Electroweak production of multiple scalars in the 2HDM

Rikard Enberg

Scalars 2017, Warsaw

UPPSALA
UNIVERSITET

Based on

RE, W. Klemm, S. Moretti, S. Munir, **1605.02498 (in PLB)**
A. Arhrib, R. Benbrik, RE, W. Klemm, S. Moretti, S. Munir, **1706.01964 (in PLB)**
RE, W. Klemm, S. Moretti, S. Munir, **in preparation**

Parameters of 2HDM (CP cons.)

7 parameters: m_h m_H m_A $m_{H\pm}$ $s_{\beta\alpha}$ $\tan\beta$ m_{12}^2

Bounded by constraints:

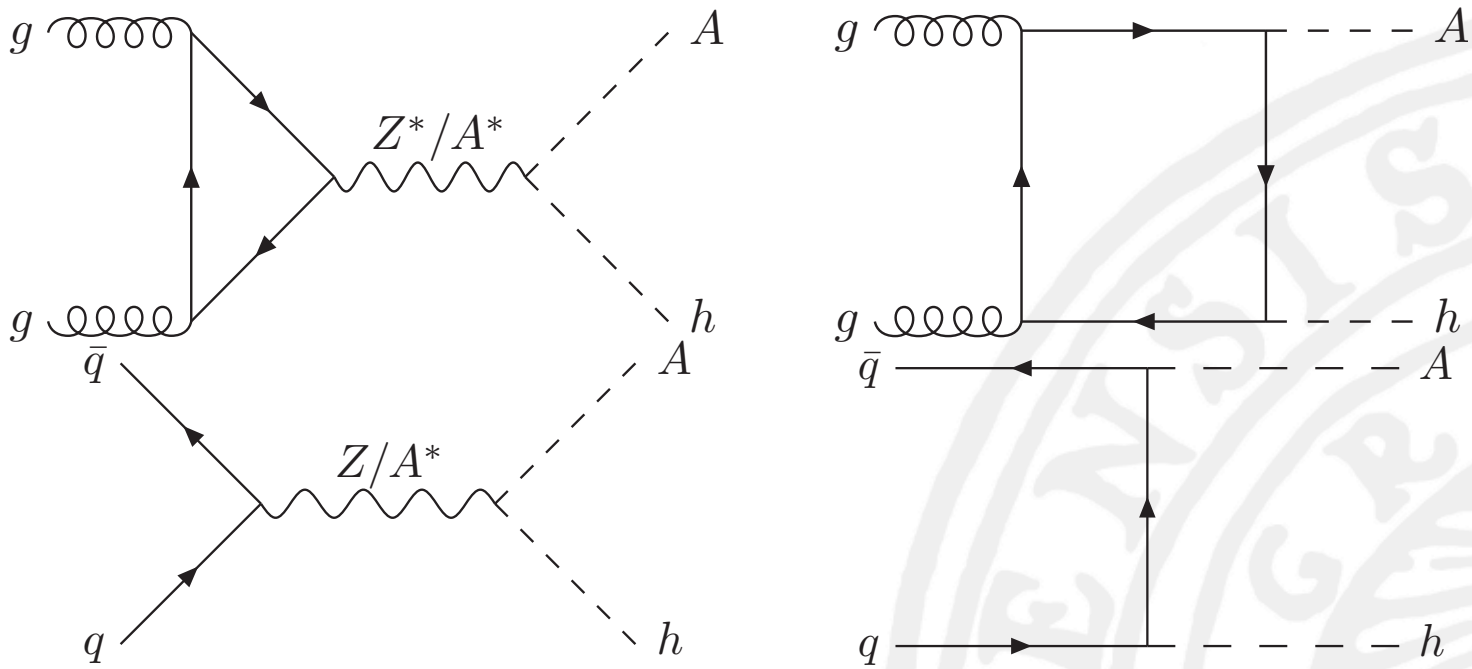
- *Theoretical:* vacuum stability, unitarity, perturbativity
- *Indirect:* oblique parameters, B-physics
- *Direct:* experimental searches for Higgs bosons
- *Observed Higgs:* one of h^0 and H^0 must be SM-like

