Electroweak production of multiple scalars in the 2HDM

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Based on

RE, W. Klemm, S. Moretti, S. Munir, **1605.02498**
A. Arhrib, R. Benbrik, RE, W. Klemm, S. Moretti, S. Munir, **1706.01964**
RE, W. Klemm, S. Moretti, S. Munir, **1812.08623**

UPPSALA UNIVERSITET

Non Minimal Higgs

European Commission

New scalars

The 2HDM allows two cases for the observed H_{125} :

1. **$H_{125} = h^0$ (with $M_H > 125$ GeV)**
2. **$H_{125} = H^0$ (with $M_h < 125$ GeV)**

- If a Higgs state is light — perhaps O(10 GeV) — then it can be hard to find because of backgrounds
- If it is heavy — O(100s of GeV) — then it can be hard to find because of low cross sections
- Decay rate into SM particles may be small

Light and heavy scalars

We consider these two cases:

1. **$H_{125} = h^0$**
   Multiphoton signatures with small background

2. **$H_{125} = H^0$**
   Two- and three-body final states and electroweak production vs QCD

Parameters of 2HDM (CP cons.)

7 parameters: m_h m_H m_A $m_{H\pm}$ $\sin(\beta-\alpha)$ $\tan\beta$ m_{12}^2

Bounded by constraints:

- *Theoretical:* vacuum stability, unitarity, perturbativity
- *Indirect:* oblique parameters, B-physics
- *Direct:* experimental searches for Higgs bosons
- *Observed Higgs:* one of h^0 and H^0 must be SM-like

Must scan over parameters, checking all constraints

(use: 2HDMC, HiggsBounds/HiggsSignals, SuperIso
by Eriksson et al, Bechtle et al, Mahmoudi)

Multiple scalars to reconstruct the scalar potential

- In order to determine potential parameters, triple Higgs couplings must be accessed experimentally

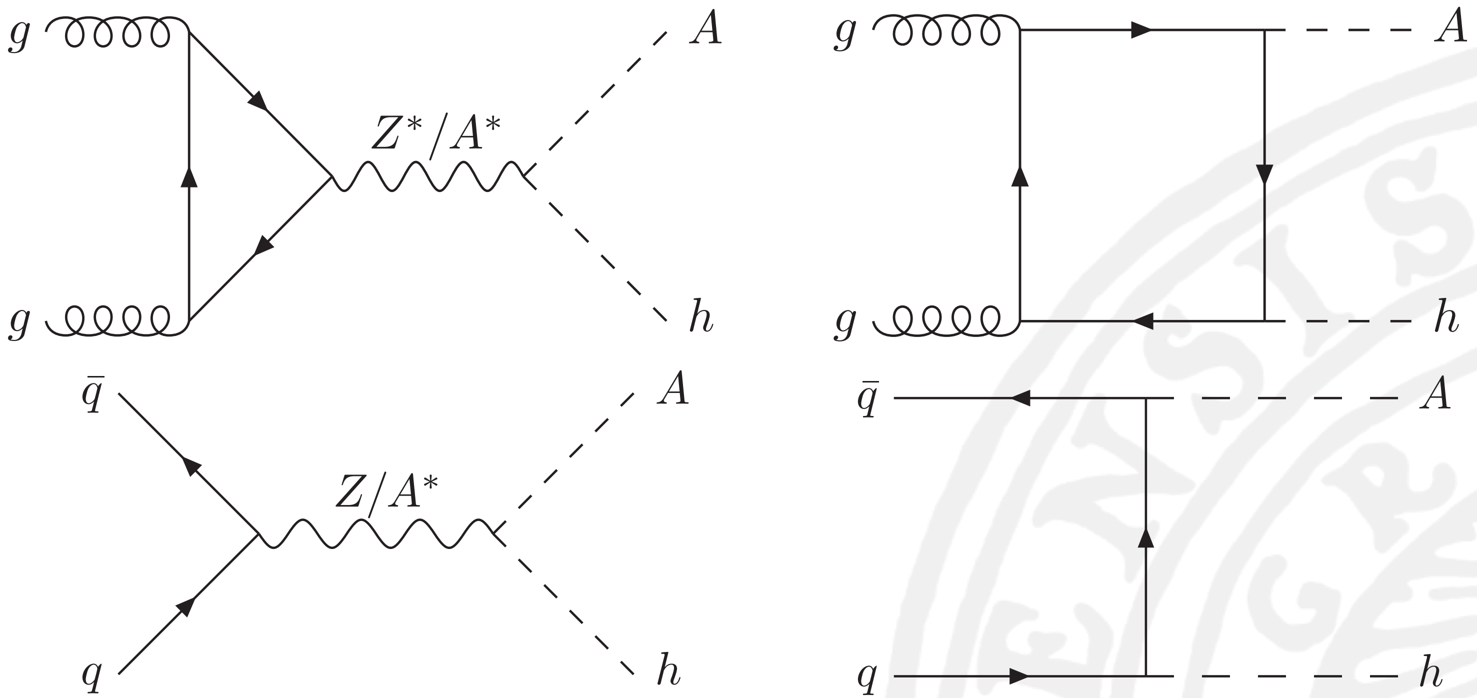
- Need multiple Higgs final states to probe these

