# Probing Two Higgs Doublet Models through production of multiple scalars at the Large Hadron Collider

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Joint work with Rikard Enberg, Stefano Moretti, and Shoaib Munir

# Overview

- The 2HDM and its couplings
- Higgs pair production from $qq'$
- Decays and three body multi-Higgs final states
- Possible sensitivity
- $W + 4\gamma$ in a fermiophobic 2HDM

# Two Higgs Doublet Model

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

$$\Phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix}\sqrt{2}\left(G^+\cos\beta - H^+\sin\beta\right) \\ v_1 - h\sin\alpha + H\cos\alpha + \mathrm{i}\left(G\cos\beta - A\sin\beta\right)\end{pmatrix} \Phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix}\sqrt{2}\left(G^+\sin\beta + H^+\cos\beta\right) \\ v_2 + h\cos\alpha + H\sin\alpha + \mathrm{i}\left(G\sin\beta + A\cos\beta\right)\end{pmatrix}$$

## Triple Higgs-Gauge couplings

| $\sin(\beta-\alpha)$ | $\cos(\beta-\alpha)$ | neither |
|---|---|---|
| $HAZ$ | $hAZ$ | – |
| $HH^+W^-$ | $hH^+W^-$ | $AH^+W^-$ |
| $hZZ$ | $HZZ$ | – |
| $hW^+W^-$ | $HW^+W^-$ | – |

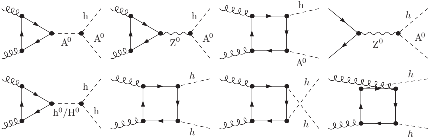
## Triple Higgs couplings –

more complicated expressions with $\lambda_i$'s

8 couplings in $CP$-conserving 2HDM
$hhh$, $hhH$, $hHH$, $HHH$,
$hAA$, $HAA$, $hH^+H^-$, $HH^+H^-$

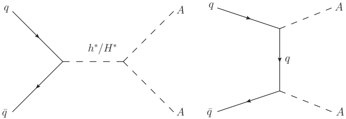
# Higgs pair production

The LHC is great for high energy gluon fusion processes...

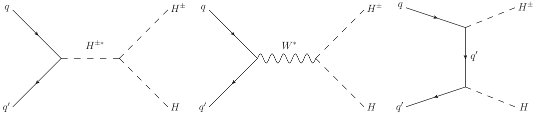



Hespel, Lopez-Val, Vryonidou 1407.0281

But $qq'$-initiated processes can provide important insight




$hAA$, $HAA$, Yukawa




$HH^\pm H^\mp$, $HH^\pm W^\mp$ , Yukawa

We need as many observations as possible to fully constrain couplings.

# Parameter scan - Type I 2HDM

Constraints on scan (95% CL)

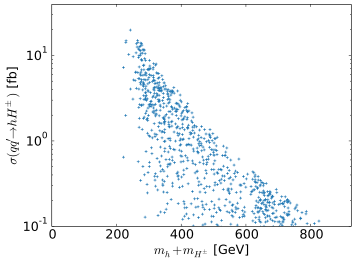
- Unitarity, perturbativity, vacuum stability [2HDMC]
- Electroweak precision observables
- LEP, Tevatron, LHC limits [HiggsBounds 5]
- B-physics observables [Superiso + derived bounds] (F. Mahmoudi 2016)
- Reproduce observed 125 GeV signal strengths [HiggsSignals]

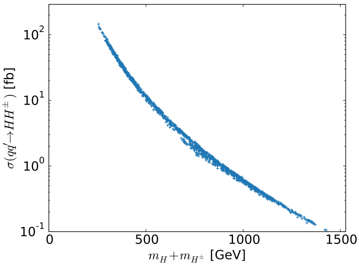
| Parameter | Scanned range |
|---|---|
| $m_h$ (GeV) | (150, 750) |
| $m_A$ (GeV) | (50, 750) |
| $m_{H^\pm}$(GeV) | (50, 750) |
| $\sin(\beta-\alpha)$ | (−1, 1) |
| $m_{12}^2$ (GeV$^2$) | (0, $m_A^2 \sin\beta\cos\beta$) |
| $\tan\beta$ | (2, 25) |

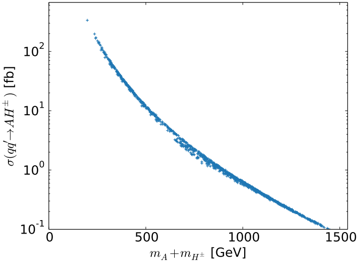
Scanned ranges of the 2HDM-I parameters.