Must scan over parameters, checking all constraints

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

Higgs pair production in 2HDM

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

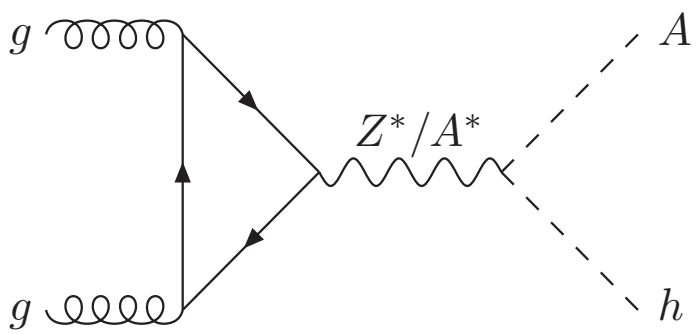


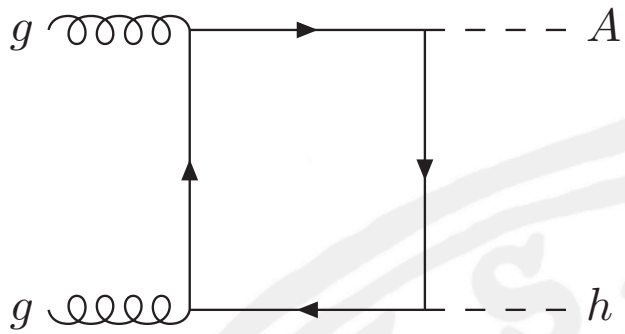
A lot of gluons in the proton, and at least one of qqbar must be a sea quark

Thus expect gg → $h_i\,h_j$ to be more important

($h_{i,j} = h^0, H^0, A^0, H^{\pm}$)

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]

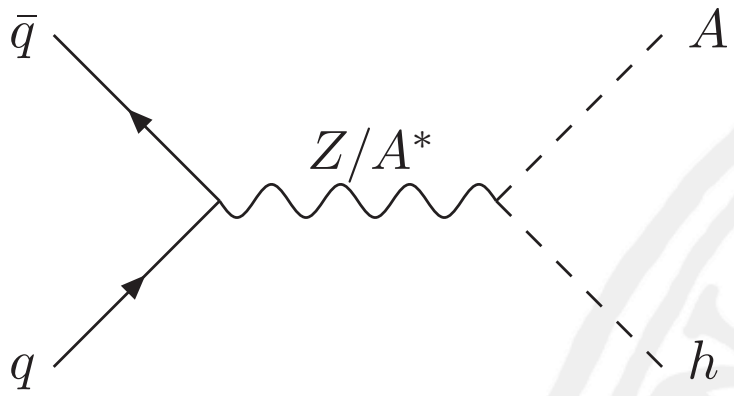
→ Much smaller cross section

→ 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 $|\sin(\beta-\alpha)| << 1$
- 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 $\tan\beta > 2$–3 this is smallish

- If $y_{hff} << 1$, then $\sin(\beta-\alpha) \approx -1/\tan\beta$
- 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

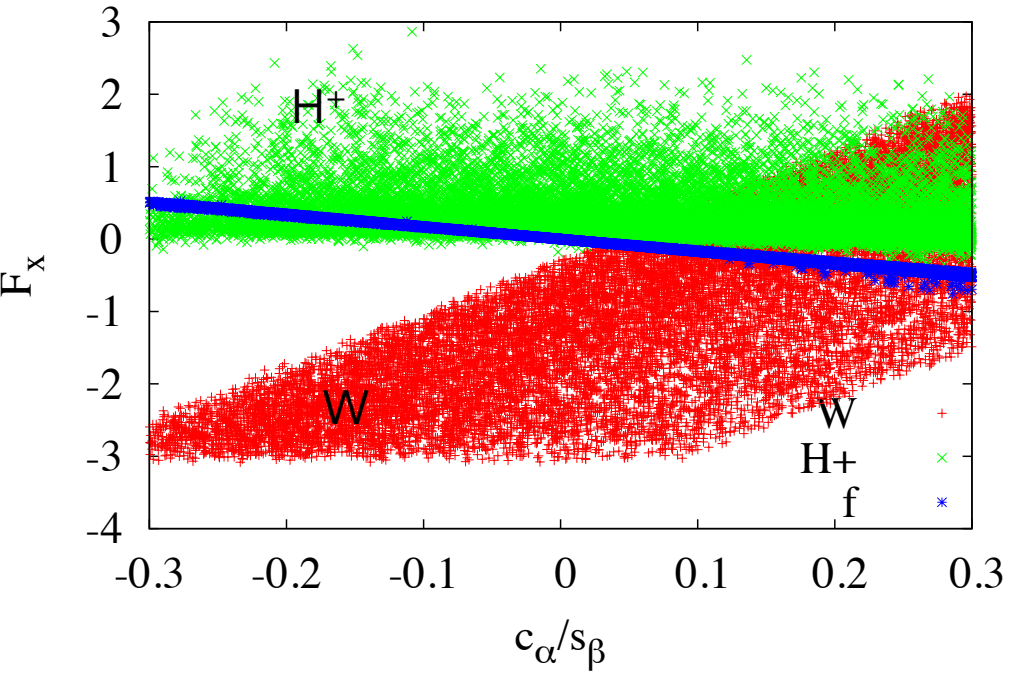
When fermion couplings of A^0 are suppressed:

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

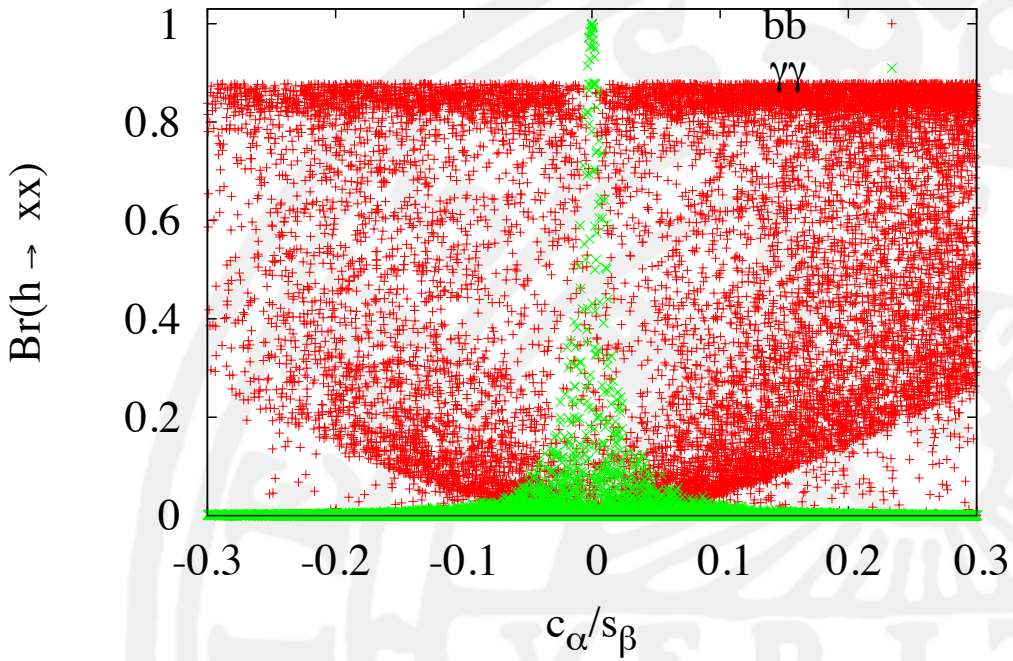
Many searches for light h^0, A^0 consider bb or $\tau^+\tau^-$ decays

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

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



BR: bb (red), γγ (green)