- Consider $\mathbf{h_i\, h_j}$ and $\mathbf{h_i\, h_j\, h_k}$, where $\mathbf{h_{i,j,k} = h^0, H^0, A^0, H^\pm}$

- Calculate cross sections using:
  - ✓ MadGraph5_aMC@NLO for qq and bb
  - ✓ Hespel, Lopez-Val, Vryonidou [1407.0281] for gg

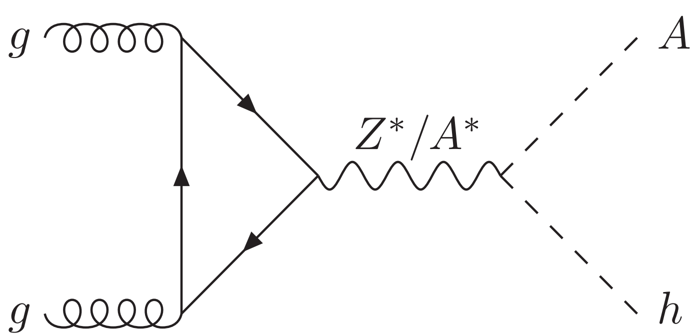
Higgs pair production in 2HDM

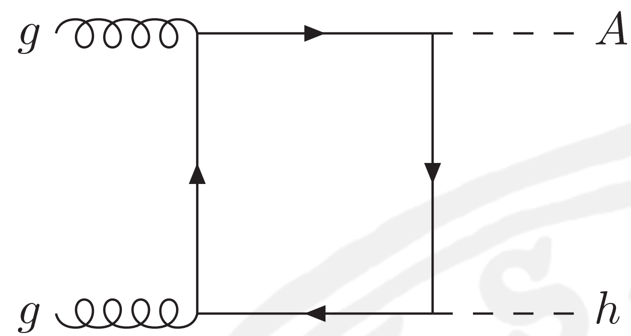
Example: $A^0\, h^0$ production:



Expect gg → $h_i\, h_j$ to be more important (large PDFs etc)

Higgs pair production in 2HDM





BUT: Landau-Yang theorem → an intermediate Z^0 must be off-shell for gg

- gg → Z → $h_i h_j$ suppressed: amplitude ~ $(q_Z^2 - M_Z^2)^{1/2}$
  [Moretti 1407.3511]

