Multi-Higgs production at the LHC in the Type-I 2HDM

Shoaib Munir

KIAS, Seoul & ICTP-EAIFR, Kigali

Workshop on Higgs as a Probe of New Physics, Osaka

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- *Type-I 2HDM at the LHC*
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  - *The $h = h_{125}$ scenario: Electroweak vs. QCD pair-production*
- *Conclusions*

Additional Higgs Bosons

KOREA INSTITUTE FOR ADVANCED STUDY

Predicted in a minimalistic new physics contender like the 2HDM as well as in extended frameworks like Supersymmetry and GUTs

Could be the earliest signatures of new physics at the LHC

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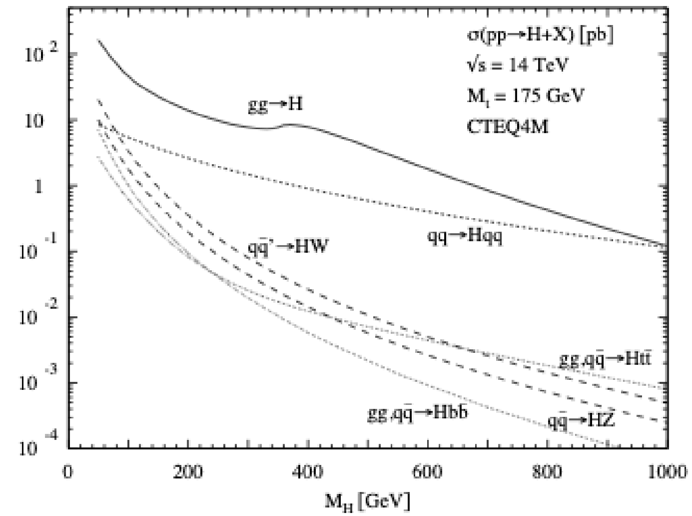
But

- ***Masses O(100) GeV:***

Small production cross section

- improve statistics



[A. Djouadi, hep-ph/0503173]

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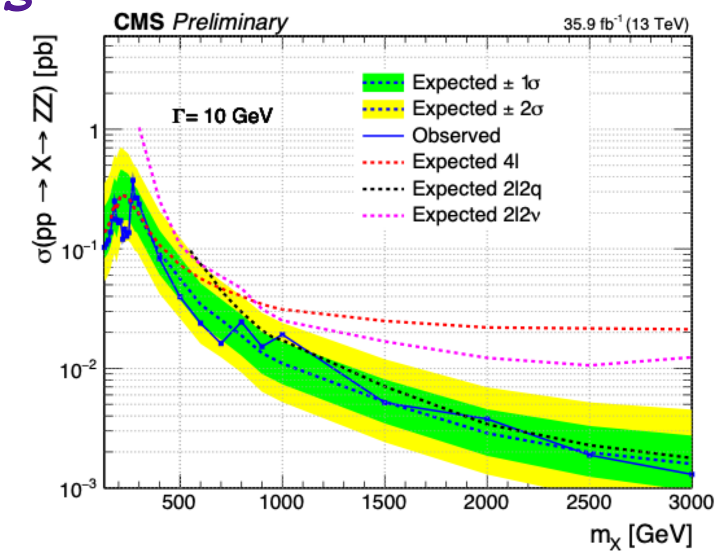

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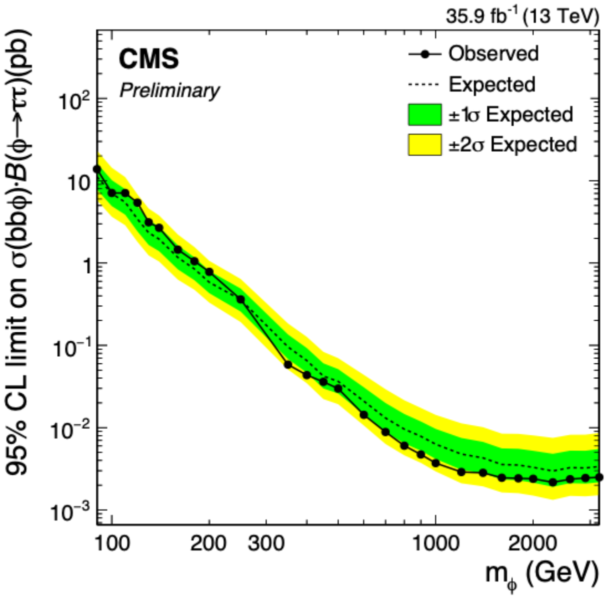

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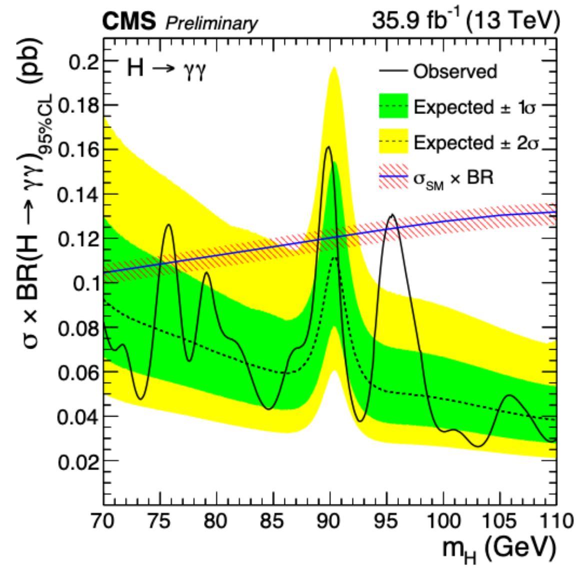
- *Masses O(10) GeV:*

Large SM Backgrounds - improve search strategies



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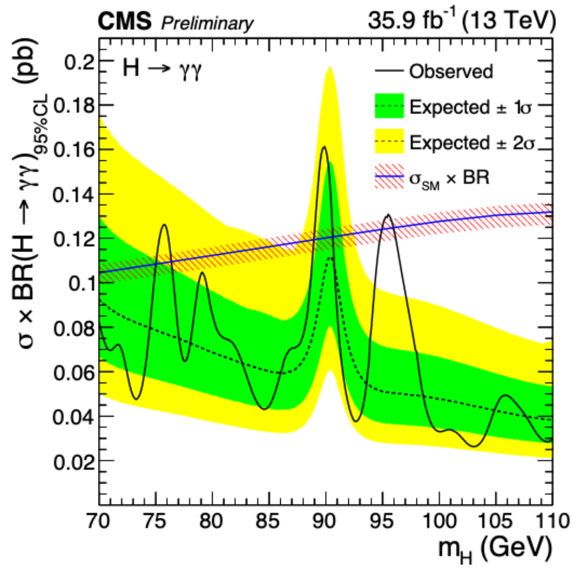

Also (in either case)

decay rates to SM particles may be suppressed

Exploit Higgs-Higgs and Higgs-gauge production

2HDM – Scalar Potential

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

After EW symmetry breaking: $\Phi_i = \begin{pmatrix} \phi_i^+ \\ (v_i + \phi_i^0 + i\omega_i^0)/\sqrt{2} \end{pmatrix}$

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

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

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

- ***Three neutral Higgs bosons (h, H, A), a $H^\pm$ pair***
- ***λ_{1-5} (CP-conserving limit: $\lambda_{6,7}=0$) can be traded for Higgs boson masses using tadpole conditions***

Minimal Flavour Violation

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

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

- ***To prevent flavour-changing neutral currents, a Z_2 symmetry can be imposed***
- ***Z_2-charge assignments ⇒ four Types of 2HDM***

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

Minimal Flavour Violation

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

$$\xi_f^h = \cos\alpha / \sin\beta$$

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

Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
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Lepton-specific	Φ_2	Φ_2	Φ_1
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$$\phi_1 \to -\phi_1$$

Numerical Analysis

Numerically scan the parameter space using the 2HDMC code [D. Eriksson, J. Rathsman, O. Stal, 0902.0851] ***, requiring consistency of each point with***

- ✓ ***Unitarity, perturbativity and vacuum stability***
- ✓ ***Measurements of oblique parameters S, T and U***
- ✓ ***Constraints from flavour physics***