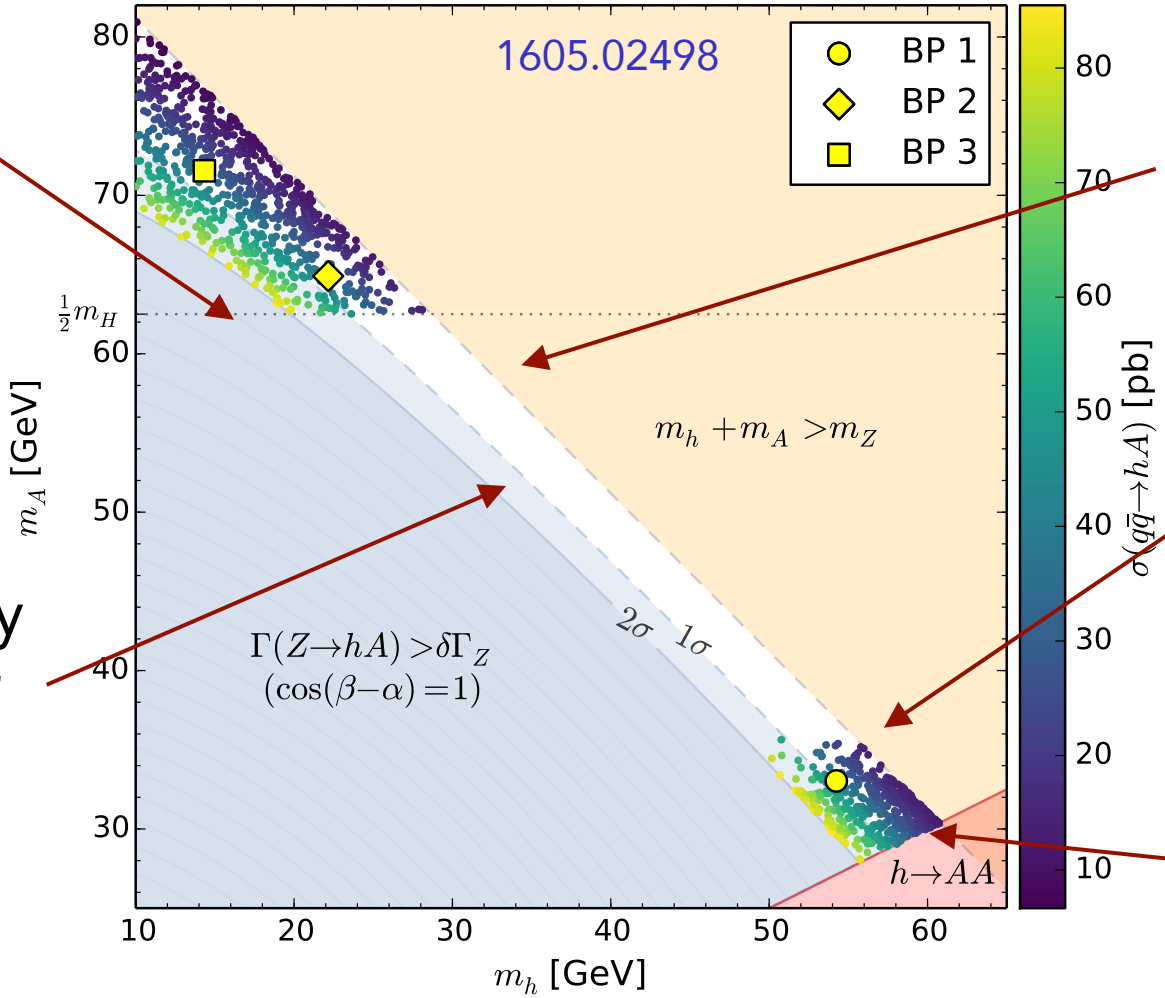
[Arhrib, Benbrik, RE, Klemm, Moretti, Munir, 1706.01964]

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

Type I allowed parameter space

$m_A=m_H/2$:

H→AA opens → non-SM-like



$m_h+m_A>m_Z$

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 2: H is SM-like, $H^{\pm}$ is light

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

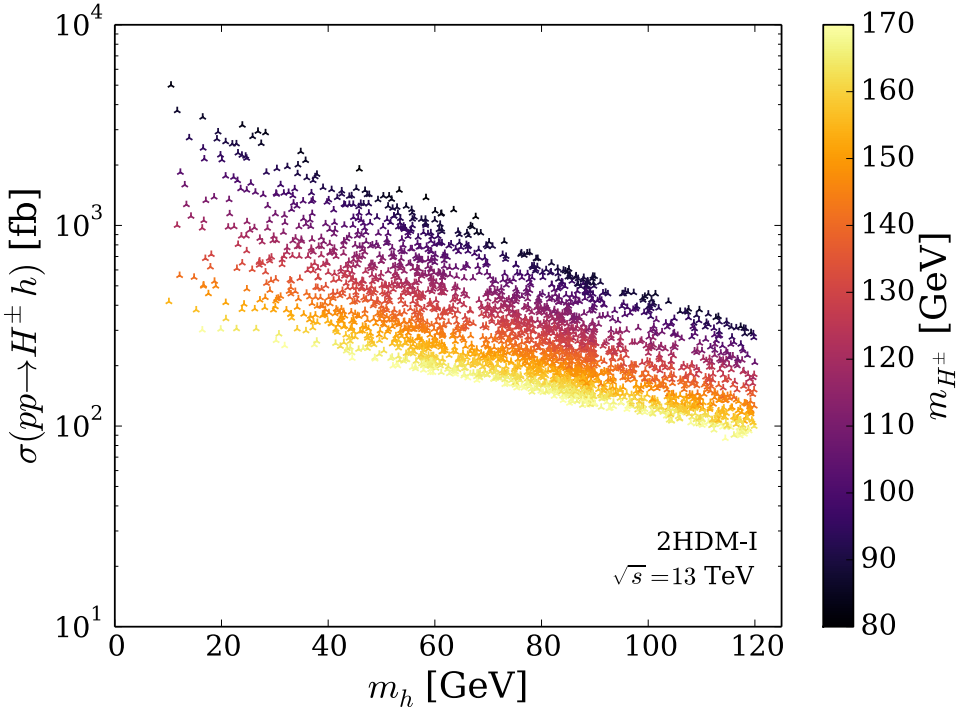
- $H^{\pm} \rightarrow W^{\pm} h$ or $H^{\pm} \rightarrow W^{\pm} A$

