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Prospects of multi-Higgs production in the 2HDM at the LHC

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Higgs Hunting 2019, Orsay/Paris

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CONTENTS

- *New Higgs bosons at the LHC*
- *The 2-Higgs-doublet model*
- *Type-I 2HDM: Electroweak pair-production of Higgs bosons*
- *Beyond di-Higgs production*
- *Conclusions*

Additional Higgs Bosons

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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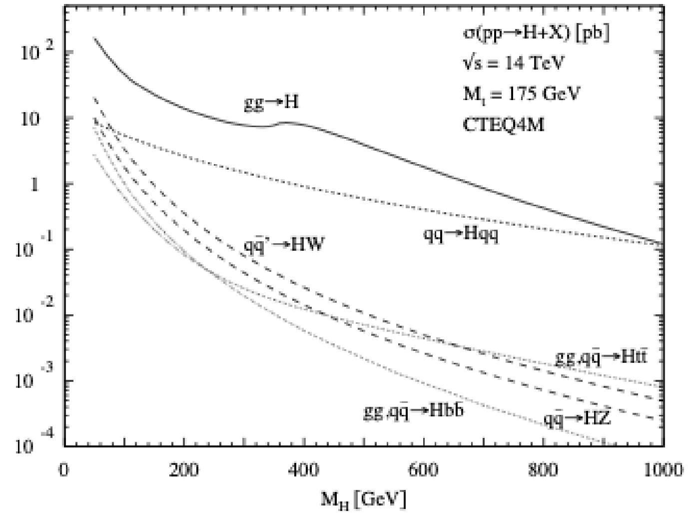
But

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

Small production cross section

- improve statistics



[A. Djouadi, hep-ph/0503173]

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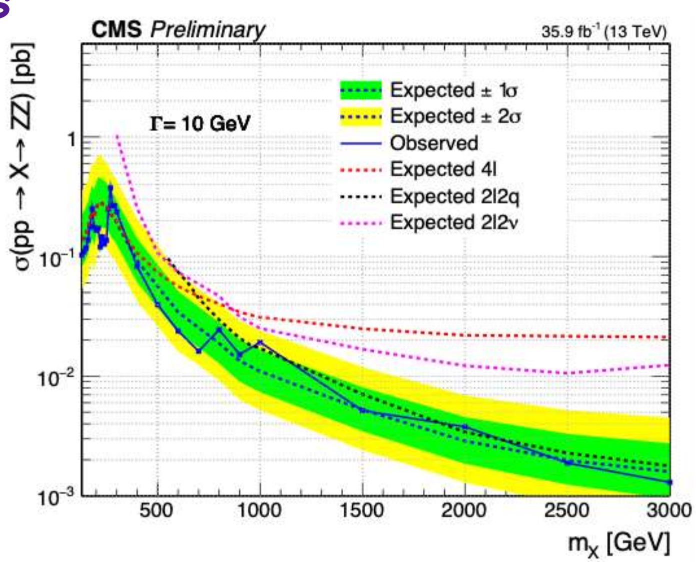

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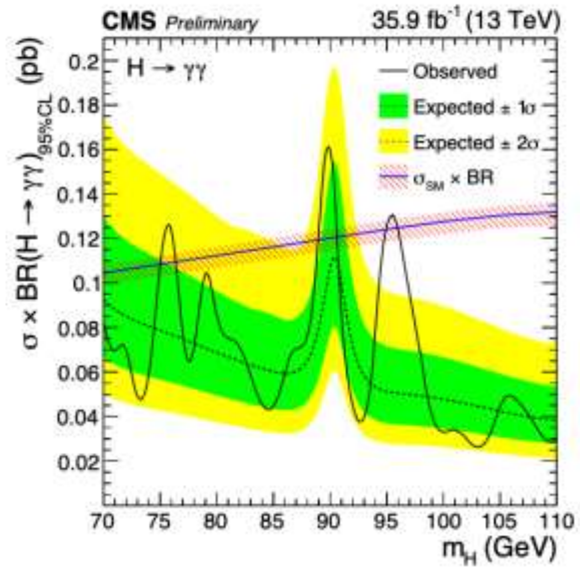

But

- *Masses O(100) GeV:*

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- *Masses O(10) GeV:*

Large SM Backgrounds - improve search strategies

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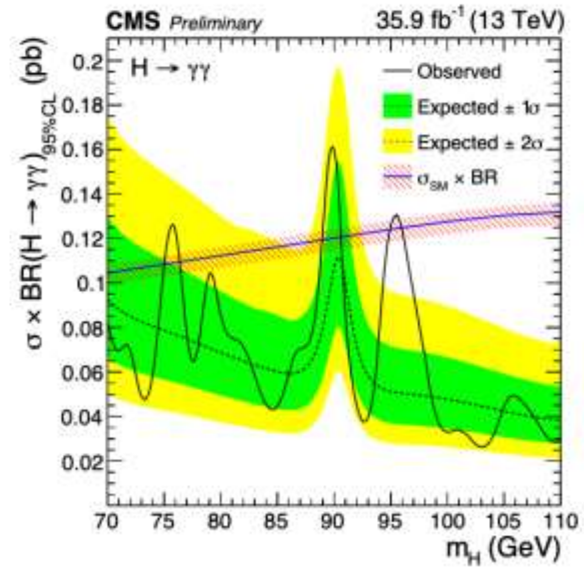

Large SM Backgrounds - improve search strategies

Also (in either case)

decay rates to SM particles may be suppressed

Exploit Higgs-Higgs and Higgs-gauge production!

