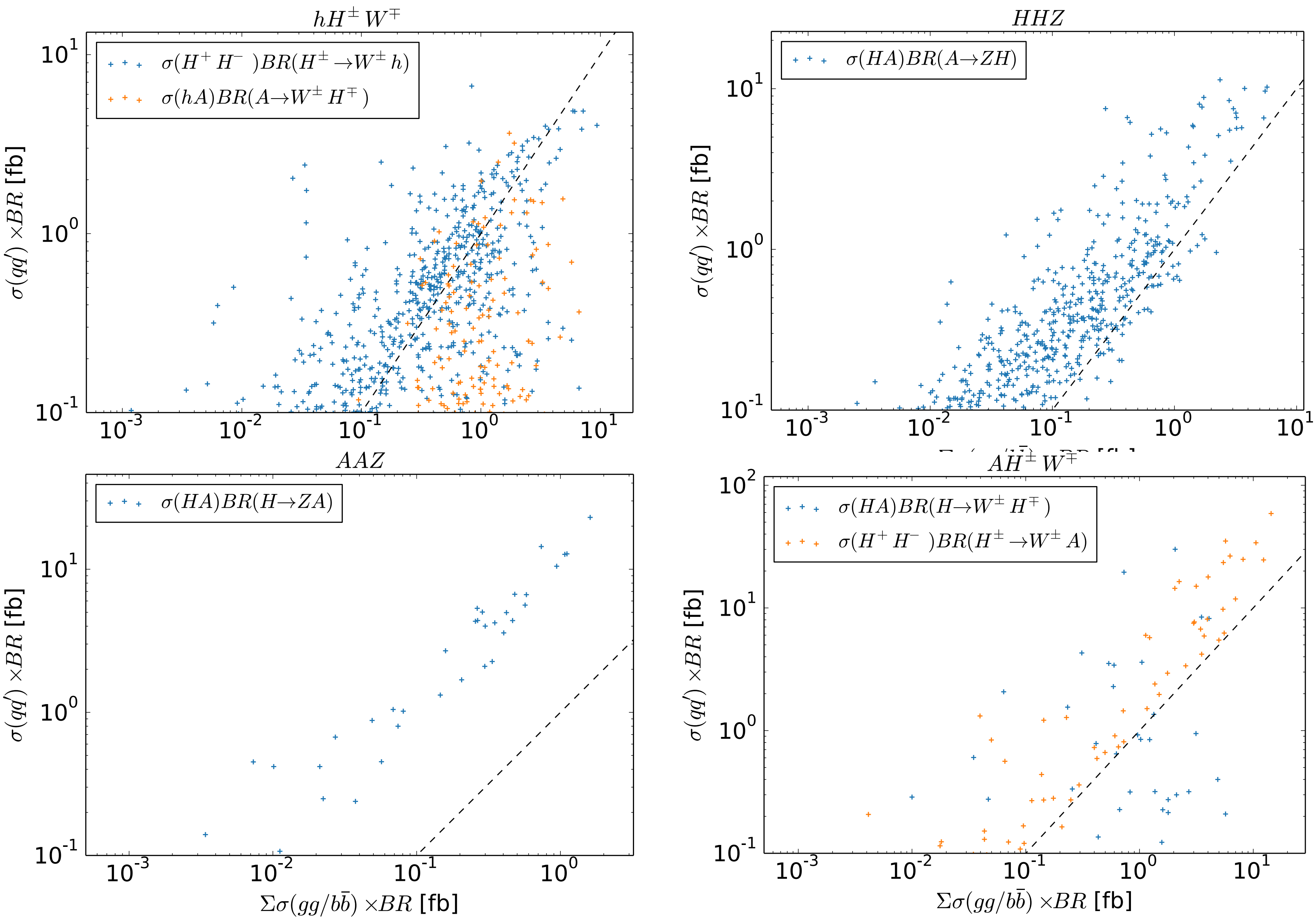


3-BODY FINAL STATES



3-BODY FINAL STATES - COMPARISON



HIGGS TRIPLE-COUPLINGS

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2BFS \ Coupling	a. hhh	b. hhH	c. hHH	d. hAA	e. hH^+H^-	f. HHH	g. HAA	h. HH^+H^-
1. hh	✓ (hhh)	✓		(hAA)	(hH^+H^-)			
2. HH		(hhH)	✓ (hHH)			✓ (HHH)	(HAA)	(HH^+H^-)
3. AA				✓ (hAA)			✓ (HAA)	
4. H^+H^-				(hH^+H^-)	✓ (hH^+H^-)			✓ (HH^+H^-)
5. hH	(hhH)	✓ (hhh)	✓ (hhH) (hH^+H^-)	(HAA)	(HH^+H^-)	(hHH)	(hAA)	
6. hA	(hhA)			✓ (hhA) (AAA)	(AH^+H^-)		(hHA)	
7. $hH^\pm$	$(hhH^\pm)$			$(AAH^\pm)$	✓ $(hhH^\pm)$ $(H^+H^-H^\pm)$			$(hHH^\pm)$
8. HA		(hhA)	(hHA)	(hHA)		(HHA)	✓ (HHA) (AAA)	(AH^+H^-)
9. $HH^\pm$		$(hhH^\pm)$	$(hHH^\pm)$		$(hHH^\pm)$	$(HHH^\pm)$	$(AAH^\pm)$	✓ $(HHH^\pm)$ $(H^+H^-H^\pm)$
10. $AH^\pm$					$(hAH^\pm)$		$(HAH^\pm)$	$(HAH^\pm)$
11. hZ	(hhZ)			(AAZ)	(H^+H^-Z)			
12. $hW^\pm$	$(hhW^\pm)$			$(AAW^\pm)$	$(H^+H^-W^\pm)$			
13. HZ		(hhZ)	(hHZ)			(HHZ)	(AAZ)	(H^+H^-Z)
14. $HW^\pm$		$(hhW^\pm)$	$(hHW^\pm)$			$(HHW^\pm)$	$(AAW^\pm)$	$(H^+H^-W^\pm)$
15. AZ				(hAZ)			(HAZ)	
16. $AW^\pm$				$(hAW^\pm)$			$(HAW^\pm)$	
17. $H^\pm Z$								
18. H^+W^-					(hH^+W^-)			