Calculate $qq$ and $gg/bb$ initiated cross sections for all Higgs pairs.

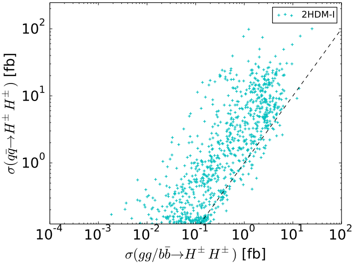
# Charged final states

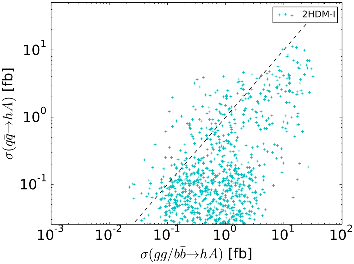


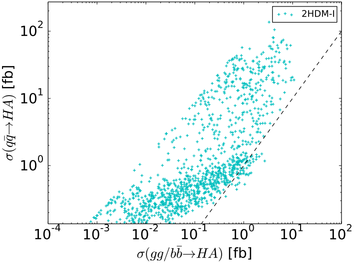



# Neutral final states




## Most interesting pairs:

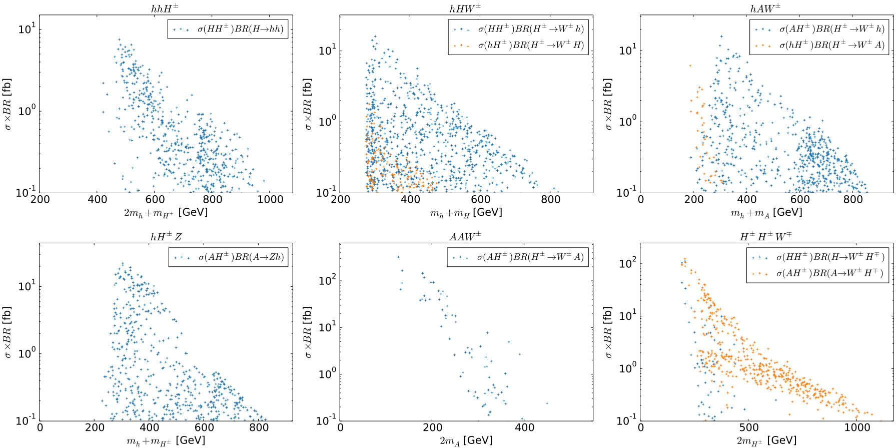
| | | | |
|---|---|---|---|
| $hh$ | $hH$ | $hA$ | $hH^\pm$ |
| | $HH$ | $HA$ | $HH^\pm$ |
| | | $AA$ | $AH^\pm$ |
| | | | $H^+H^-$ |

# Three body final states

What if we allow Higgs→Higgs decays? All possible (on-shell) decays are potentially relevant, excepting $H \to H^+H^-$.