The 2-Higgs-doublet model

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

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 $\Rightarrow$ 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

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

$$\boxed{\xi_f^h = \cos\alpha/\sin\beta}$$

$$\boxed{\xi_f^H = \sin\alpha/\sin\beta}$$

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

Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
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$$\boxed{\phi_1 \to -\phi_1}$$

Type-I 2HDM: Numerical Analysis

Numerically scan the parameter space

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

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

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***

Type-I 2HDM: Numerical Analysis

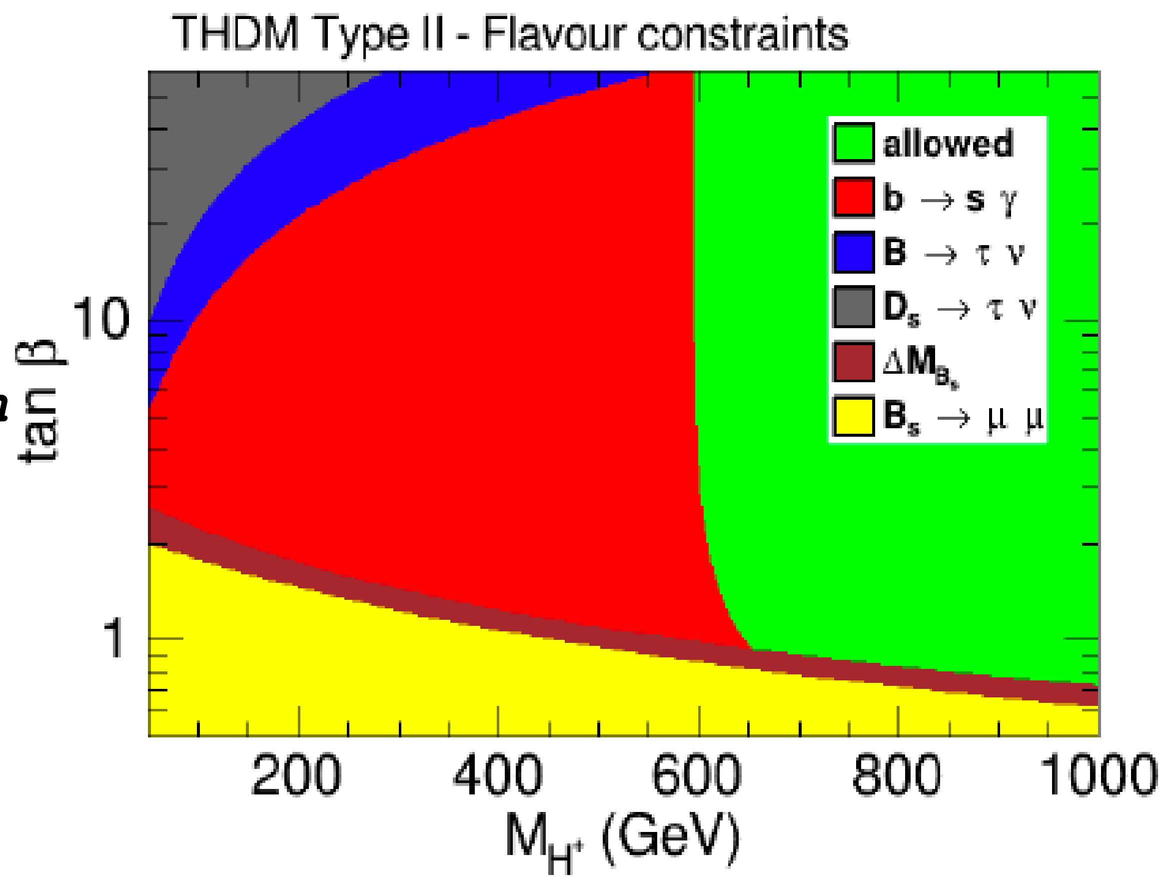
[A. Arbey, F. Mahmoudi, O. Stal, T. Stefaniak, [1706.07414]