Numerical Analysis

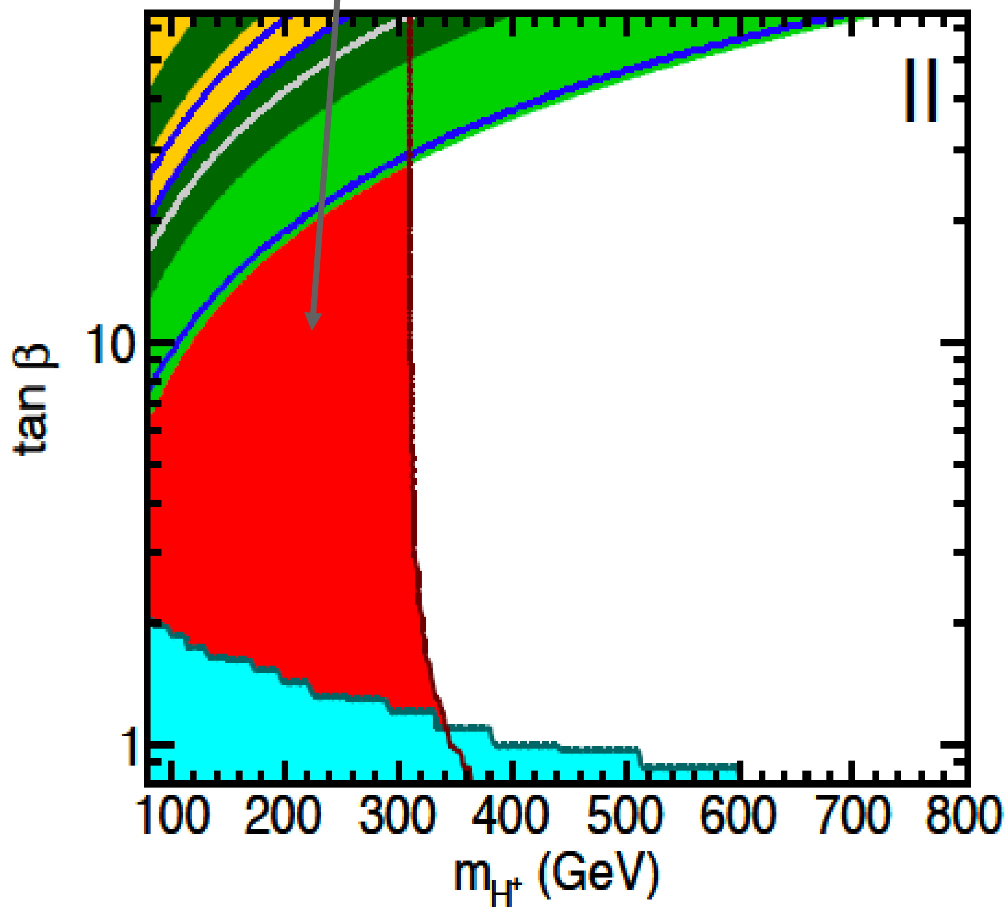
[F. Mahmoudi, O. Stal [0907.1791]]

$$2.63 \leq \mathrm{BR}(B \to X_s \gamma) \times 10^4 \leq 4.23$$

$$0.71 < \mathrm{BR}(B_u \to \tau \nu_\tau) \times 10^4 < 2.57$$

$$1.3 < \mathrm{BR}(B_s \to \mu^+ \mu^-) \times 10^9 < 4.5$$

- ✓ ***Constraints from flavour physics***



Numerical Analysis

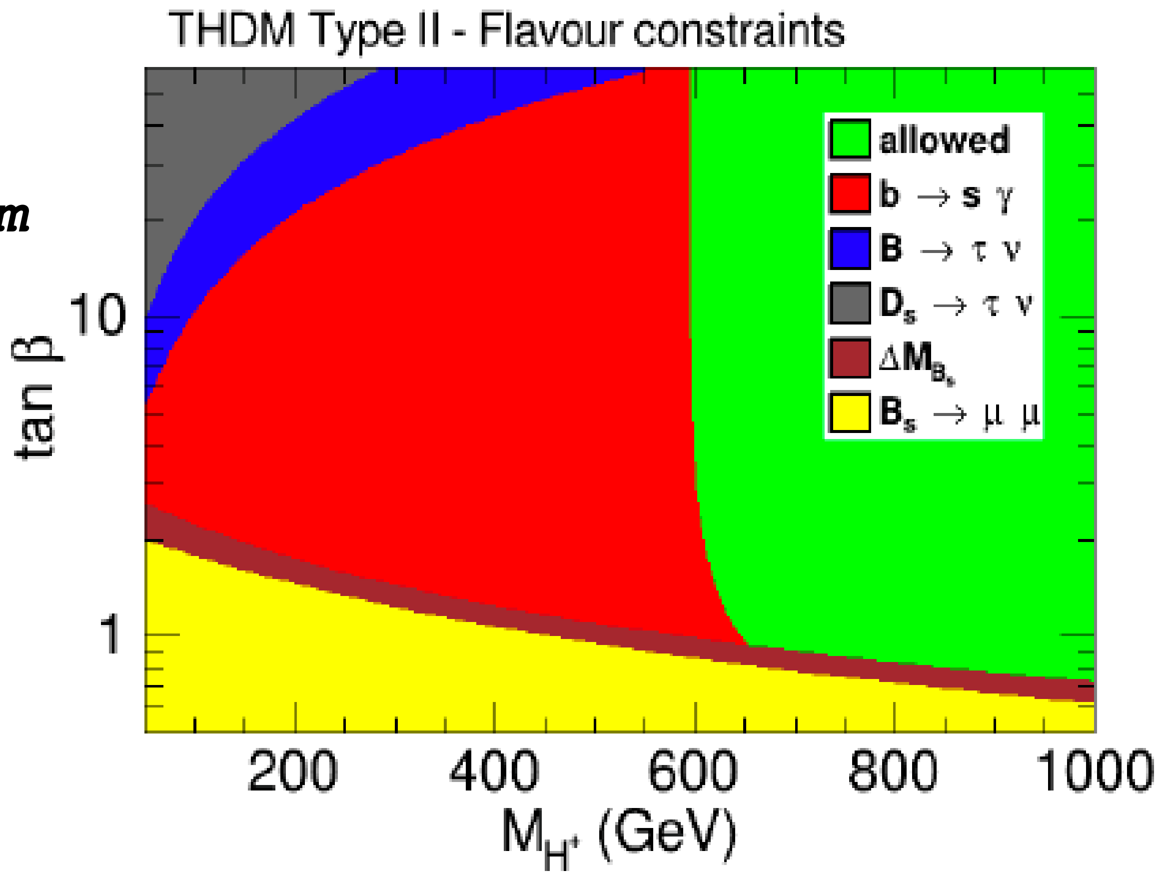
[A. Arbey, F. Mahmoudi, O. Stal, T. Stefaniak, [1706.07414]

HFLAV Coll., 1612.07233]

LHCb Coll., 1703.05747]

$$3.17 \leq \mathrm{BR}(B \to X_s\gamma) \times 10^4 \leq 3.47$$
$$0.87 \leq \mathrm{BR}(B_u \to \tau\nu_\tau) \times 10^4 \leq 1.25$$
$$2.15 \leq \mathrm{BR}(B_s \to \mu^+\mu^-) \times 10^9 \leq 3.85$$

- ✓ ***Constraints from flavour physics***



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- ✓ ***Limits from additional Higgs searches(HiggsBounds)***

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Parameters with fixed ranges across all scenarios:

$$\sin(\beta-\alpha) = -1-1\,;\;\; m_{12}^2 = 0 - m_A^2 \sin\beta\cos\beta\,;\;\; \tan\beta = 2-25$$

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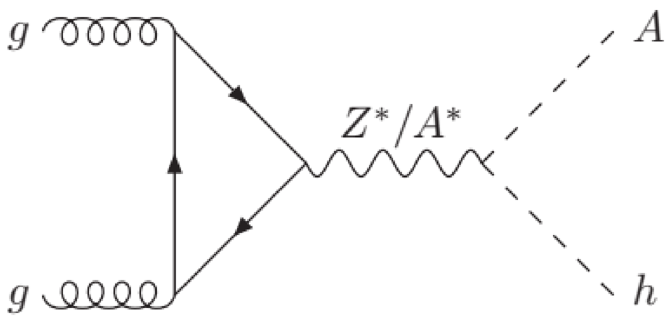
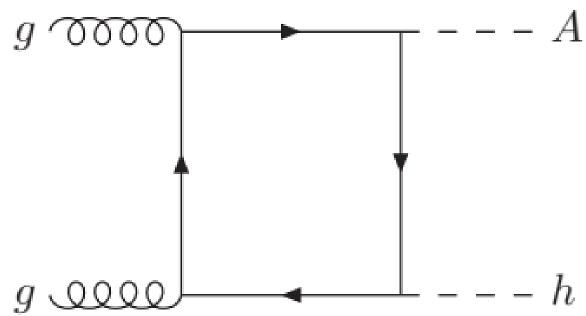
➢ *Cross sections calculated with MadGraph5_aMC@NLO*

Scenario 1: $H = h_{125}$

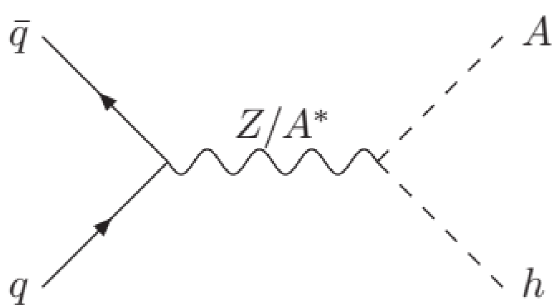
A Light hA Pair

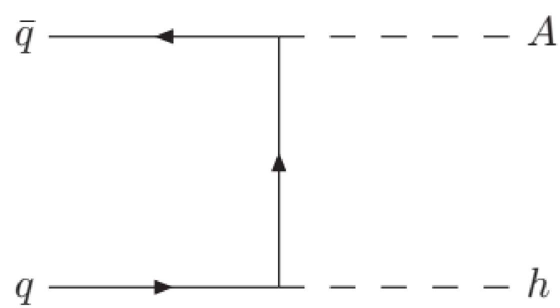
The Landau-Yang theorem forbids the contribution of a resonant Z boson to the QCD production of a hA pair