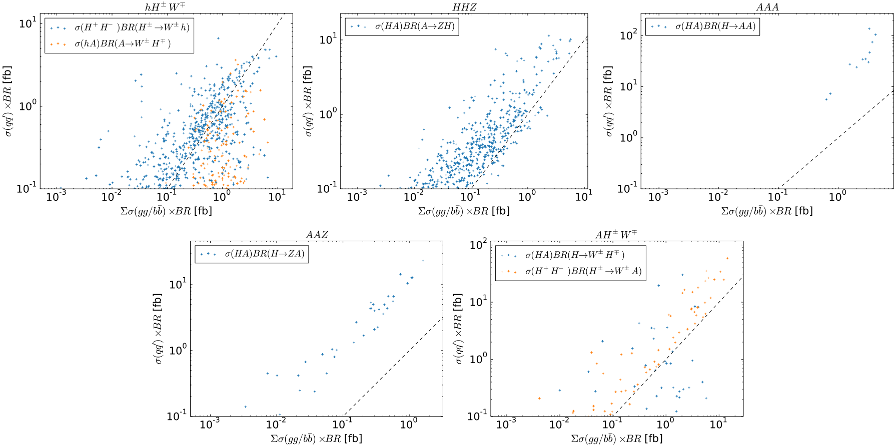
| 3BFS | Process 1 $\sigma$ | BR | $\sigma^{\max}_{qq'}$ [fb] | Process 2 $\sigma$ | BR | $\sigma^{\max}_{qq'}$ [fb] | $\sigma^{\max}_{gg/bb}$ [fb] |
|---|---|---|---|---|---|---|---|
| $AAW$ | $AH^\pm$ | $(H^\pm \to W^\pm A)$ | 322 | | | | – |
| $AAA$ | $HA$ | $(H \to AA)$ | 135 | | | | 4 |
| $H^\pm H^\pm W$ | $AH^\pm$ | $(A \to W^\pm H^\mp)$ | 124 | $HH^\pm$ | $(H \to W^\pm H^\mp)$ | 112 | – |
| $AAH^\pm$ | $HH^\pm$ | $(H \to AA)$ | 95 | | | | – |
| $HAW$ | $HH^\pm$ | $(H^\pm \to W^\pm A)$ | 91 | $AH^\pm$ | $(H^\pm \to W^\pm H)$ | 10 | – |
| $AH^\pm W$ | $H^+H^-$ | $(H^\pm \to W^\pm A)$ | 58 | $HA$ | $(H \to W^\pm H^\mp)$ | 30 | 14 |
| $HH^\pm W$ | $HA$ | $(A \to W^\pm H^\mp)$ | 36 | $H^+H^-$ | $(H^\pm \to W^\pm H)$ | 3 | 3 |
| $AAZ$ | $HA$ | $(H \to ZA)$ | 23 | | | | 1 |
| $hH^\pm Z$ | $AH^\pm$ | $(A \to Zh)$ | 22 | | | | – |
| $HHW$ | $HH^\pm$ | $(H^\pm \to W^\pm H)$ | 16 | | | | – |
| $hHW$ | $HH^\pm$ | $(H^\pm \to W^\pm h)$ | 16 | $hH^\pm$ | $(H^\pm \to W^\pm H)$ | 1 | – |
| $hAW$ | $AH^\pm$ | $(H^\pm \to W^\pm h)$ | 15 | $hH^\pm$ | $(H^\pm \to W^\pm A)$ | 6 | – |
| $AH^\pm Z$ | $HH^\pm$ | $(H \to ZA)$ | 13 | | | | – |
| $hHZ$ | $HA$ | $(A \to Zh)$ | 13 | | | | 5 |
| $HHZ$ | $HA$ | $(A \to ZH)$ | 11 | | | | 5 |
| $HH^\pm Z$ | $AH^\pm$ | $(A \to ZH)$ | 8 | | | | – |
| $hhH^\pm$ | $HH^\pm$ | $(H \to hh)$ | 7 | | | | – |
| $hH^\pm W$ | $H^+H^-$ | $(H^\pm \to W^\pm h)$ | 6 | $hA$ | $(A \to W^\pm H^\mp)$ | 3 | 9 |
| $hhA$ | $HA$ | $(H \to hh)$ | 3 | | | | 0.3 |
| $hhZ$ | $hA$ | $(A \to Zh)$ | 2 | | | | 4 |
| $hhW$ | $hH^\pm$ | $(H^\pm \to W^\pm h)$ | 2 | | | | – |

# Charged 3BFS




Cross sections of $qq'$-initiated subprocesses for selected charged three body final states.

# Neutral 3BFS




Comparison of $qq'$-initiated subprocesses with their $gg/bb$-initiated cross sections for selected neutral three body final states. The dashed line indicates where the cross sections are of equal magnitude.

# (Possible) sensitivity to couplings

| Coupling | 2BFS | Decay |
|---|---|---|
| $hhh$ | $hh$ | |
| $hhH$ | $hh$, $hH$ | $H \to hh$ |
| $hHH$ | $HH$, $hH$ | |
| $HHH$ | $HH$ | |
| $hAA$ | $AA$, $hA$ | |
| $HAA$ | $AA$, $HA$ | $H \to AA$ |
| $hH^+H^-$ | $H^+H^-$, $hH^\pm$ | $H \to H^+H^-$ |
| $HH^+H^-$ | $H^+H^-$, $HH^\pm$ | |
| $hAZ$ | $hA$ | $A \to Zh$ |
| $hH^+W^-$ | $hH^\pm$ | $H^\pm \to W^\pm h$ |
| $HAZ$ | $HA$ | $H \to ZA$, $A \to ZH$ |
| $HH^+W^-$ | $HH^\pm$ | $H \to W^\pm H^\mp$, $H^\pm \to W^\pm H$ |
| $AH^+W^-$ | $AH^\pm$ | $A \to W^\pm H^\mp$, $H^\pm \to W^\pm A$ |