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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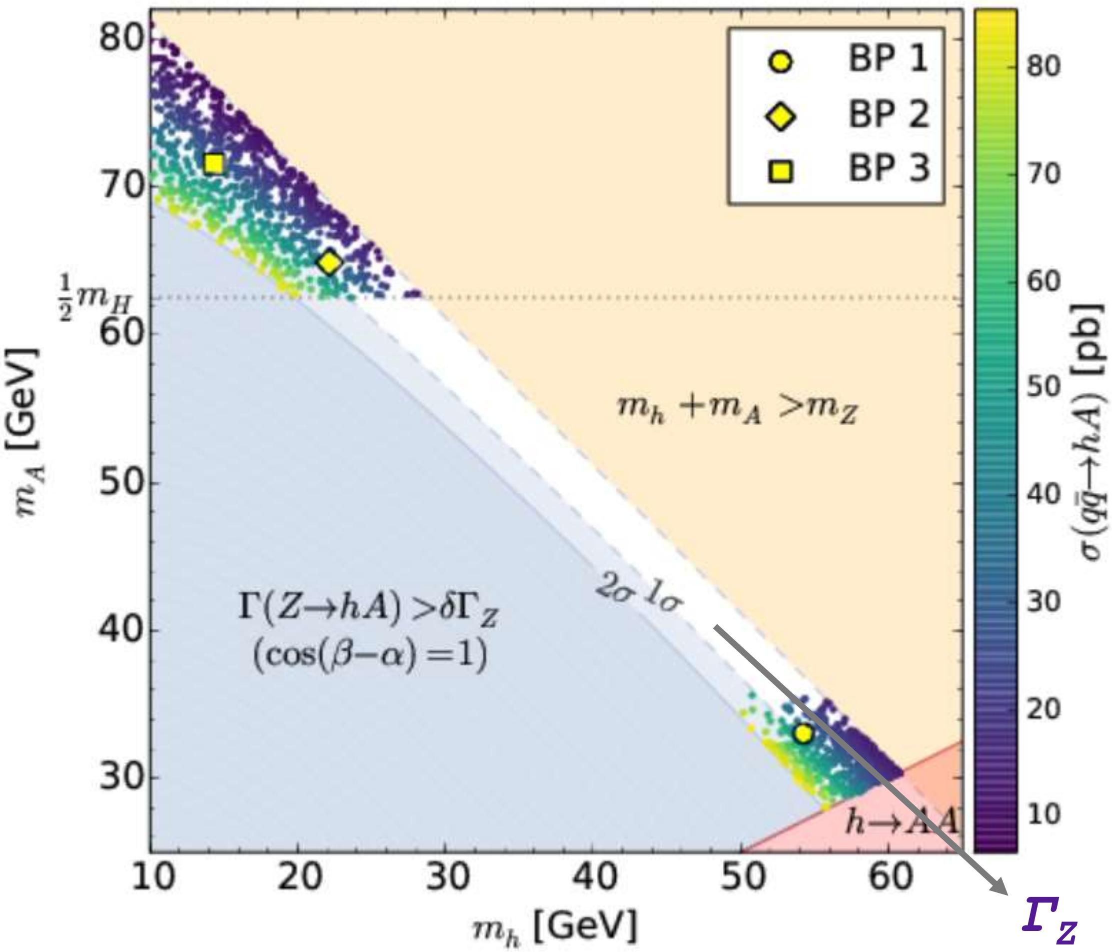
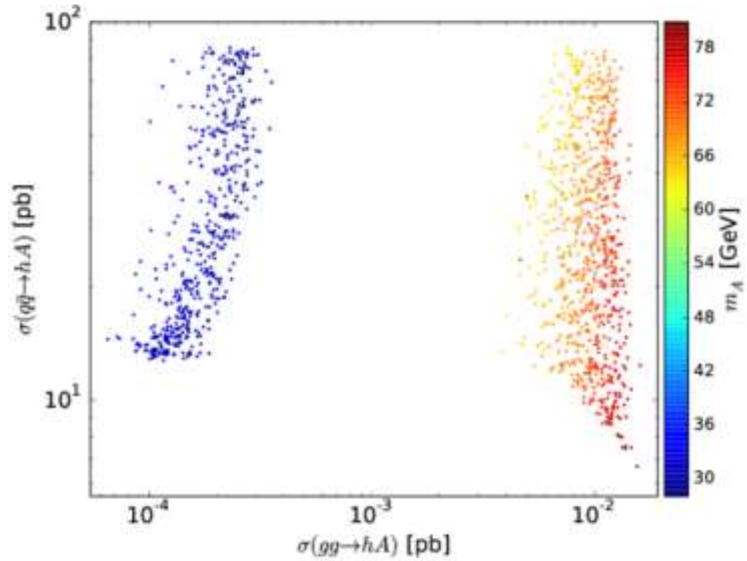
Using the 2HDMC code [D. Eriksson, J. Rathsman, O. Stal, 0902.0851]*, requiring consistency of each point with*

- ✓ *Unitarity, perturbativity and vacuum stability*
- ✓ *Measurements of oblique parameters S, T and U*
- ✓ *Constraints from flavour physics*
- ✓ *Measured h_{125} signal strengths (using HiggsSignals)*
- ✓ *Limits from LHC searches for additional Higgs bosons (using HiggsBounds)*

The $H = h_{125}$ scenario: hA production





EW production can be highly dominant over QCD production!