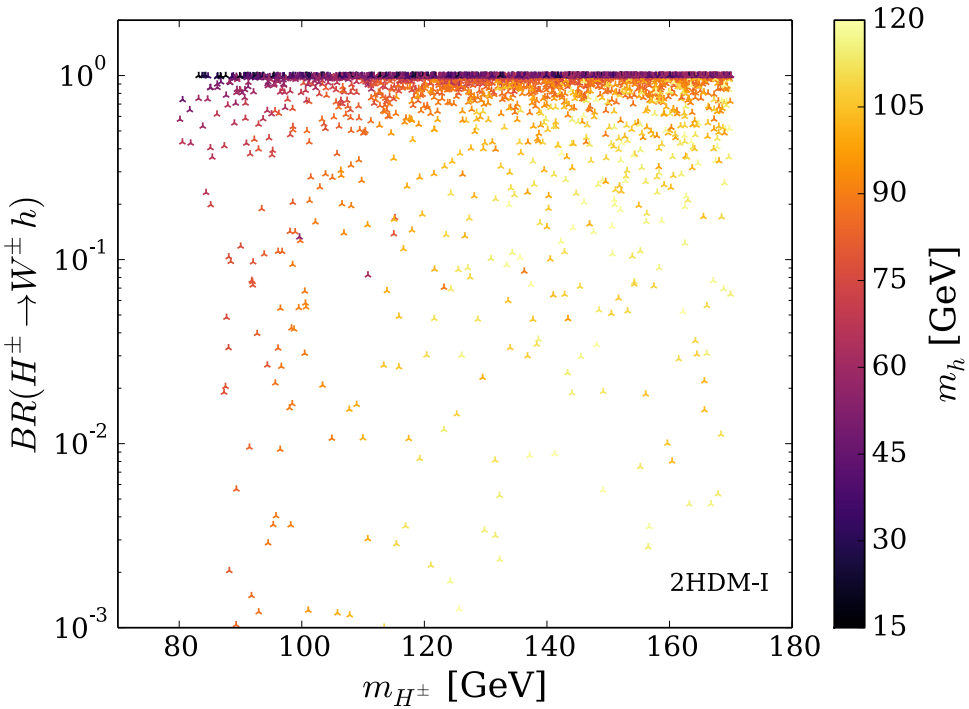
Production

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

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 2: LHC signals

If h or A are light enough and fermiophobic:

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

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 background! (~ 10^{-3} fb)