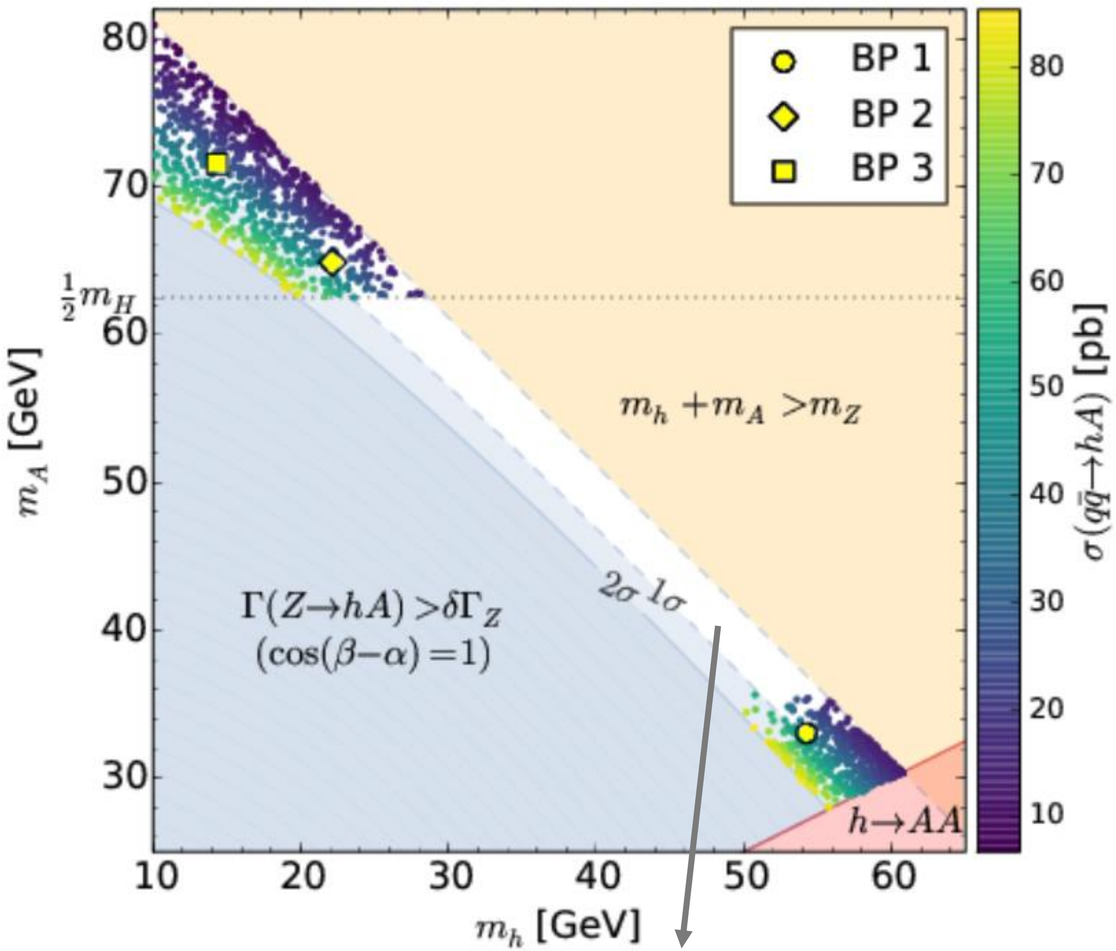


but not to EW production: enhanced cross sections?





$m_h + m_A < m_Z$

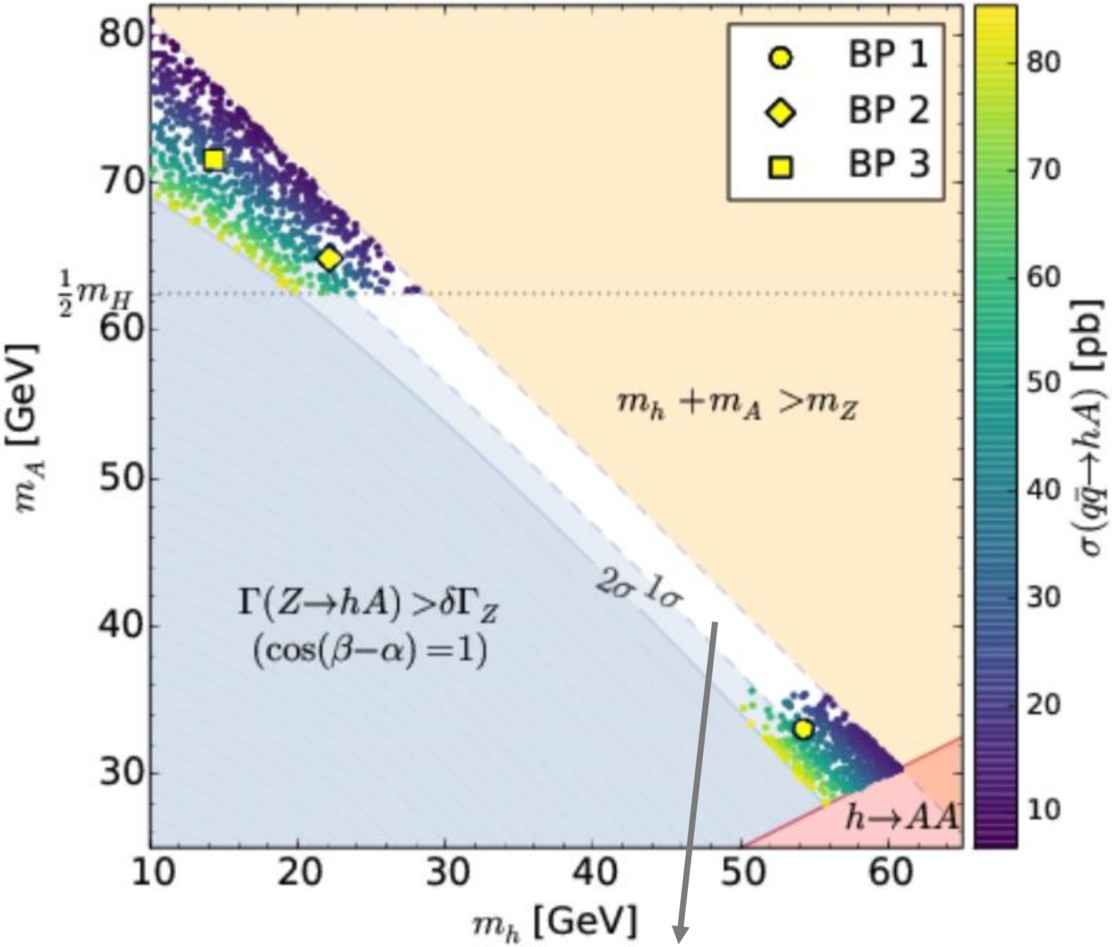


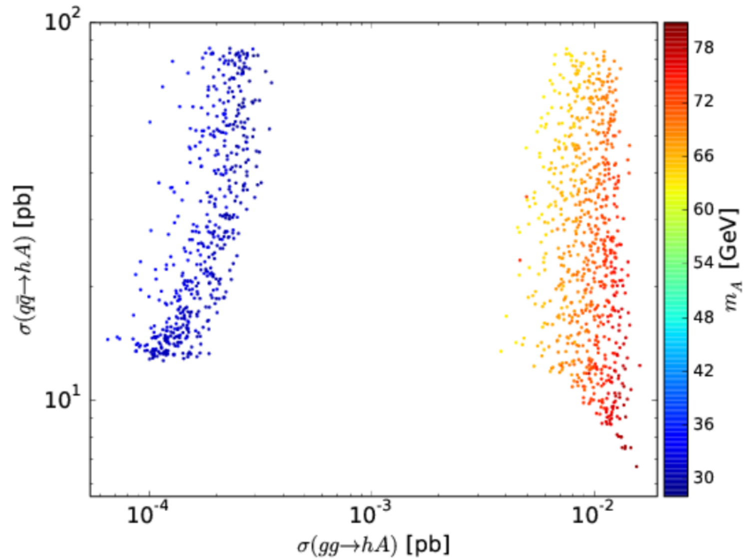
$\Gamma_Z = 2.4952 \pm 0.0023$ GeV

$$m_h = 10 - 80\,\text{GeV}\,;\;\; m_A = 10 - M_Z - m_h\;\,\text{GeV}\,;\;\; m_{H^\pm} = 90 - 500\,\text{GeV}$$

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

$\mathbf{m_h + m_A < m_Z}$





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

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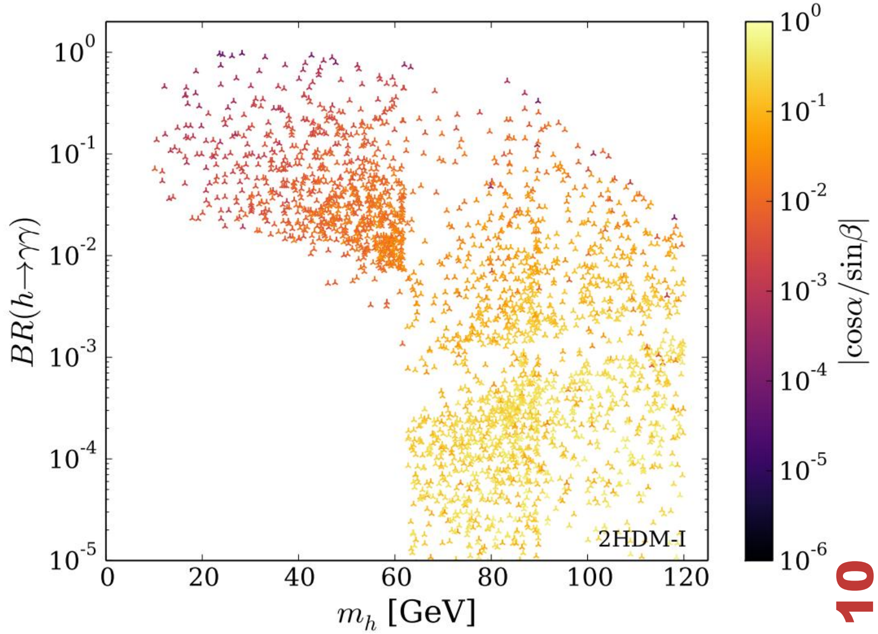
Dominant Search Channels