$\Gamma_Z = 2.4952 \pm 0.0023$ GeV

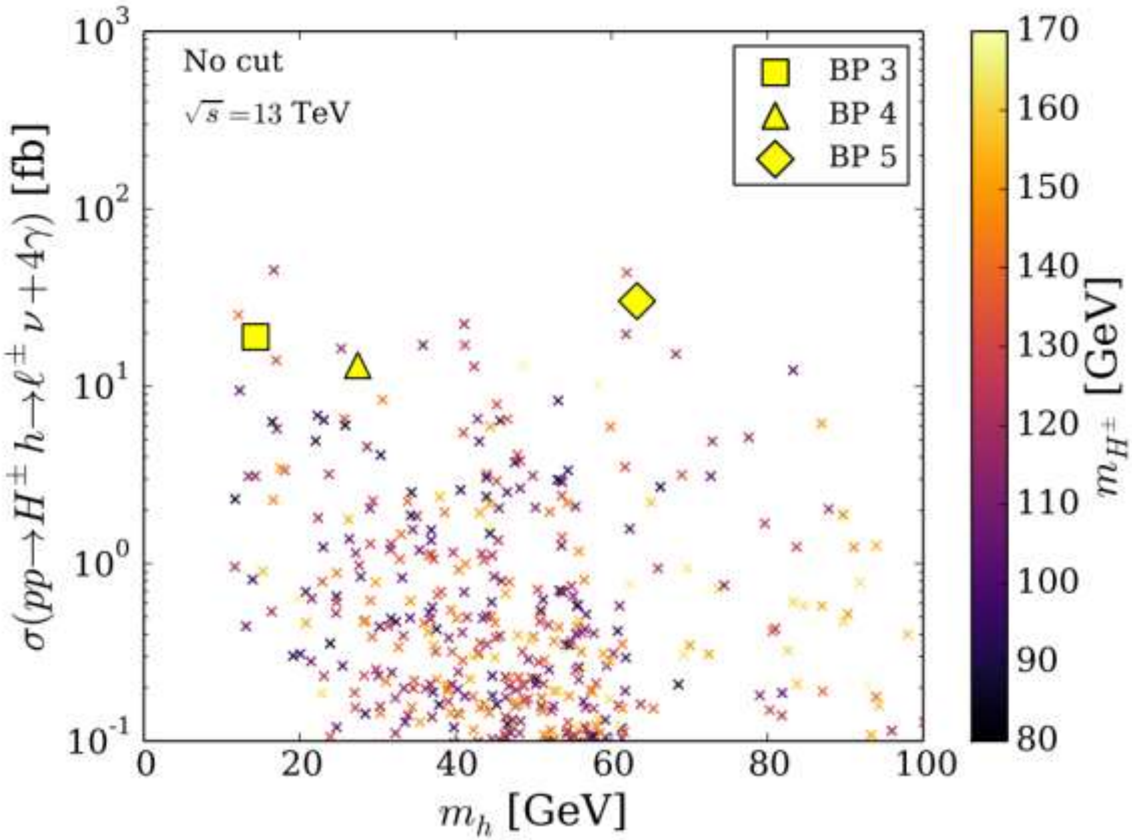
BP	σ [fb]		BR($h \to \ldots$) [%]				BR($A \to \ldots$) [%]		
	$q\bar{q} \to hA$	$gg \to hA$	Z^*A	$b\bar{b}$	$\gamma\gamma$	$\tau\tau$	Z^*h	$b\bar{b}$	$\tau\tau$
1	41.2	1.5×10^{-4}	94	5	< 1	< 1	0	86	7
2	34.4	7.2×10^{-3}	0	83	3	7	86	12	1

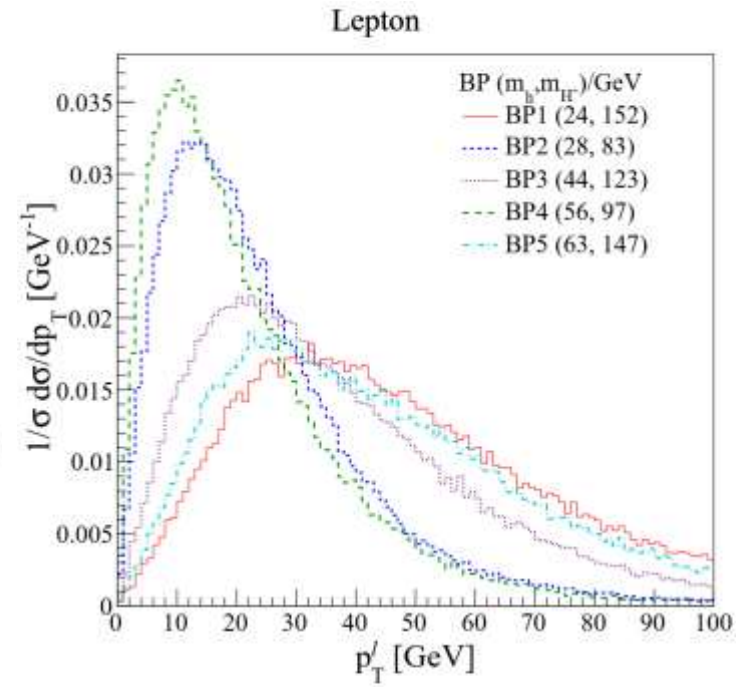
[R. Enberg, W. Klemm, S. Moretti, SM, 1605.02498]