- Most couplings appear in potentially interesting channel
- Production depends on several couplings
- Decays require knowledge of width/competing decays

For all processes, sensitivity will depend on Higgs decays and corresponding backgrounds.

# A specific example - $W + 4\gamma$ in the 2HDM-I

A. Arhrib, R. Benbrik, R. Enberg, WK, S. Moretti, and S. Munir [arXiv:1706.01964]

Constraints on scan (95% CL)

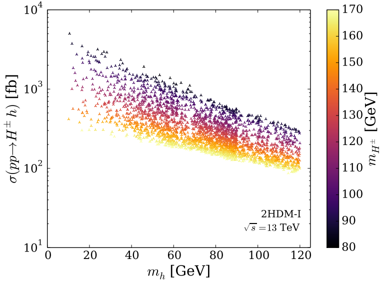
- Unitarity, perturbativity, vacuum stability [2HDMC]
- Electroweak precision observables
- LEP, Tevatron, LHC limits [HiggsBounds 5]
- B-physics observables [Superiso]
- Reproduce observed 125 GeV signal strengths [HiggsSignals]

| Parameter | Scanned range |
|---|---|
| $m_h$ (GeV) | (10, 120) |
| $m_H$ (GeV) | 125 |
| $m_A$ (GeV) | (10, 500) |
| $m_{H^\pm}$(GeV) | (80, 170) |
| $\sin(\beta-\alpha)$ | $(-1, 1)$ |
| $m_{12}^2$ (GeV$^2$) | $(0,\ m_A^2 \sin\beta\cos\beta)$ |
| $\tan\beta$ | (2, 25) |

Scanned ranges of the 2HDM-I parameters.

Considered possible production mechanisms and decays – several points with large $pp \to H^\pm h \to W^{\pm(*)} hh \to W^{\pm(*)} + 4\gamma$.

# $pp \to H^\pm h \to W^\pm + 4\gamma$ in a near fermiophobic 2HDM-I

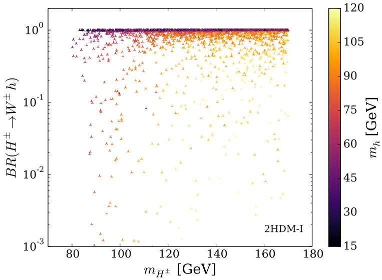


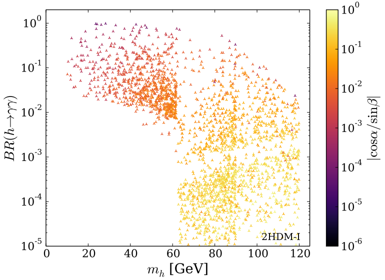

small $hH^+W^- \propto \cos(\beta - \alpha) \approx 1$

- $pp \to W^{\pm *} \to H^\pm h$ maximized, can exceed $tbH^\pm$ at large $\tan\beta$
- $BR(H^\pm \to W^\pm h)$ also enhanced

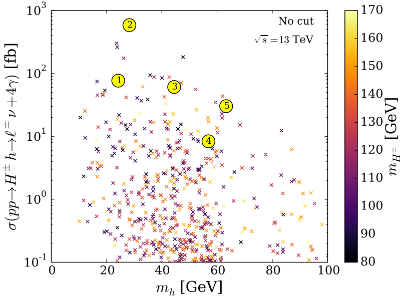
$hf\bar{f} \propto \cos\alpha / \sin\beta \approx 0$

- $BR(h \to \gamma\gamma) \to 1$ in fermiophobic limit



# $pp \to H^{\pm}h \to W^{\pm} + 4\gamma$




| BP | $H^{\pm} \to W^{\pm}h$ | $h \to \gamma\gamma$ | $A \to b\bar{b}$ |
|---|---|---|---|
| 1 | 1.00 | 0.94 | $4.6 \times 10^{-3}$ |
| 2 | 1.00 | 0.97 | $7.4 \times 10^{-3}$ |
| 3 | 1.00 | 0.70 | 0.031 |
| 4 | 0.90 | 0.22 | 0.18 |
| 5 | 1.00 | 0.71 | 0.017 |