BP	m_h [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	$\sin(\beta-\alpha)$	m_{12}^2 [GeV^2]	$\tan\beta$	$\cos\alpha/\sin\beta$
1	54.2	33.0	95.9	-0.11590	118.3	9.0947	-6.7×10^{-3}
2	22.2	64.9	101.5	-0.046960	10.6	22.114	-1.8×10^{-3}

BP	σ [fb]		BR($h\to\ldots$) [%]				BR($A\to\ldots$) [%]		
	$q\bar{q}\to hA$	$gg\to hA$	Z^*A	$b\bar{b}$	$\gamma\gamma$	$\tau\tau$	Z^*h	$b\bar{b}$	$\tau\tau$
1	41.2	1.5×10^{-4}	94	5	<1	<1	0	86	7
2	34.4	7.2×10^{-3}	0	83	3	7	86	12	1

$\sin(\beta-\alpha)\to0$ ➔ "Alignment limit" ➔ Maximal hAZ coupling; enhanced BR($H\to\gamma\gamma$)!

For $m_A>m_h$, $Z^*\gamma\gamma\gamma\gamma$ could be a crucial signature



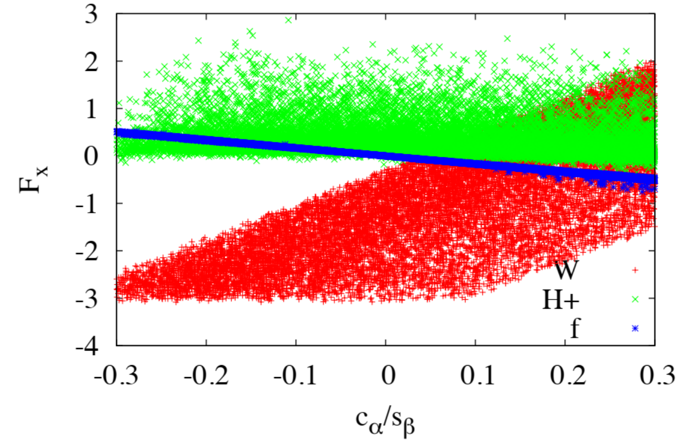
[A. Arhrib, R. Benbrik, R. Enberg, W. Klemm, S. Moretti, SM, 1706.01964]

A Fermiophobic h along with the $H^{\pm}$

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

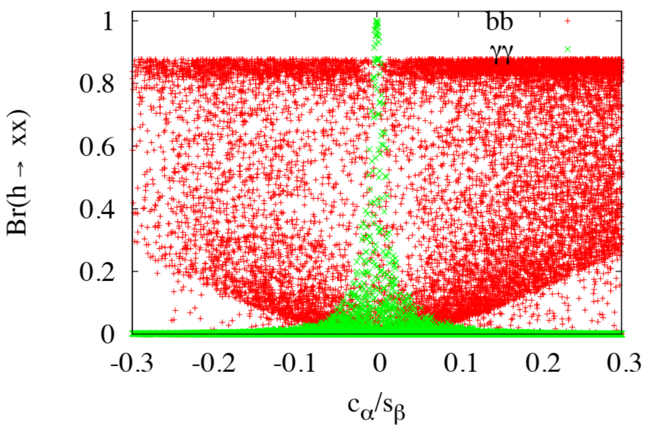
$$F_{H^\pm} = \frac{g_{hH^\pm H^\mp}}{\tau_{H^\pm}^2} \frac{m_W^2}{m_{H^\pm}^2} (\tau_{H^\pm} - I(\tau_{H^\pm})),$$

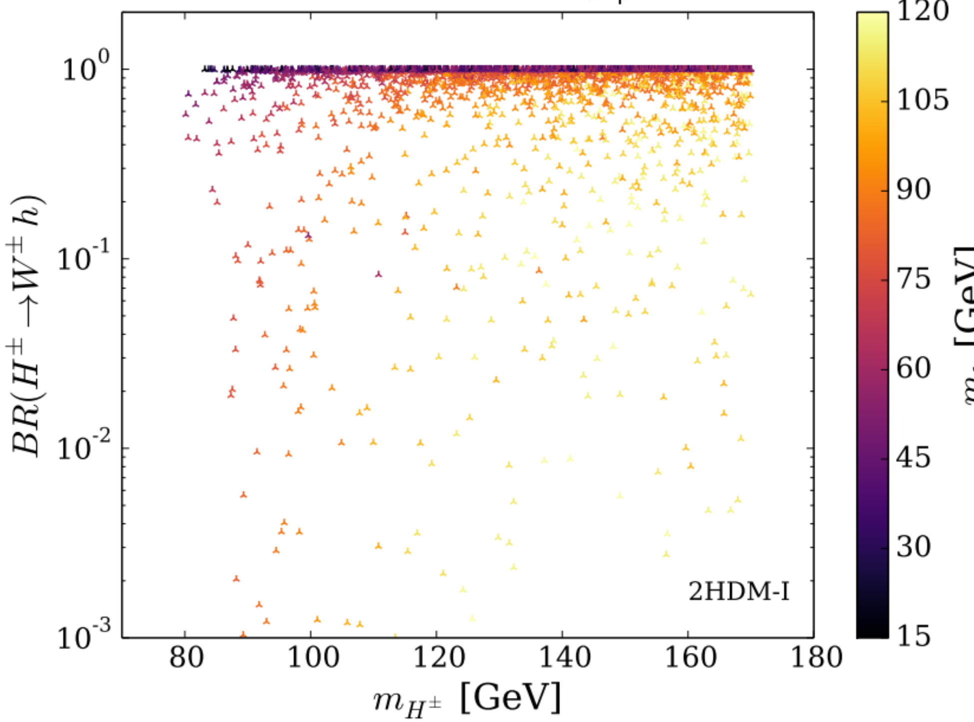
$$F_W = \frac{\sin(\beta - \alpha)}{\tau_W^2} (2\tau_W^2 + 3\tau_W + 3(2\tau_W - 1) I(\tau_W))$$



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

→ "Alignment limit" → Maximal hAZ and $H^{\pm}hW^{\pm}$ coupling



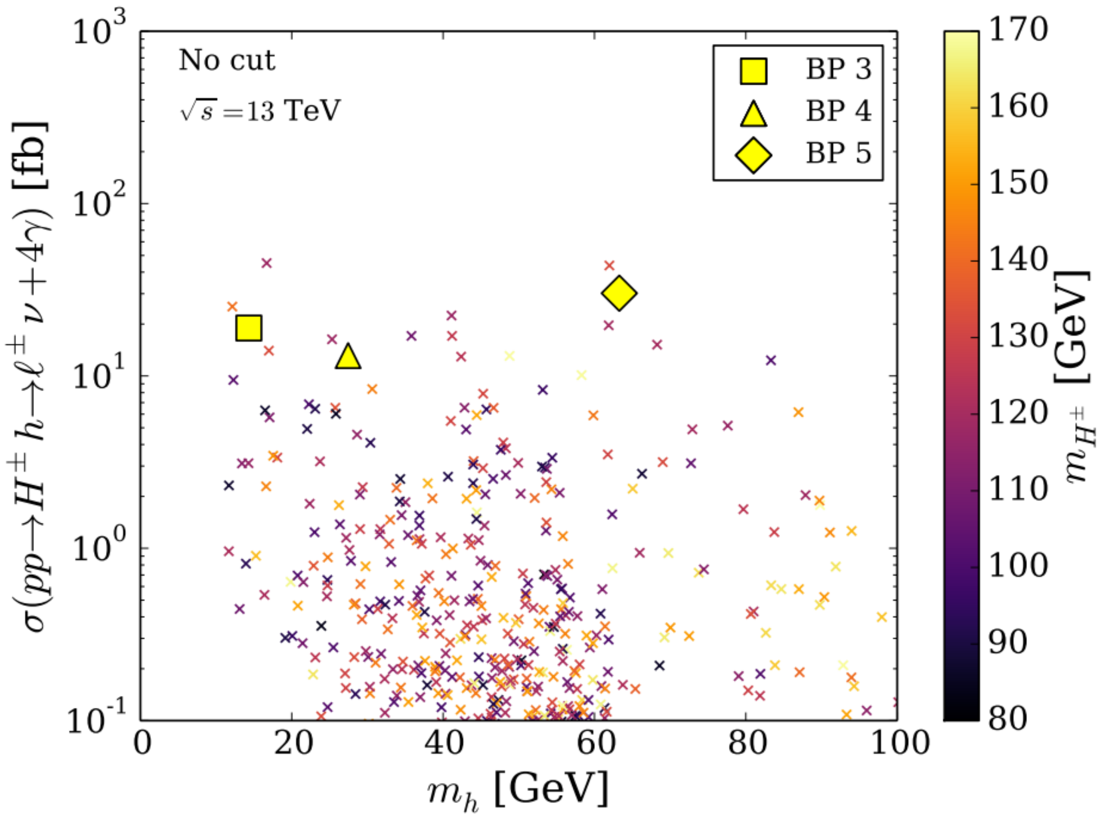


$$m_h = 10 - 120\,\text{GeV}\,;\;\; m_A = 10 - 500\,\text{GeV}\,;\;\; m_{H^\pm} = 80 - 170\,\text{GeV}$$