The $H = h_{125}$ scenario: $hH^{\pm}$ production

$\boxed{q = u, d, c, s}$

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





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

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

The $h = h_{125}$ scenario

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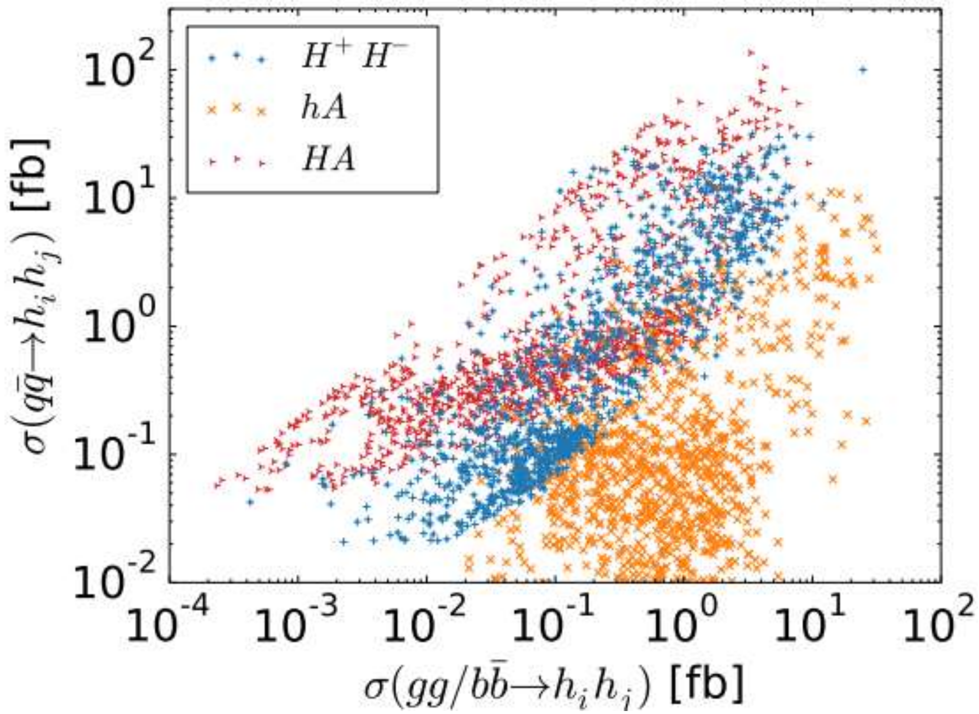
1. Can the EW production of some neutral di-Higgs states dominate their QCD production?



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

Cross sections calculated with MadGraph5_aMC@NLO

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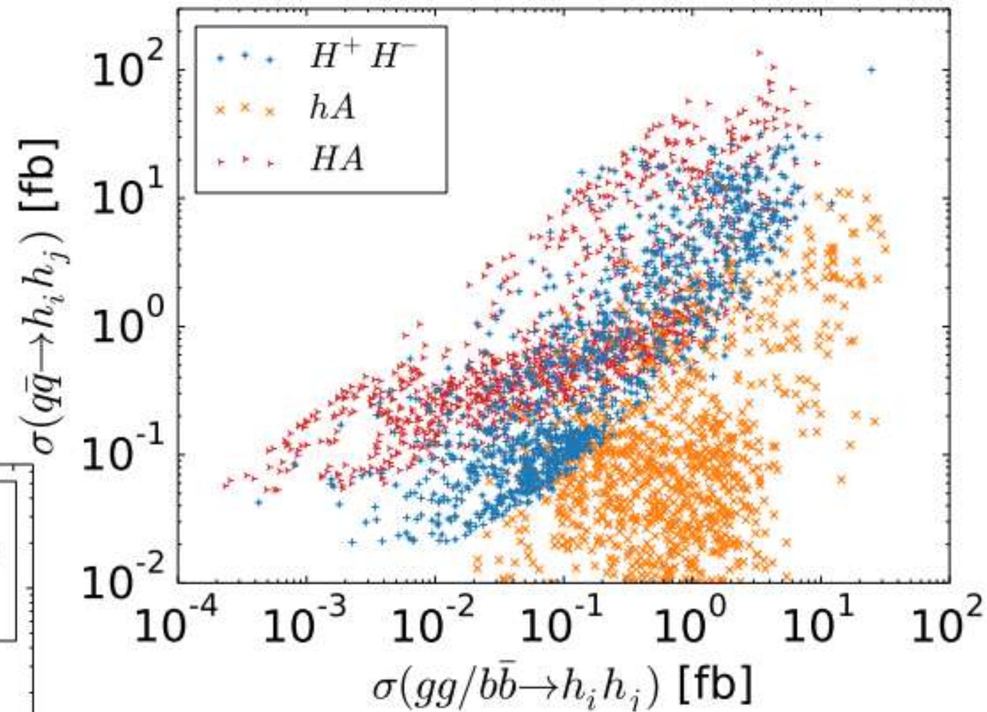