Branching Ratios ↑

| BP | $m_h$ | $m_{H^{\pm}}$ | $m_A$ | $s_{\beta-\alpha}$ | $m_{12}^2$ | $\tan\beta$ | $\cos\alpha/\sin\beta$ | $\sigma(W^{\pm}4\gamma)$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 24.2 | 152.2 | 111.1 | -0.048 | 19.0 | 20.9 | $1.1 \times 10^{-4}$ | 359 |
| 2 | 28.3 | 83.7 | 109.1 | -0.050 | 31.3 | 20.2 | $-5.9 \times 10^{-5}$ | 2740 |
| 3 | 44.5 | 123.1 | 119.9 | -0.090 | 30.8 | 10.9 | $6.8 \times 10^{-4}$ | 285 |
| 4 | 56.9 | 97.0 | 120.3 | -0.174 | 243.9 | 5.9 | $-6.5 \times 10^{-3}$ | 39 |
| 5 | 63.3 | 148.0 | 129.2 | -0.049 | 173.1 | 20.7 | $-4.2 \times 10^{-4}$ | 141 |

(masses in GeV, cross sections in fb)

# Discovery potential at 13 TeV LHC

Nearly background free, but objects tend to be soft: multi-object trigger?

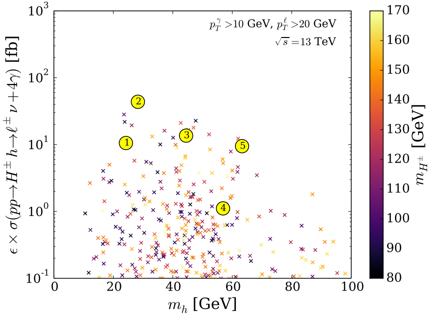
$p_T^\gamma > 10$ GeV, $p_T^\ell > 20$ GeV

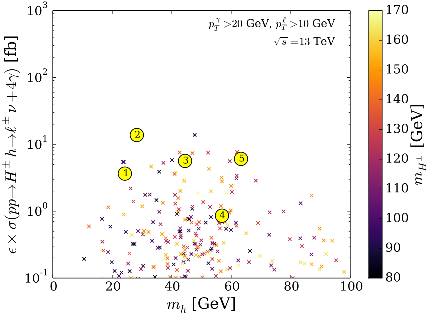
| $m_{H^+} \setminus m_h$ | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
|---|---|---|---|---|---|---|---|---|---|
| 80 | 0.04 | 0.08 | 0.10 | 0.08 | 0.05 | <0.01 | | | |
| 90 | 0.05 | 0.10 | 0.13 | 0.13 | 0.10 | 0.06 | <0.01 | | |
| 100 | 0.05 | 0.14 | 0.16 | 0.16 | 0.13 | 0.11 | 0.06 | <0.01 | |
| 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 |

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

| $m_{H^+} \setminus m_h$ | 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 |

Efficiencies, $\epsilon = \sigma(\text{cuts})/\sigma(\text{no cuts})$ ↑ ↓ Cross sections after cuts



# Summary

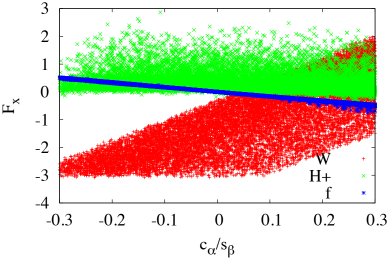
- Many $qq$-initiated multi-Higgs processes can have large cross sections at the LHC, often exceeding gluon fusion
- Most triple multi-Higgs couplings contribute to some of these processes
- Need decays of Higgses for true sensitivity
- For a light mass spectrum, a spectacular $W + 4\gamma$ signal could be seen at the LHC.