Discovery Potential

$q = u, d, c, s$

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



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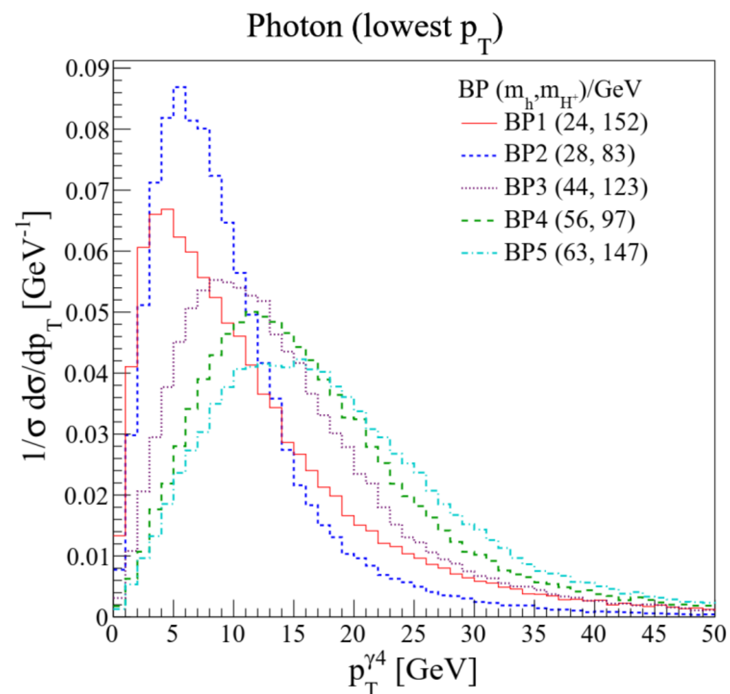

BP	m_h	m_A	$m_{H^\pm}$	$\sin(\beta-\alpha)$	m_{12}^2	$\tan\beta$	$\cos\alpha/\sin\beta$
4	27.5	117.8	86.8	-0.14705	44.5	6.8946	-3.6×10^{-3}
5	63.3	129.2	148.0	-0.048763	173.1	20.660	-4.2×10^{-4}

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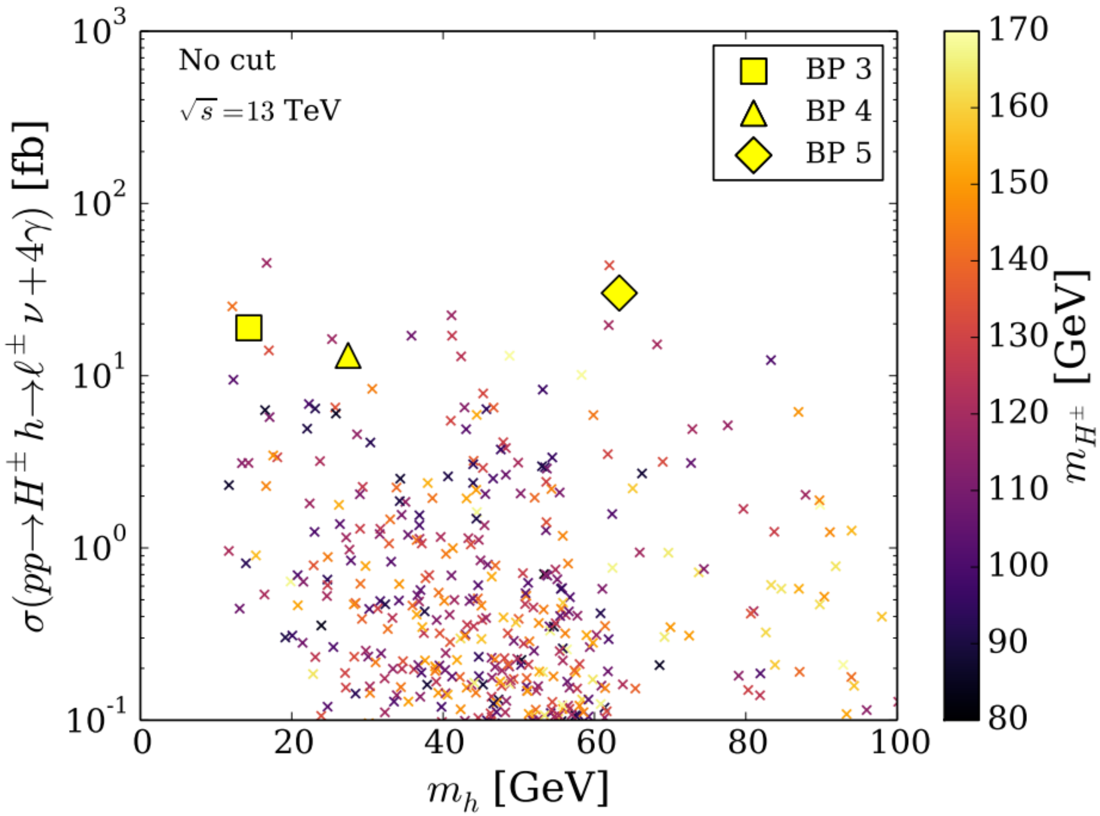
$q = u, d, c, s$

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



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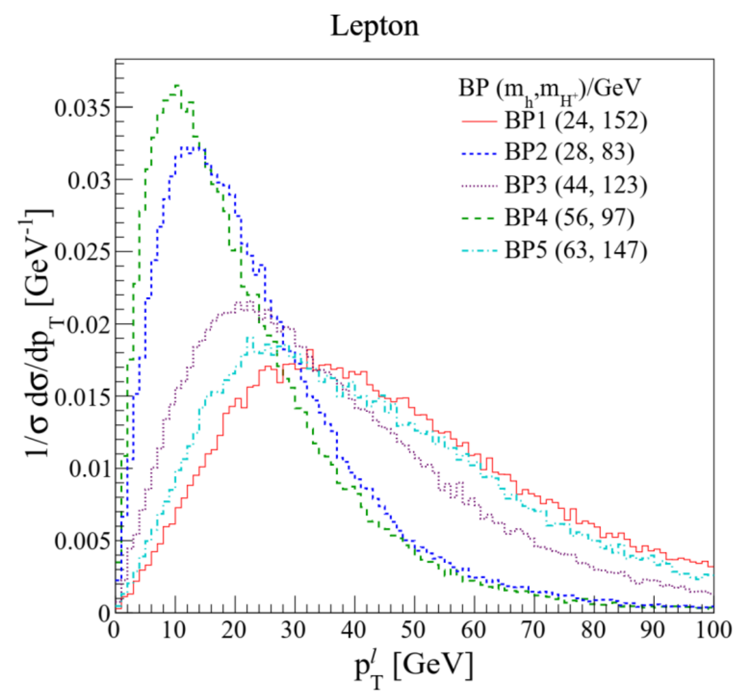


BP	BR [%]			σ [fb]	
	$H^{\pm} \to W^{\pm}h$	$A \to Z^*h$	$h \to \gamma\gamma$	$W^{\pm} + 4\gamma$	$W^{\pm}Z^* + 4\gamma$
4	98	94	16	61.5	7.4
5	100	98	71	141.4	55.7

Vanishing background

Cut Efficiencies

$p_T^{\gamma} > 20$ 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

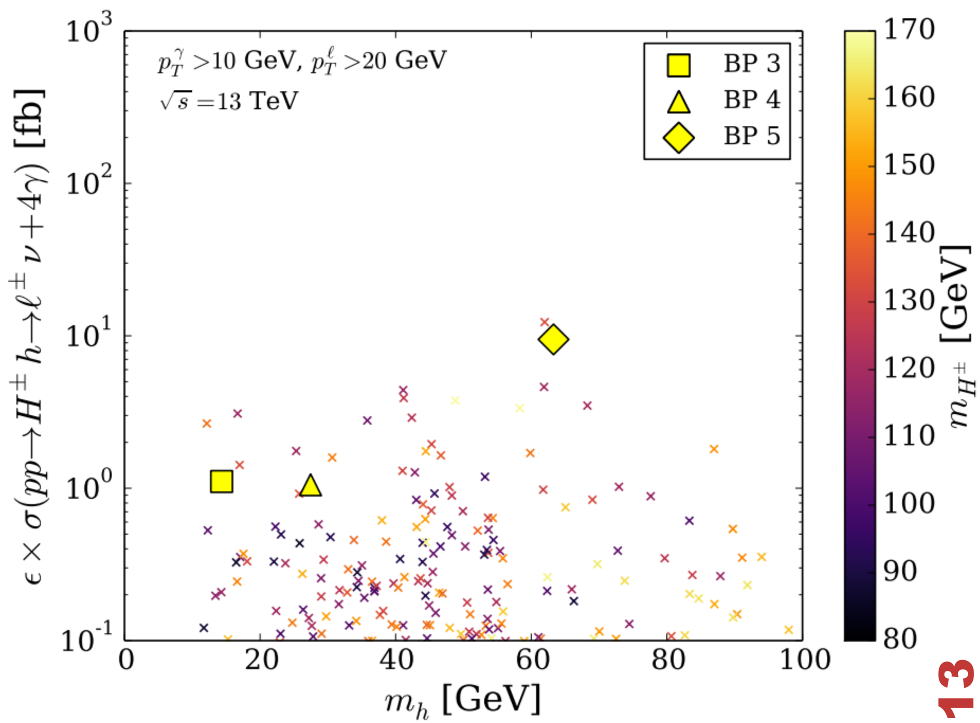
$$\sqrt{s} = 13 \text{ TeV}$$

$$|\eta| < 2.5$$

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

$p_T^{\gamma} > 10$ 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 fb

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

A 3-fold 4-photon Signature

BP	m_h	m_A	$m_{H^\pm}$	$\sin(\beta-\alpha)$	m_{12}^2	$\tan\beta$	$\cos\alpha/\sin\beta$
3	14.3	71.6	107.2	-0.061929	2.9	16.307	-7.2×10^{-4}