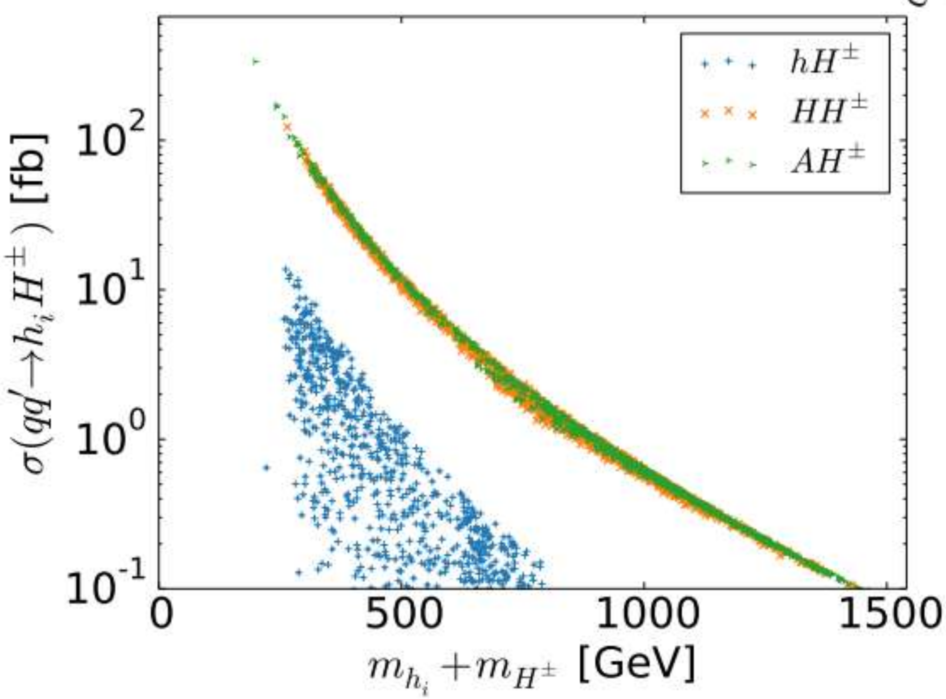

2. How large can the cross sections for the charged di-Higgs states be?

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

Cross sections calculated with MadGraph5_aMC@NLO

Reconstructing the 2HDM Lagrangian

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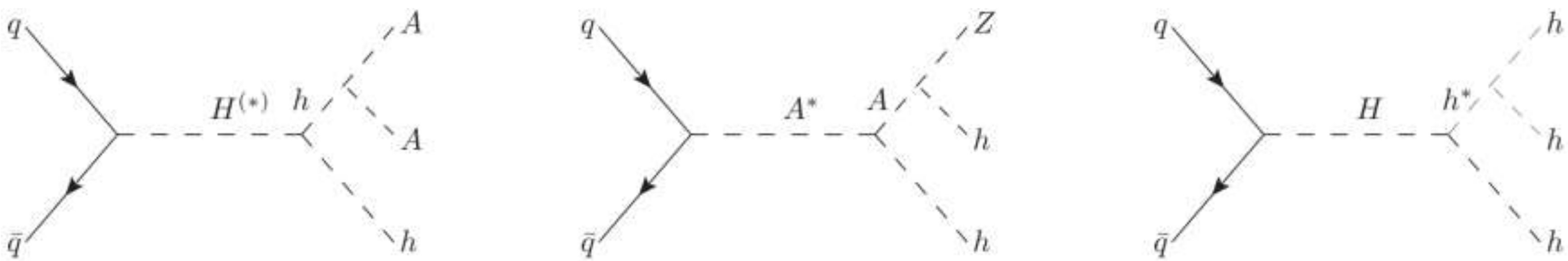
3.Which Higgs-Higgs and Higgs-gauge couplings of 2HDM-I can be probed in various di-Higgs states?

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]

Beyond pair-production

- ***Allow di-Higgs or Higgs-gauge decays of one of the two Higgs bosons***



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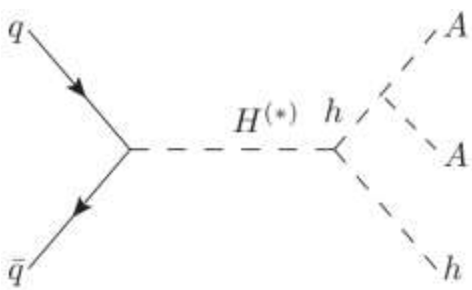
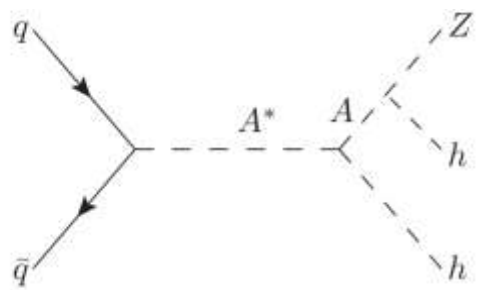
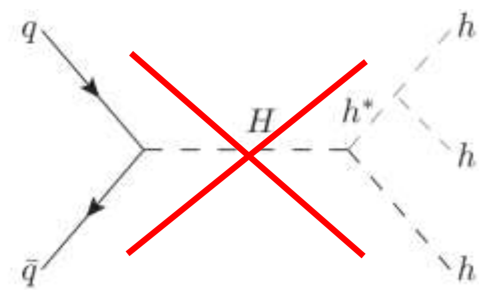