[R. Enberg, W. Klemm, S. Moretti, SM, 1809.XXXXX]

HIGGS-GAUGE COUPLINGS

2BFS \ Coupling	m. hAZ	n. HAZ	o. H^+H^-Z	p. hH^+W^-	q. HH^+W^-	r. AH^+W^-	s. hZZ	t. HZZ	u. hW^+W^-	v. HW^+W^-
1. hh	(hAZ)			(hH^+W^-)			(hZZ)		(hW^+W^-)	
2. HH		(HAZ)			(HH^+W^-)			(HZZ)		(HW^+W^-)
3. AA	(hAZ)	(HAZ)				(AH^+W^-)				
4. H^+H^-			✓ (H^+H^-Z)	$(\boxed{hH^+W^-})$	(HH^+W^-)	$(\boxed{AH^+W^-})$				
5. hH	(HAZ)	(hAZ)		(HH^+W^-)	(hH^+W^-)		(HZZ)	(hZZ)	(HW^+W^-)	(hW^+W^-)
6. hA	✓ (hhZ) (AAZ)	(hHZ)		(hH^+W^-) (AH^+W^-)			(AZZ)		(AW^+W^-)	
7. $hH^\pm$	$(AH^\pm Z)$			✓ $(hhW^\pm)$ $(H^+H^-W^\pm)$	$(\boxed{hHW^\pm})$	$(\boxed{hAW^\pm})$	$(H^\pm ZZ)$		$(H^\pm W^+W^-)$	
8. HA	(hHZ)	✓ $(\boxed{HHZ})$ $(\boxed{AAZ})$			(HH^+W^-) $(\boxed{AH^+W^-})$			(AZZ)		(AW^+W^-)
9. $HH^\pm$		$(AH^\pm Z)$		$(\boxed{hHW^\pm})$	✓ $(HHW^\pm)$ $(\boxed{H^+H^-W^\pm})$	$(HAW^\pm)$		$(H^\pm ZZ)$		$(H^\pm W^+W^-)$
10. $AH^\pm$	$(\boxed{hH^\pm Z})$	$(HH^\pm Z)$		$(\boxed{hAW^\pm})$	$(HAW^\pm)$	✓ $(AAW^\pm)$ $(\boxed{H^+H^-W^\pm})$				
11. hZ	✓ (hhA) (AZZ)	(hHA)		(H^+ZW^-)			✓ (hhZ)	(hHZ)		
12. $hW^\pm$				✓ $(hhH^\pm)$ $(hHH^\pm)$ $(H^\pm W^+W^-)$		$(hAH^\pm)$			✓ $(hhW^\pm)$	$(hHW^\pm)$
13. HZ	(hHA)	✓ (HHA) (AZZ)			(H^+ZW^-)			✓ (HHZ)		
14. $HW^\pm$				$(hHH^\pm)$	✓ $(HHH^\pm)$ $(H^\pm W^+W^-)$	$(HAH^\pm)$			$(hHW^\pm)$	✓ $(HHW^\pm)$
15. AZ	✓ (hAA) (hZZ)	✓ (HAA) (HZZ)				(H^+ZW^-)	(hAZ)	(HAZ)		
16. $AW^\pm$				$(hAH^\pm)$	$(HAH^\pm)$	✓ $(H^\pm W^+W^-)$			$(hAW^\pm)$	$(HAW^\pm)$
17. $H^\pm Z$	$(hAH^\pm)$	$(HAH^\pm)$	✓				$(hH^\pm Z)$	$(HH^\pm Z$		
18. H^+W^-				✓ (hH^+H^-) (hW^+W^-)	✓ (HH^+H^-) (HW^+W^-)	✓ (AH^+H^-) (AW^+W^-)			(hH^+W^-)	(HH^+W^-)

[R. Enberg, W. Klemm, S. Moretti, SM, 1809.XXXXX]

CONCLUSIONS

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- *Additional Higgs bosons are predicted in most new physics frameworks - can be lighter or heavier than 125 GeV*
- *Even when light, they are difficult to detect at the LHC in the conventional channels, owing to generally reduced couplings to the SM*
- *Their pair-production can provide crucial probes*
- *In the Type-I 2HDM, a light scalar-pseudoscalar pair as well as a light $H^{\pm}$ could be accessible in multi-photon final states*
- *EW pair-production - essential when a charged Higgs boson is involved - can dominate over QCD even for certain neutral Higgs boson combinations*

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