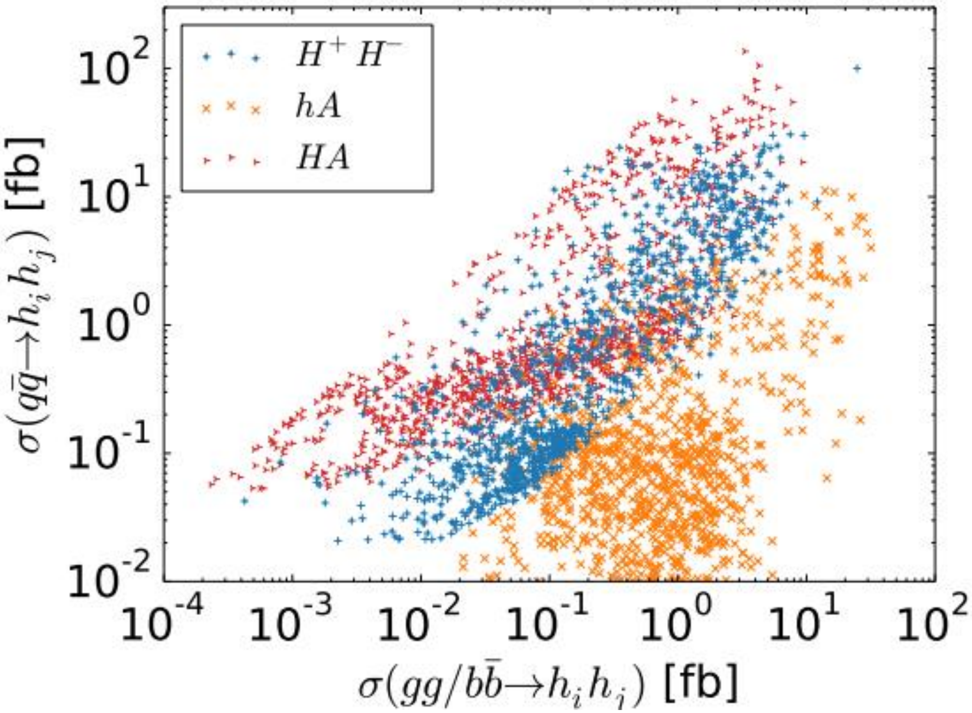
BP 3	
$\sigma(q\bar{q}\to hA\to Z^*+4\gamma)$ $[\sigma(gg\to hA\to Z^*+4\gamma)]$	1.64 fb $[5.7\times10^{-4}$ fb$]$
$\sigma(q\bar{q}\to H^\pm h\to W^\pm+4\gamma)$ $\sigma(q\bar{q}\to H^\pm A\to W^\pm Z^*+4\gamma)$	88.8 fb 26.8 fb
$\mathrm{BR}(H^\pm\to W^\pm h)$ $\mathrm{BR}(A\to Z^*h)$	100 % 90 %
$\mathrm{BR}(h\to\gamma\gamma)$ $\mathrm{BR}(h\to b\bar{b})$	24 % 60 %

Scenario 1: $h = h_{125}$

Higgs Pair-Production at the LHC

$$m_H = 150 - 750\,\text{GeV}\,;\ m_A = 50 - 750\,\text{GeV}\,;\ m_{H^\pm} = 50 - 750\,\text{GeV}$$

1. *Can the EW production of some neutral di-Higgs states dominate their QCD production?*

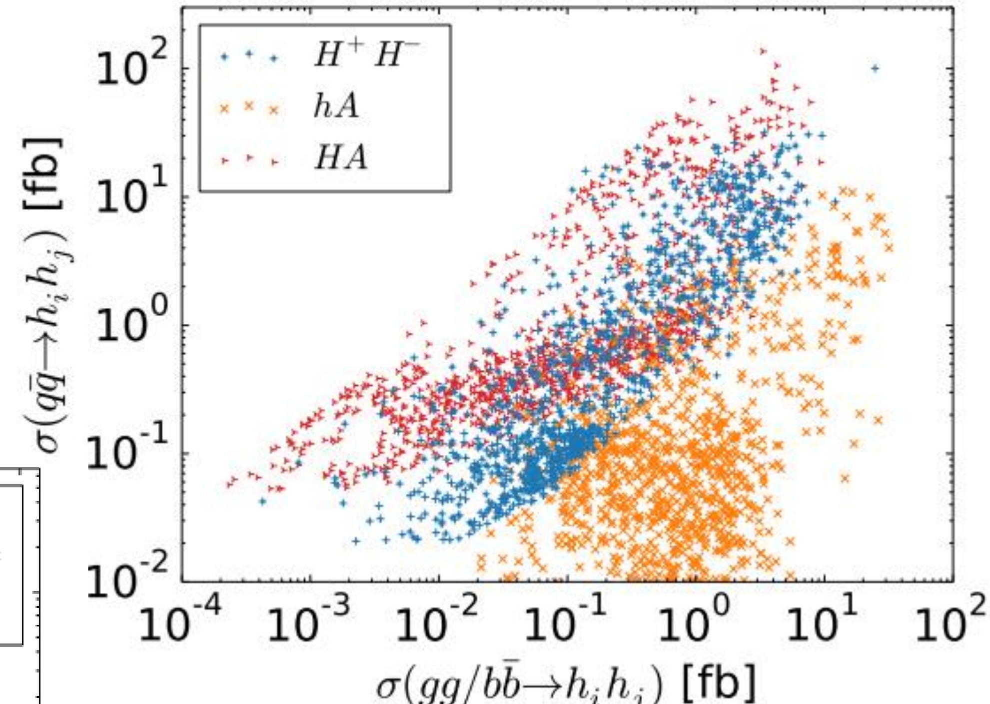


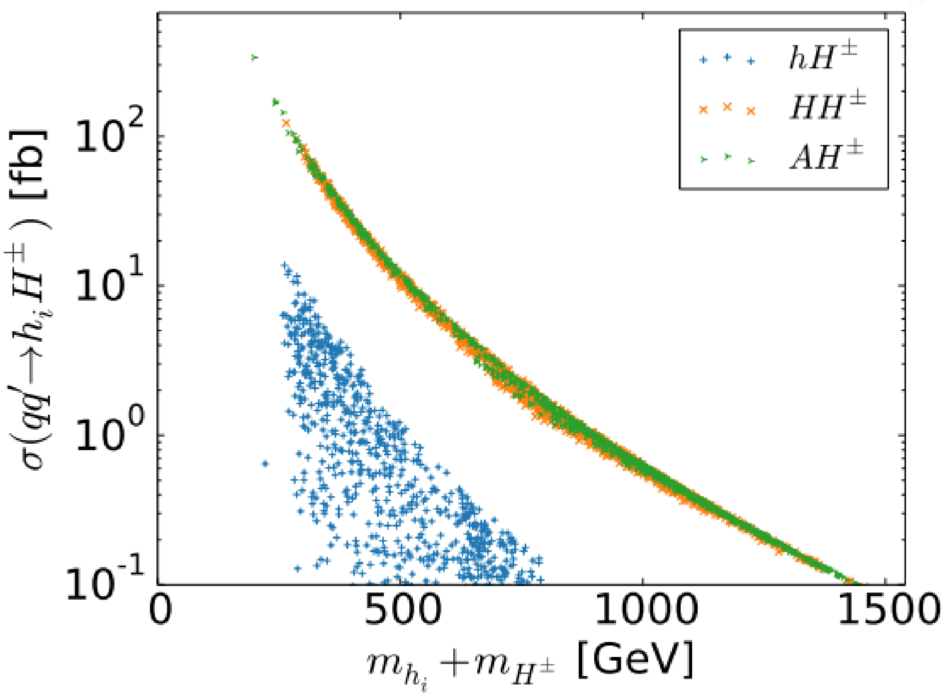
[R. Enberg, W. Klemm, S. Moretti, SM, 1812.08623]

Higgs Pair-Production at the LHC

$$m_H = 150 - 750\,\text{GeV}\,;\ m_A = 50 - 750\,\text{GeV}\,;\ m_{H^\pm} = 50 - 750\,\text{GeV}$$