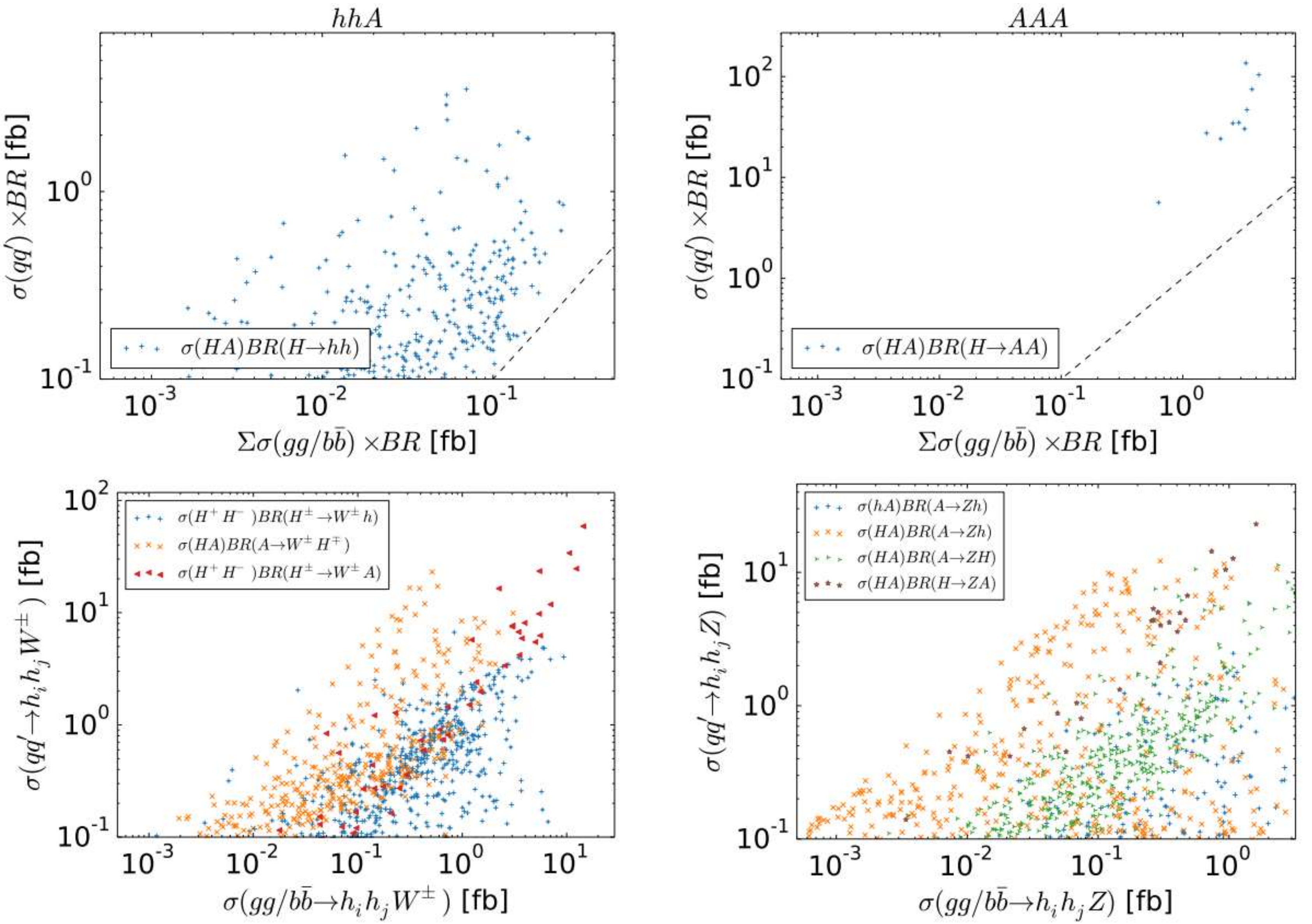




- *Calculate QCD and/or EW production cross sections (in the narrow-width approximation) as*