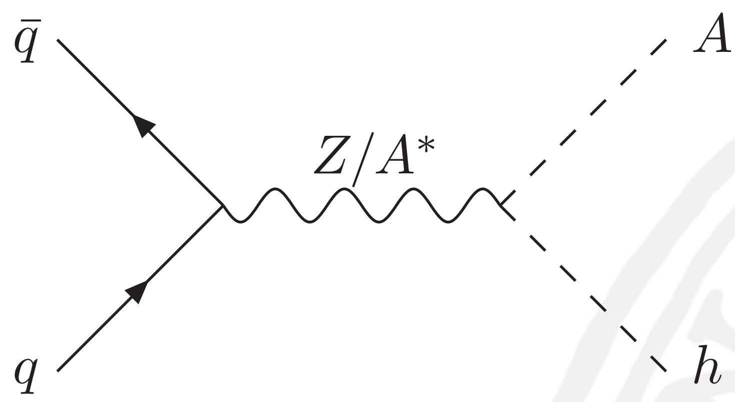
→ Much smaller cross section

→ Cannot use Z-mass to suppress background

(Intermediate scalars can be important if resonant)

Thus: "Electroweak production"

No such restriction on qq-initated process



Upshot: gg → $h_i\, h_j$ needs off-shell Z^0

qq → $h_i\, h_j$ may have on-shell Z^0

→ Will study the relevance for 2HDM pair production for allowed combinations of $h_i\, h_j$ and s-channel particles

Scenario 1: $m_h+m_A<m_Z$; H^0 is SM-like

- The heavier H is SM-like → alignment $|\sin(\boldsymbol{\beta}-\boldsymbol{\alpha})| << 1$
- LEP constraints → h or A more or less fermiophobic – i.e. Yukawa couplings suppressed. In Type I:

$$y_{hf\bar{f}} \propto \frac{\cos\alpha}{\sin\beta} = \sin(\beta-\alpha) + \frac{\cos(\beta-\alpha)}{\tan\beta}$$

  If $|\sin(\beta-\alpha)| << 1$ and tan$\boldsymbol{\beta}$ > 2–3 this is smallish

- If $y_{hff} << 1$, then $\sin(\beta-\alpha) \approx -1/\tan\boldsymbol{\beta}$
- Note also $y_{Af\bar{f}} \propto \cot\beta$

Fermiophobic light h^0 or A^0

When fermion couplings of h^0 are suppressed:

- $h \rightarrow AZ^*$ can dominate if A is light enough
- $h \rightarrow \gamma\gamma$ can be large if $h \rightarrow AZ^*$ is not possible

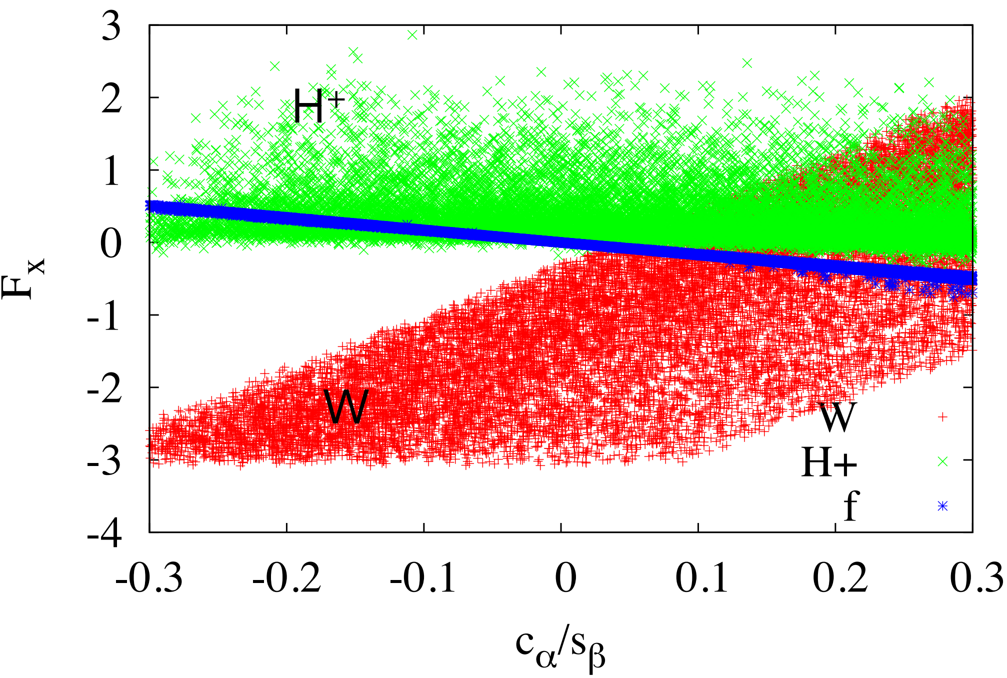
When fermion couplings of A^0 are suppressed:

- $A \rightarrow hZ^*$ can dominate if h is light enough
- $A \rightarrow \gamma\gamma$ not possible if fermiophobic (no WW)

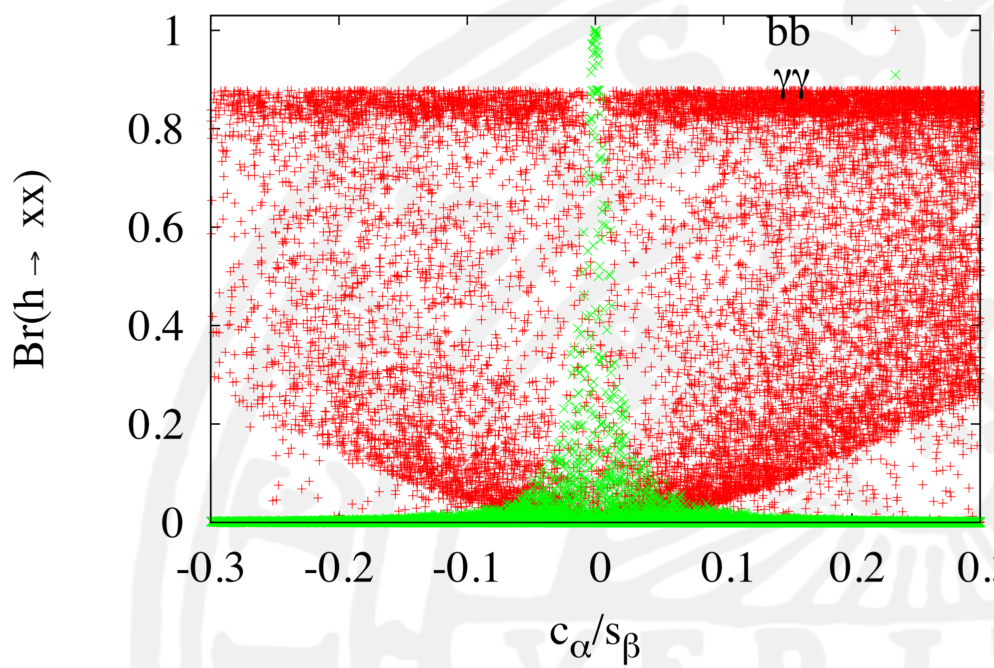
Many searches for light h^0, A^0 consider bb or $\tau^+\tau^-$ decays

Dominant $h^0 \rightarrow \gamma\gamma$

Loop factor for the decay:
W (red), H^+ (green), f (blue)



BR: bb (red), $\gamma\gamma$ (green)



[Arhrib, Benbrik, RE, Klemm, Moretti, Munir, 1706.01964]