1. Can the EW production of some neutral di-Higgs states dominate their QCD production?

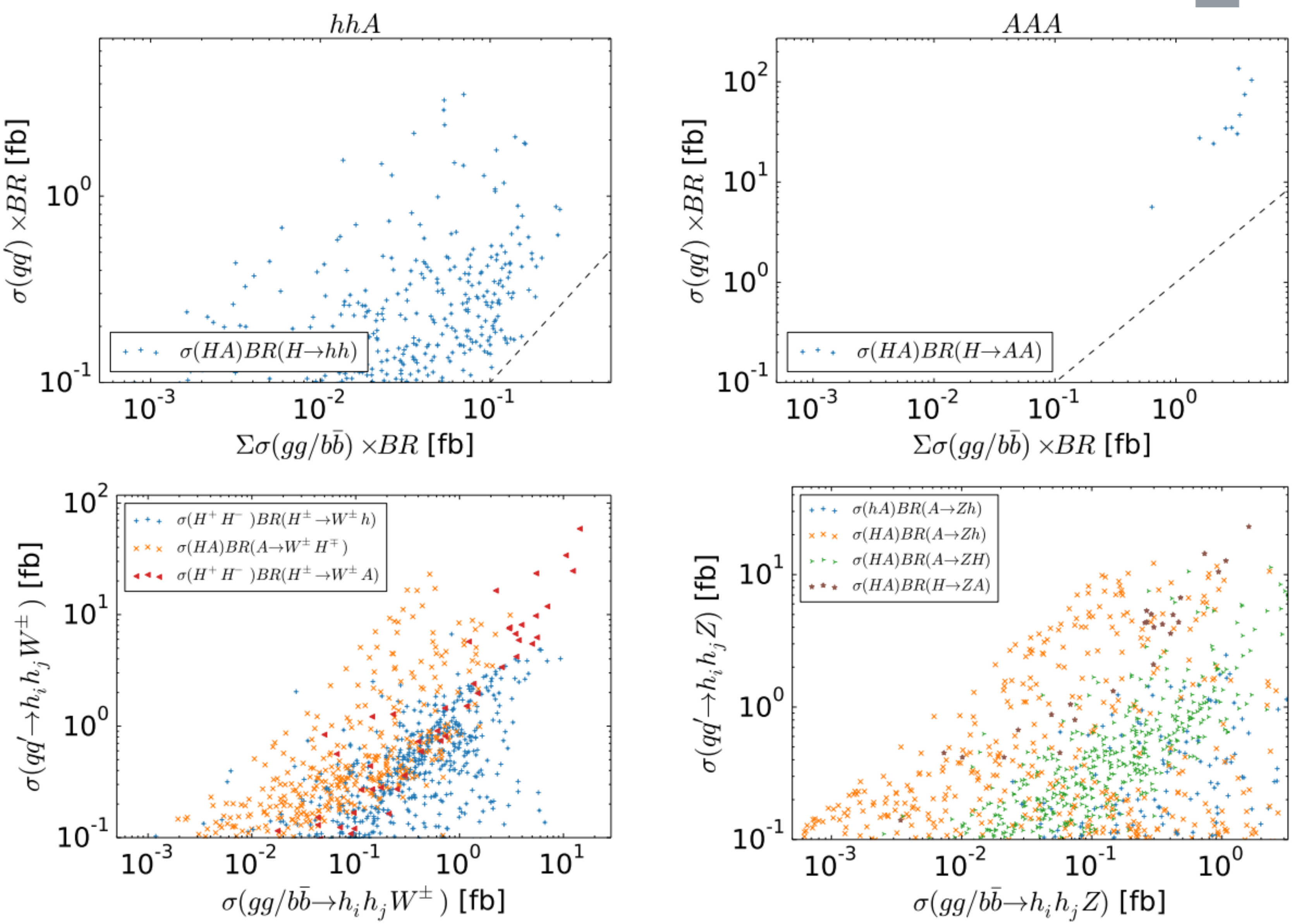




2. What cross sections can be obtained for the charged di-Higgs states?

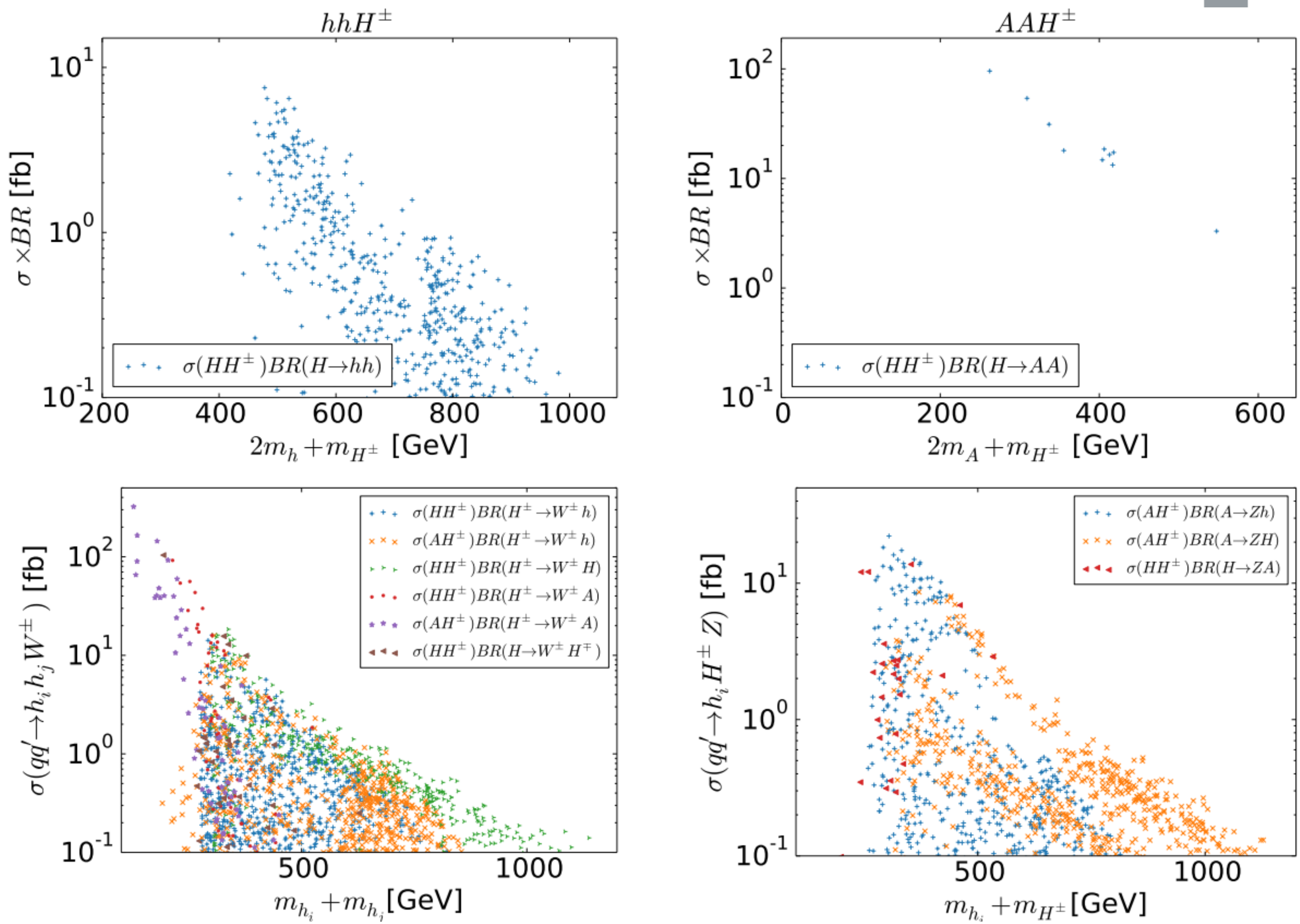
[R. Enberg, W. Klemm, S. Moretti, SM, 1812.08623]

Neutral 3-body States



[R. Enberg, W. Klemm, S. Moretti, SM, 1812.08623]

Charged 3-body States



[R. Enberg, W. Klemm, S. Moretti, SM, 1812.08623]

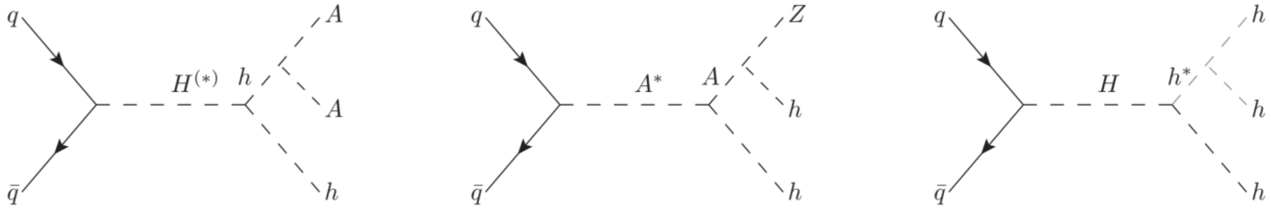
Couplings of the Higgs Bosons

3. Which Higgs-Higgs and Higgs-gauge couplings of the 2HDM can be probed in various di-Higgs states?

Coupling	1. hh	2. HH	3. AA	4. $\boxed{H^+H^-}$	5. hH	6. $\boxed{hA}$	7. $\boldsymbol{hH^\pm}$	8. $\boxed{HA}$	9. $\boldsymbol{HH^\pm}$	10. $\boldsymbol{AH^\pm}$
a. λ_{hhh}	✓									
b. λ_{hhH}	✓				✓					
c. λ_{hHH}		✓			✓					
d. λ_{hAA}			✓			✓				
e. $\lambda_{hH^+H^-}$				✓			✓			
f. λ_{HHH}		✓								
g. λ_{HAA}			✓					✓		
h. $\lambda_{HH^+H^-}$				✓					✓	
i. λ_{hAZ}						✓				
j. λ_{HAZ}								✓		
k. $\lambda_{H^+H^-Z}$				✓						
l. $\lambda_{hH^+W^-}$							✓			
m. $\lambda_{HH^+W^-}$									✓	
n. $\lambda_{AH^+W^-}$										✓