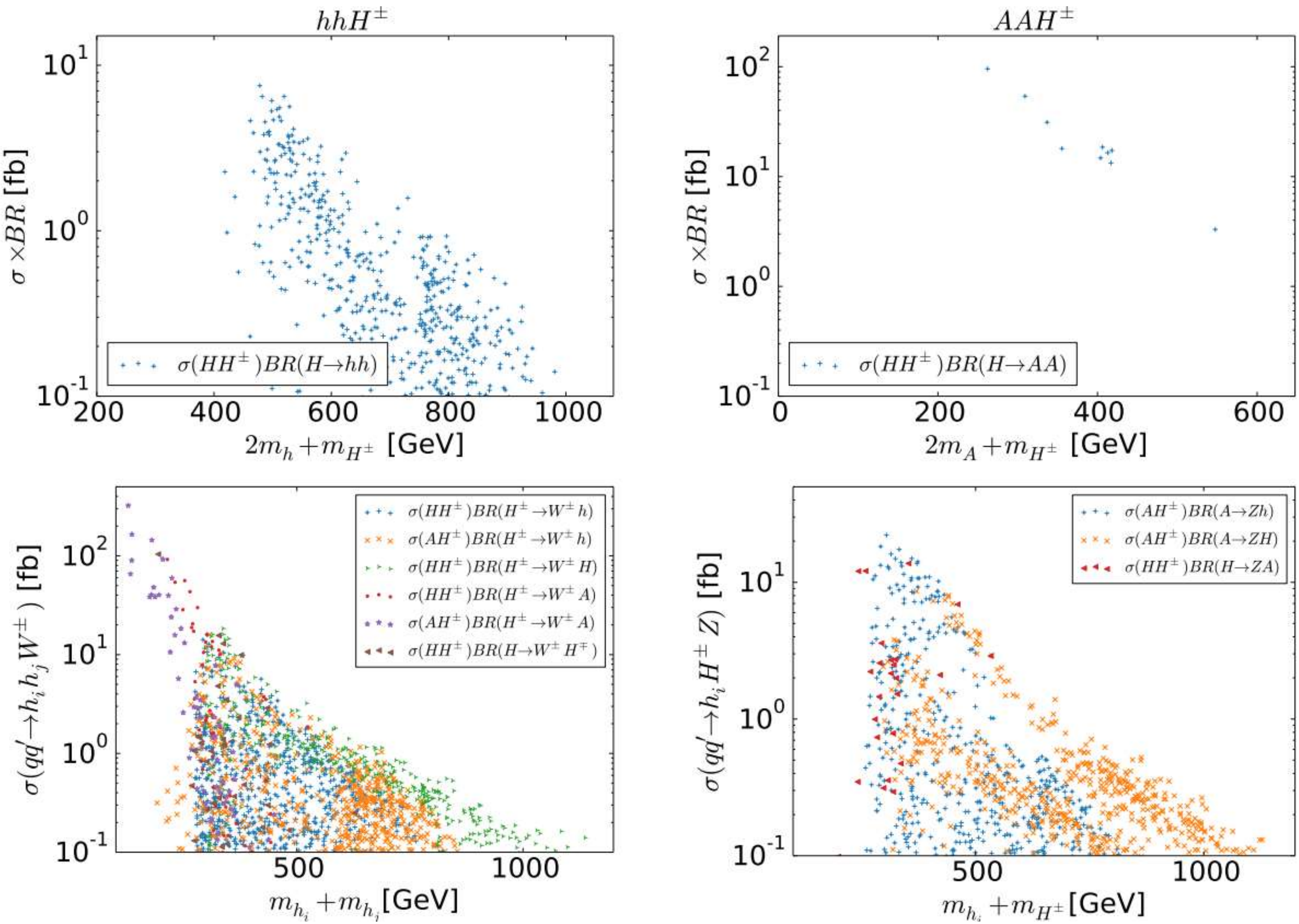
$$\sigma(gg/qq^{(')} \longrightarrow h_i h_j) \times BR(h_{i/j} \longrightarrow h_k h_l / h_k V)$$

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 at the LHC

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(Enhanced) Access compared to the 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}	$(hhh)^*$				$(hhH)^*$	$(hhA)^*$	$(hhH^\pm)^*$			
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^-	$\boxed{AH^+W^-}$			$\boxed{\boldsymbol{hAW^\pm}}$		$\boxed{\boldsymbol{HAW^\pm}}$	$\boxed{\boldsymbol{AAW^\pm}}$ $\boxed{\boldsymbol{H^+H^-W^\pm}}$

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

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a. λ_{hhh}	$(hhh)^*$				$(hhH)^*$	$(hhA)^*$	$(hhH^\pm)^*$			
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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^-	$\boxed{AH^+W^-}$			$\boxed{\boldsymbol{hAW^\pm}}$		$\boxed{\boldsymbol{HAW^\pm}}$	$\boxed{\boldsymbol{AAW^\pm}}$ $\boxed{\boldsymbol{H^+H^-W^\pm}}$

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

Concluding remarks

- *The 2HDM Higgs bosons other than the h_{125} one, even when lighter than it, can be challenging to produce singly at the LHC*
- *Their pair-production might lead to some unconventional, but relatively clean, signatures*
- *For certain 2HDM parameter configurations, EW production of di-Higgs states can dominate over QCD production*
- *Access to some triple-Higgs couplings offered by these states can be greatly supplemented by the tri-Higgs probes*


THANK YOU!
MURAKOZE!