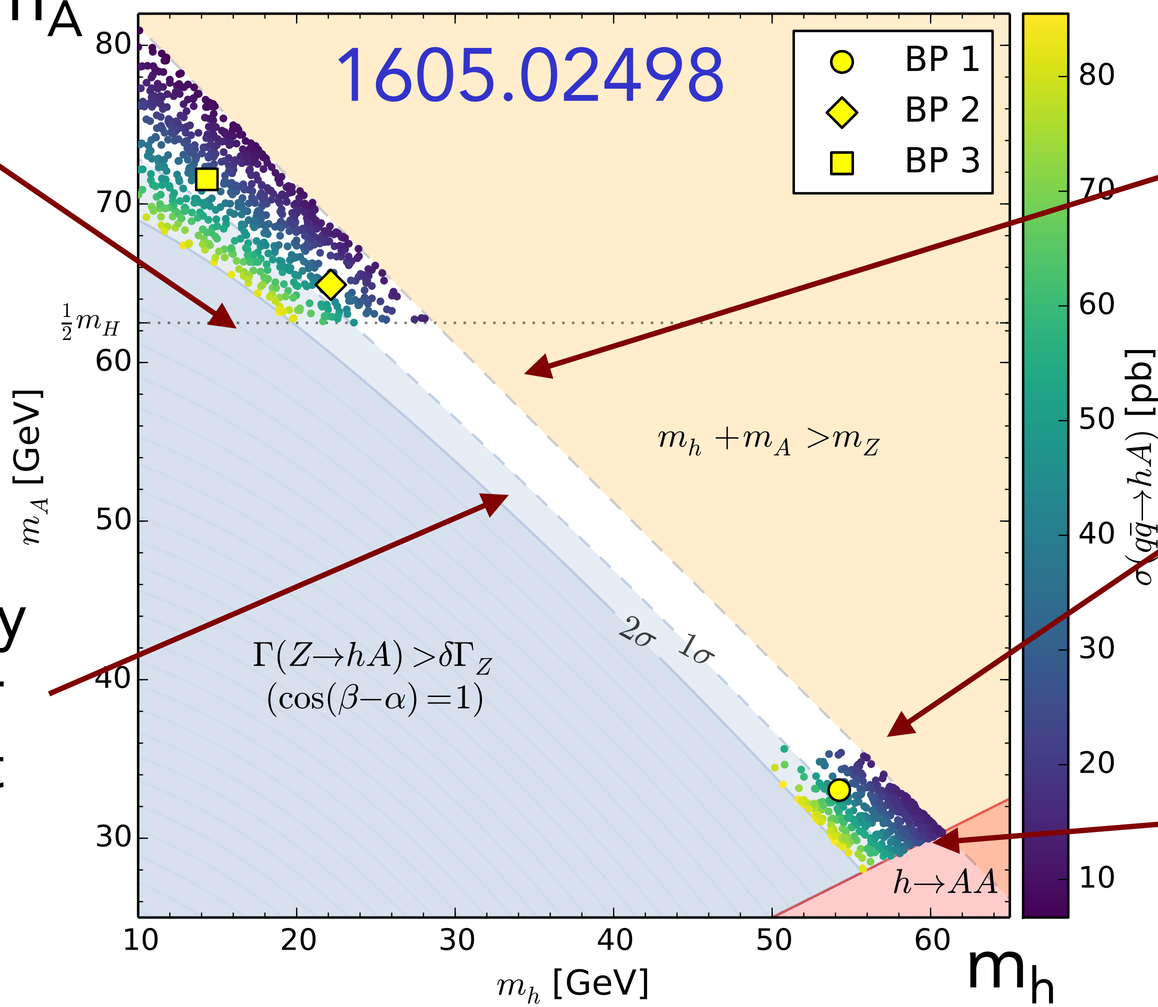
For small c_α BR($h^0 \rightarrow \gamma\gamma$)$\approx$1 is possible: fermiophobic h^0

Type I allowed parameter space

m_A

$m_A = m_H/2$:

H→AA opens → H non-SM-like



m_h

$m_h + m_A > m_Z$

Small enough HAA coupling

Z → hA decay too large for Γ_Z constraint

$m_h = 2m_A$:

h→AA opens → LEP constraints

We find that σ(qq) is indeed much larger than σ(gg) in this sample

Scenario 1B: H^0 is SM-like, $H^{\pm}$ is light

Either h or A is lighter than $H^{\pm}$ so

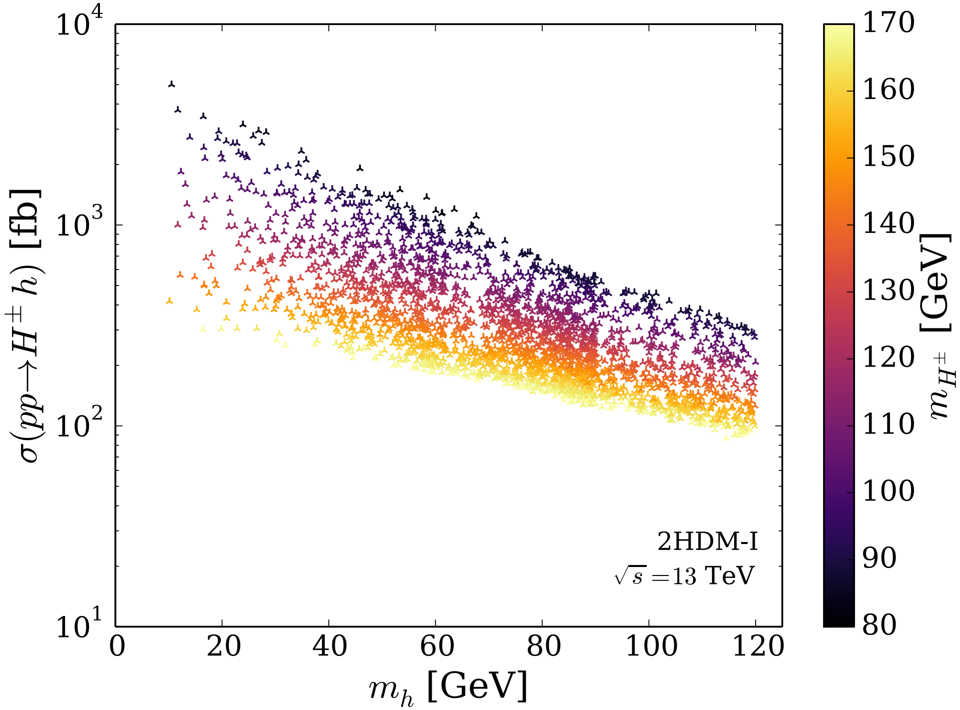
- $H^{\pm} \to W^{\pm} h$ or $H^{\pm} \to W^{\pm} A$