[R. Enberg, W. Klemm, S. Moretti, SM, 1812.01147]

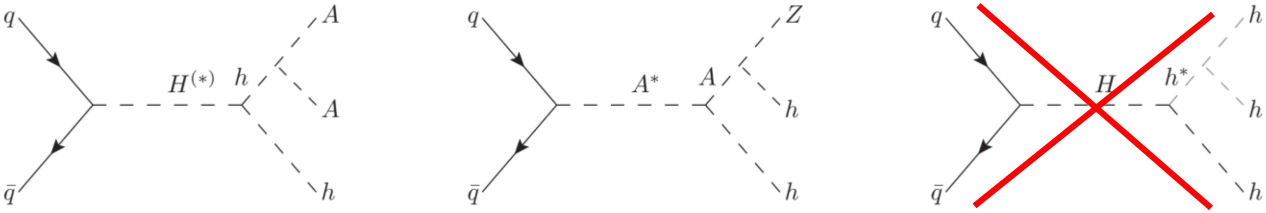
Higgs-Higgs/Gauge Couplings



[R. Enberg, W. Klemm, S. Moretti, SM, 1812.01147]

Coupling	1. hh	2. HH	3. AA	4. $\boxed{H^+H^-}$	5. hH	6. $\boxed{hA}$	7. $\boldsymbol{hH^\pm}$	8. $\boxed{HA}$	9. $\boldsymbol{HH^\pm}$	10. $\boldsymbol{AH^\pm}$
a. λ_{hhh}	$(hhh)^*$				$(hhH)^*$	$(hhA)^*$	$(hhH^\pm)^*$			
b. λ_{hhH}		hhH			hhh			$\boxed{hhA}$	$\boxed{\boldsymbol{hhH^\pm}}$	
c. λ_{hHH}		$(hHH)^*$			$(hhH)^*$ hH^+H^-			$(hHA)^*$	$(hHH^\pm)^*$	
d. λ_{hAA}	(hAA)		$(hAA)^*$	$(hH^+H^-)^*$	HAA	$(hhA)^*$ AAA	$(AAH^\pm)^*$	$(hHA)^*$		
e. $\lambda_{hH^+H^-}$	hH^+H^-			$(hH^+H^-)^*$	HH^+H^-	AH^+H^-	$(hhH^\pm)^*$ $\boldsymbol{H^+H^-H^\pm}$		$(hHH^\pm)^*$	$(hAH^\pm)^*$
f. λ_{HHH}		$(HHH)^*$			$(hHH)^*$			$(HHA)^*$	$(HHH^\pm)^*$	
g. λ_{HAA}		HAA	$(HAA)^*$		hAA	$(hHA)^*$		$(HHA)^*$ $\boxed{AAA}$	$\boxed{\boldsymbol{AAH^\pm}}$	$\boldsymbol{HAH^\pm}$
h. $\lambda_{HH^+H^-}$		HH^+H^-		$(HH^+H^-)^*$			$(hHH^\pm)^*$	AH^+H^-	$(HHH^\pm)^*$ $\boldsymbol{H^+H^-H^\pm}$	$(HAH^\pm)^*$
i. λ_{hAZ}	hAZ		hAZ		HAZ	$\boxed{hhZ}$ AAZ	$\boldsymbol{AH^\pm Z}$	$\boxed{hHZ}$		$\boxed{\boldsymbol{hH^\pm Z}}$
j. λ_{HAZ}		HAZ	HAZ		hAZ	$\boxed{hHZ}$		$\boxed{HHZ}$ $\boxed{AAZ}$	$\boxed{\boldsymbol{AH^\pm Z}}$	$\boxed{\boldsymbol{HH^\pm Z}}$
k. $\lambda_{H^+H^-Z}$				H^+H^-Z						
l. $\lambda_{hH^+W^-}$	hH^+W^-			$\boxed{hH^+W^-}$	HH^+W^-	$\boxed{hH^+W^-}$ AH^+W^-	$\boxed{\boldsymbol{hhW^\pm}}$ $\boldsymbol{H^+H^-W^\pm}$		$\boxed{\boldsymbol{hHW^\pm}}$	$\boxed{\boldsymbol{hAW^\pm}}$
m. $\lambda_{HH^+W^-}$		HH^+W^-		$\boxed{HH^+W^-}$	hH^+W^-		$\boxed{\boldsymbol{hHW^\pm}}$	$\boxed{HH^+W^-}$ $\boxed{AH^+W^-}$	$\boxed{\boldsymbol{HHW^\pm}}$ $\boxed{\boldsymbol{H^+H^-W^\pm}}$	$\boxed{\boldsymbol{HAW^\pm}}$
n. $\lambda_{AH^+W^-}$			AH^+W^-	$\boxed{AH^+W^-}$			$\boxed{\boldsymbol{hAW^\pm}}$		$\boxed{\boldsymbol{HAW^\pm}}$	$\boxed{\boldsymbol{AAW^\pm}}$ $\boxed{\boldsymbol{H^+H^-W^\pm}}$

Higgs-Higgs/Gauge Couplings



[R. Enberg, W. Klemm, S. Moretti, SM, 1812.01147]

Coupling	1. hh	2. HH	3. AA	4. H^+H^-	5. hH	6. hA	7. $hH^\pm$	8. HA	9. $HH^\pm$	10. $AH^\pm$
a. λ_{hhh}	$(hhh)^*$				$(hhH)^*$	$(hhA)^*$	$(hhH^\pm)^*$			
b. λ_{hhH}		hhH			hhh			hhA	$hhH^\pm$	
c. λ_{hHH}		$(hHH)^*$			$(hhH)^*$ hH^+H^-			$(hHA)^*$	$(hHH^\pm)^*$	
d. λ_{hAA}	(hAA)		$(hAA)^*$	$(hH^+H^-)^*$	HAA	$(hhA)^*$ AAA	$(AAH^\pm)^*$	$(hHA)^*$		
e. $\lambda_{hH^+H^-}$	hH^+H^-			$(hH^+H^-)^*$	HH^+H^-	AH^+H^-	$(hhH^\pm)^*$ $H^+H^-H^\pm$		$(hHH^\pm)^*$	$(hAH^\pm)^*$
f. λ_{HHH}		$(HHH)^*$			$(hHH)^*$			$(HHA)^*$	$(HHH^\pm)^*$	
g. λ_{HAA}		HAA	$(HAA)^*$		hAA	$(hHA)^*$		$(HHA)^*$ AAA	$AAH^\pm$	$HAH^\pm$
h. $\lambda_{HH^+H^-}$		HH^+H^-		$(HH^+H^-)^*$			$(hHH^\pm)^*$	AH^+H^-	$(HHH^\pm)^*$ $H^+H^-H^\pm$	$(HAH^\pm)^*$
i. λ_{hAZ}	hAZ		hAZ		HAZ	hhZ AAZ	$AH^\pm Z$	hHZ		$hH^\pm Z$
j. λ_{HAZ}		HAZ	HAZ		hAZ	hHZ		HHZ AAZ	$AH^\pm Z$	$HH^\pm Z$
k. $\lambda_{H^+H^-Z}$				H^+H^-Z						
l. $\lambda_{hH^+W^-}$	hH^+W^-			hH^+W^-	HH^+W^-	hH^+W^- AH^+W^-	$hhW^\pm$ $H^+H^-W^\pm$		$hHW^\pm$	$hAW^\pm$
m. $\lambda_{HH^+W^-}$		HH^+W^-		HH^+W^-	hH^+W^-		$hHW^\pm$	HH^+W^- AH^+W^-	$HHW^\pm$ $H^+H^-W^\pm$	$HAW^\pm$
n. $\lambda_{AH^+W^-}$			AH^+W^-	AH^+W^-			$hAW^\pm$		$HAW^\pm$	$AAW^\pm$ $H^+H^-W^\pm$

CONCLUSIONS

- *Additional Higgs bosons are predicted in most new physics frameworks - can be lighter or heavier than the h_{125}*
- *Even when light, they are difficult to detect at the LHC in the conventional channels, owing to reduced couplings to the SM generally*
- *In the Type-I 2HDM, 4-photon final states could serve as important probes of a light hA pair as well as of a light $hH^{\pm}$ pair*
- *EW production - essential for charged di-Higgs states - can dominate over QCD even for neutral Higgs boson pairs*

KIAS KOREA INSTITUTE FOR ADVANCED STUDY

THANK YOU!
감사합니다!

Backup: Flavour Constraints

SuperIso Manual [F. Mahmoudi, 0808.3144]

- ✓ ***Constraints from flavour physics***

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