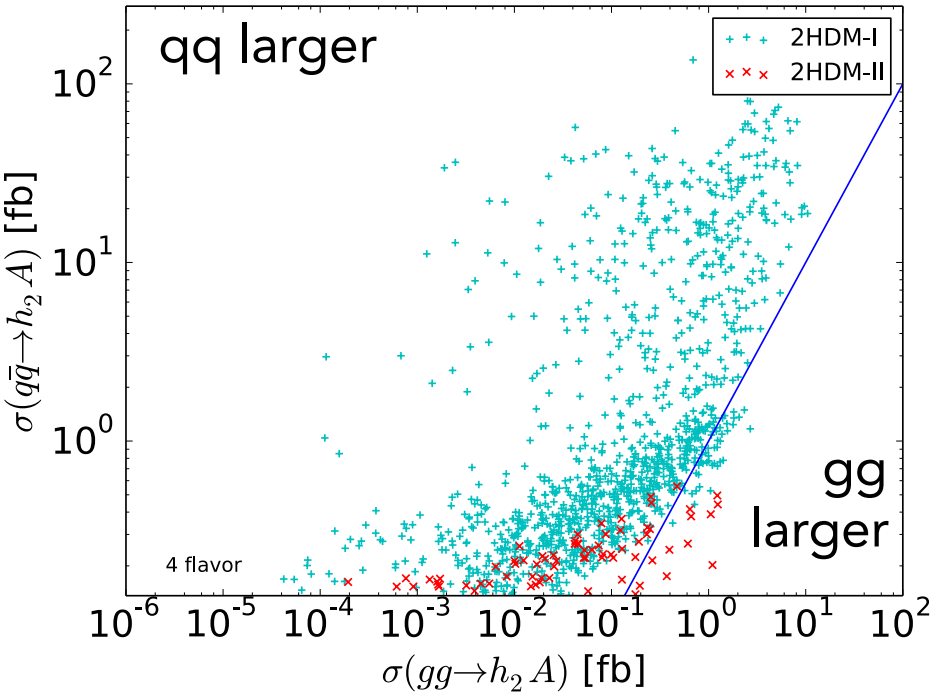
MC study in 1706.01964

Scenario 3:
h^0 is SM-like, other scalars heavier

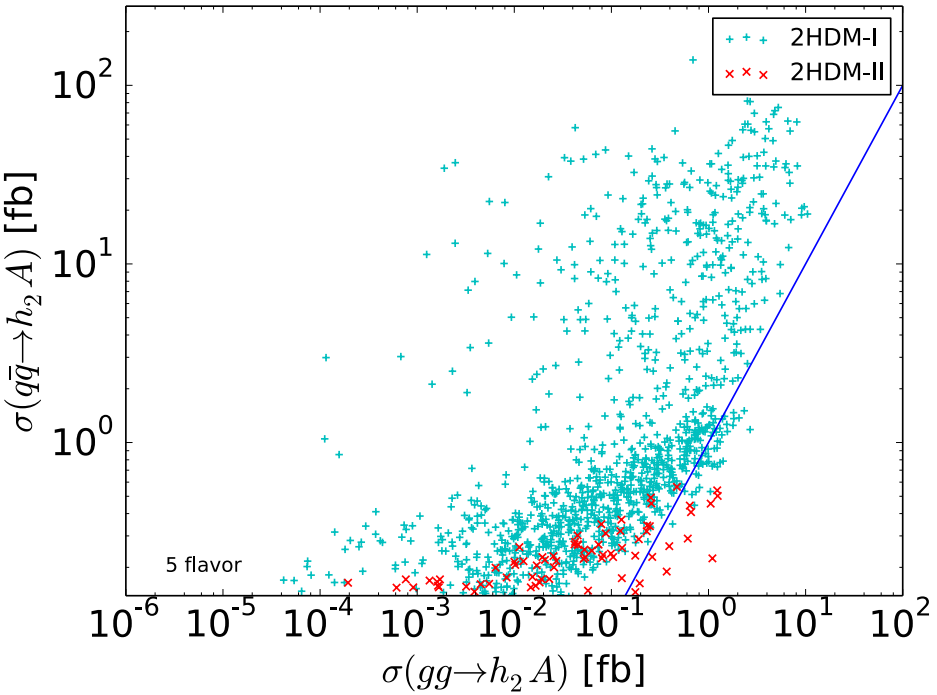
- Will we have the same effect for heavier scalars?
  → Will depend on if vector propagator allowed
- Consider Type I and II
- Production of pairs h_i h_j as well as 3 or 4 scalars for $h_{i,j} = h^0, H^0, A^0, H^\pm$
- Find that gg → h_i h_j is usually larger than qq → h_i h_j but there are exceptions: 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→H⁰ A⁰: qq vs gg production