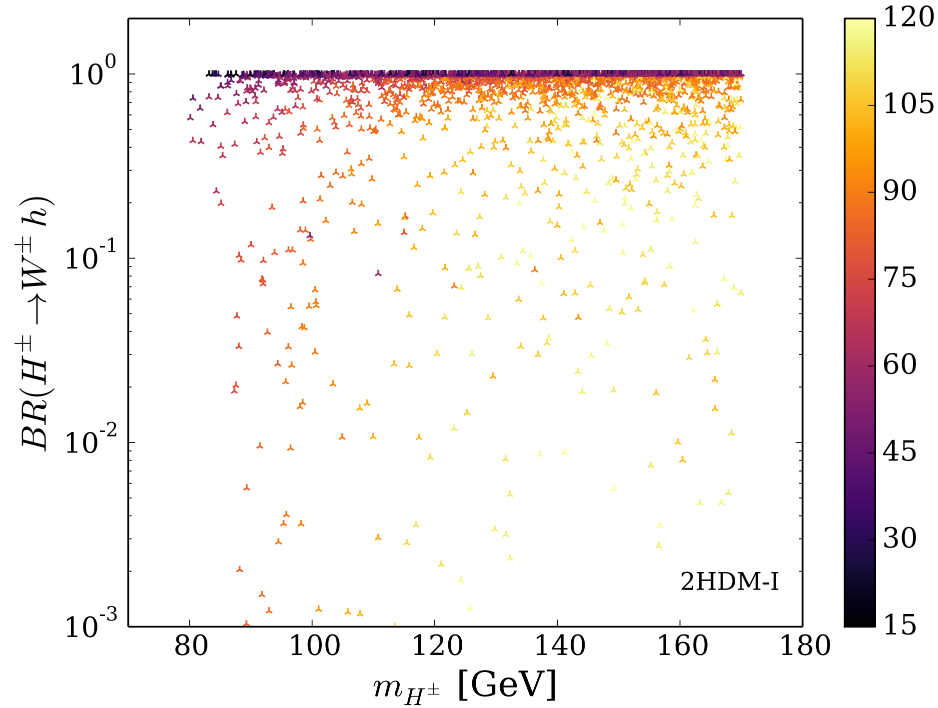
Production

- $pp \to H^{+} h$
- $pp \to H^{+} H^{-}$
- $pp \to H^{+} A$
- $pp \to H^{+} W^{-}$

Partially same parameter space as Scenario 1 but we allow also heavier h or A

$H^\pm$ production & decay





$\sigma(pp \to W^{\pm *} \to H^\pm h^0)$

large because $H^\pm W^\pm h^0$ coupling ~ $\cos(\beta-\alpha) \sim 1$ and large phase space

$BR(H^\pm \to W^\pm h^0)$

Again large because same $H^\pm W^\pm h^0$ coupling

[Arhrib, Benbrik, RE, Klemm, Moretti, Munir, 1706.01964]

Scenario 1B: LHC signals

If h or A are light enough and fermiophobic:

- $pp \to H^+ h \to (W^*h)\, h \to W^*\gamma\gamma\gamma\gamma$
- $pp \to H^+ H^- \to (W^*h)(W^*h) \to W^*W^*\gamma\gamma\gamma\gamma$

Such signals are challenging:

Typically would need to trigger on leptons and photons with pT of 10-20 GeV (this is possible!)

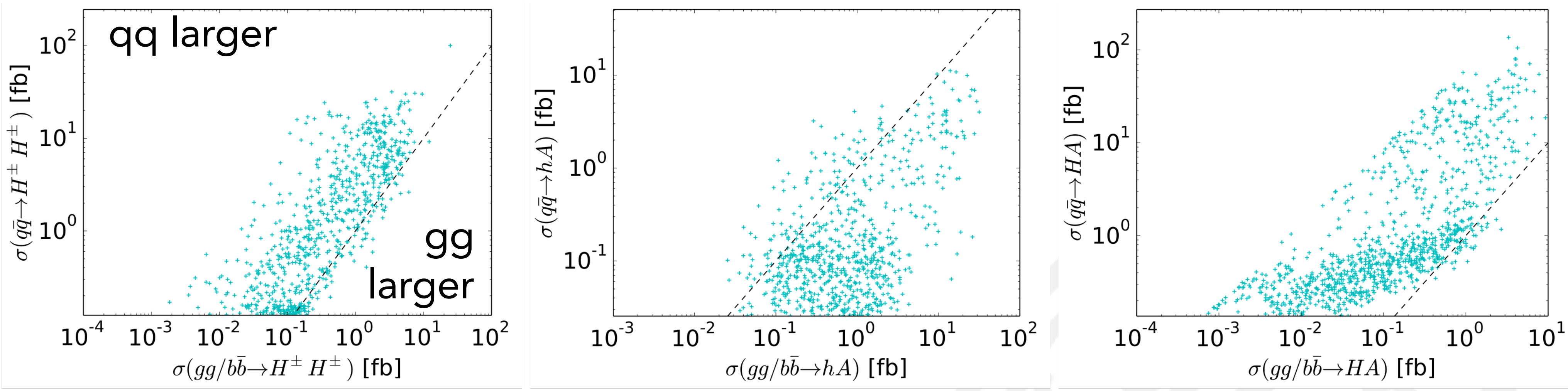
But there is no irreducible background! (~ 10^{-3} fb)