Backup

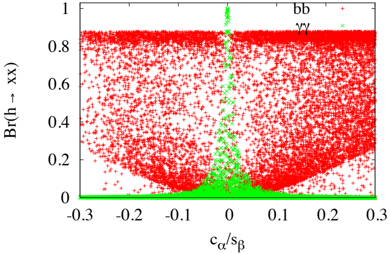
# Fermiophobic $h$ in the 2HDM-I

$h$ couplings:
$hf\bar{f} \propto \cos\alpha/\sin\beta$
$hVV \propto \sin(\beta-\alpha) \approx 0$ (SM-like $H$)
$hH^+H^- \sim$ potential parameters

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




- If $\cos\alpha$ vanishes, $h \to \gamma\gamma$ can be large, dominated by $H^+$ loop
- $h \to f\bar{f}/gg$ suppressed by $\cos\alpha$
- $h \to VV$ suppressed by $\sin(\beta-\alpha)$ and kinematics




Large $BR(h \to \gamma\gamma)$

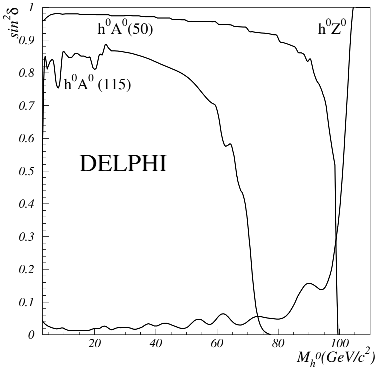
# Constraints on Fermiophobic Models

Suppressed in our scenario by
$hVV \propto \sin(\beta - \alpha)$:

- LEP-II $e^+e^- \to Zh(h \to \gamma\gamma)$
- Tevatron $pp \to Vh$, VBF

Complimentary channel:

- $e^+e^-/pp \to hA$
  $(ZhA \propto \cos(\beta - \alpha))$

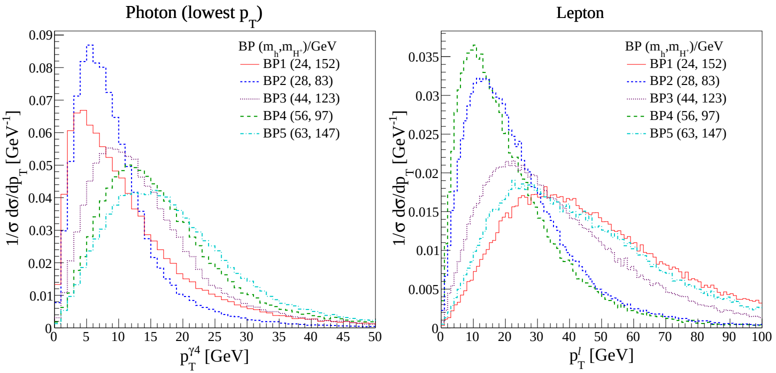



DELPHI $hA + Zh$ combination excludes most $(m_h, m_A)$ accessible at LEP-II energies for exactly fermiophobic models [hep-ex/0406012].

- We model their results and extrapolate to constrain our points.

# Discovery potential at 13 TeV LHC

- Nearly background free $\sigma(\ell^{\pm} + 4\gamma) < 10^{-6} pb$ for $p_T > 10$ GeV
- Challenge $\rightarrow$ objects are very soft




$\ell^{\pm}\nu + 4\gamma$

$\Delta R > 0.4$

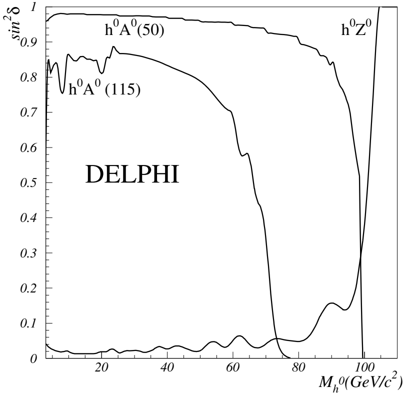
$|\eta| < 2.5$

- Likely require multi-object trigger

  e.g. $p_T(1\gamma) > 120$ GeV, $p_T(2\gamma) > 22$ GeV.

# DELPHI $e^+e^- \to hA$ limit

- Search for fermiophobic $e^+e^- \to hA$, with $h \to \gamma\gamma$, $A \to b\bar{b}$ or $A \to Zh \to Z\gamma\gamma$ when kinematically allowed [hep-ex/0406012]
- No general limits on $(m_h, m_A)$




$$\delta = \beta - \alpha$$