4 flavor



5 flavor

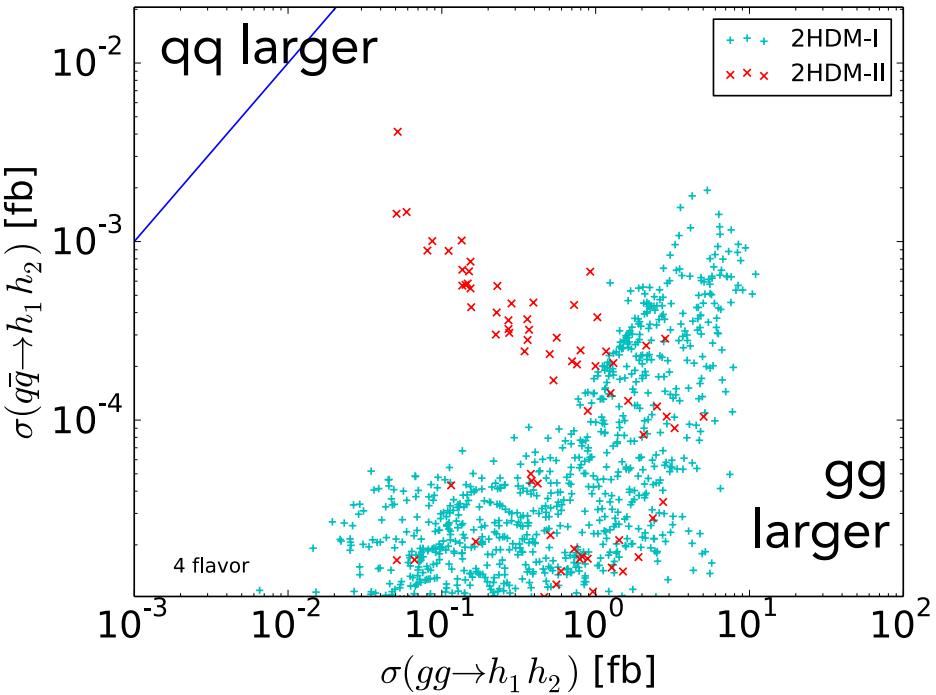


Here qq can still dominate: Z exchange
is allowed for CP even + CP odd
No enhancement from bb production

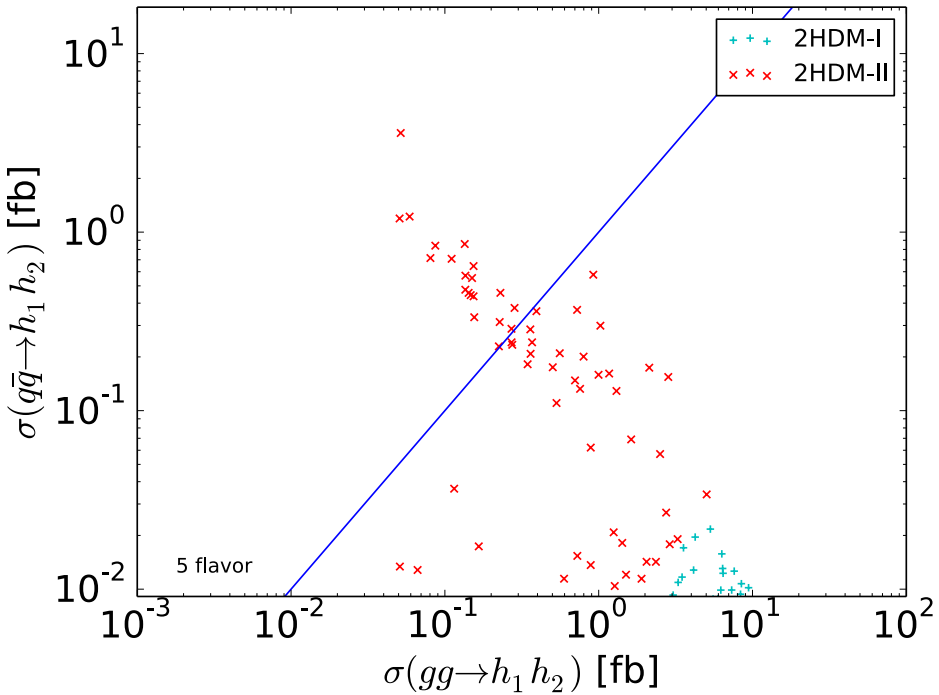
R. Enberg, Scalars 2017

pp→H⁰ h⁰: qq vs gg production

4 flavor



5 flavor



No vector boson in s-channel allowed
Large enhancement from bb in Type II:
t-channel or CP-even Higgs in s-channel

R. Enberg, Scalars 2017

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
- Especially for light h^0, A^0, $H^\pm$ in Type I