(See our MC study in 1706.01964)

Scenario 2: h^0 is SM-like, other scalars heavier

- Will we have the same effect for heavier scalars?
  → Will depend on if vector propagator allowed
- Consider Type I
- Production of pairs h_i h_j and triples h_i h_j h_k, for $h_{i,j,k} = h^0, H^0, A^0, H^\pm$
- Find that gg → h_i h_j is usually larger than qq → h_i h_j but there are exceptions: Z or W propagator
- I will only give a couple of examples here, but we have calculated cross sections for all possible pairs of neutral and charged Higgs bosons

pp→h_i h_j : qq vs gg production

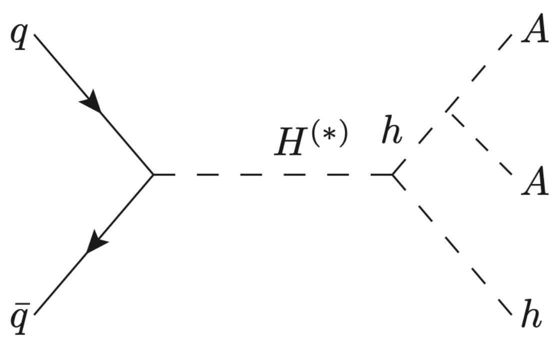


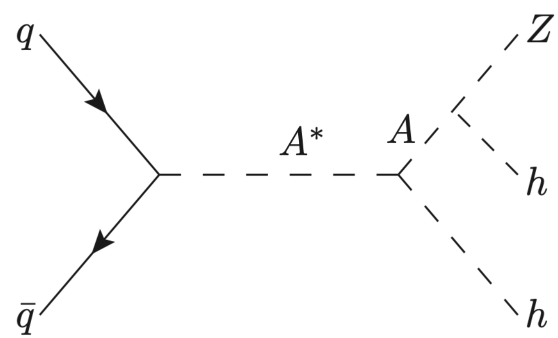
H^+H^- h^0A^0 H^0A^0

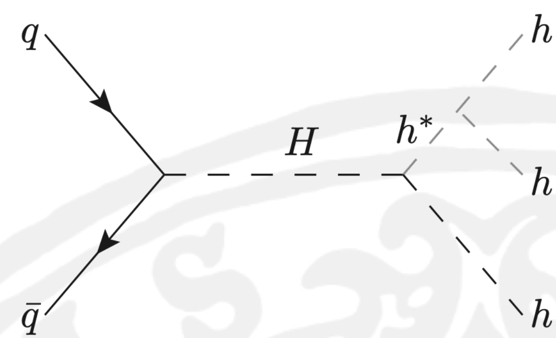
Here qq can still dominate: Z exchange
is allowed for CP even + CP odd
No enhancement from bb production

h^0h^0, H^0H^0, h^0H, A^0A^0 : gg fusion dominates

Three-body final states







(Not this one)

We also consider three-body final states in a narrow-width approximation with decays from a two-body final state

What couplings can we access? 2-body final 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. $\lambda_{AH^+W^-}$										✓

Box or bold = qq production largest (or can be)

3-body final 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^-	$\boxed{AH^+W^-}$			$\boxed{\boldsymbol{hAW^\pm}}$		$\boxed{\boldsymbol{HAW^\pm}}$	$\boxed{\boldsymbol{AAW^\pm}}$ $\boxed{\boldsymbol{H^+H^-W^\pm}}$

Box or bold = qq production largest (or can be)

Summary

- If a Z or W is allowed in s-channel, cross section for qqbar production can be large
- Especially if Z can be onshell, which it can't be in gg production
- There are regions of 2HDM parameter space where this happens
- Multiphoton signatures
- Might be a way to access triple Higgs couplings