# Identifying a light charged Higgs boson at the LHC Run II

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Joint work with Abdesslam Arhrib, Rachid Benbrik, Rikard Enberg, Stefano Moretti, and Shoaib Munir [arXiv:1706.01964]

# Overview

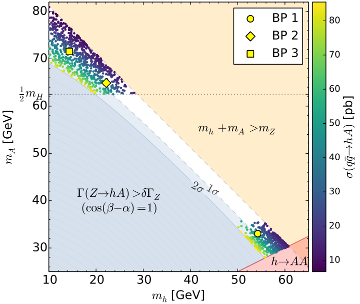
- Background
- Parameter scans of 2HDM-I
- Fermiophic models and constraints
- The $pp \to H^\pm h \to W^\pm + 4\gamma$ signal and discovery potential
- Extending the DELPHI fermiophobic $e^+e^- \to hA$ limit

# Background

Previously: $q\bar{q} \to Z \to hA$ production and the Landau-Yang Theorem

- 2HDM-I with $m_h + m_A < m_Z$
- Light states easily accessible at LEP
- $h/A$ hiding behind $Z^*A/Z^*h$ decays
- Light $H^\pm$ hiding behind $W^*h/W^*A$ decays
- (see also AA, RB, SMo – 1607.02402)

What are the signatures of a light $H^\pm$ in the 2HDM-I with $m_h < m_H = 125$ GeV?




[1605.02498] (RE, WK, SMo, SMu)

| BP | $m_h$ | $m_A$ | $m_{H^\pm}$ |
|---|---|---|---|
| 1 | 54.2 | 33.0 | 95.9 |
| 2 | 22.2 | 64.9 | 101.5 |
| 3 | 14.3 | 71.6 | 107.2 |

# Parameter scan

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) |
| $m_A$ (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) |

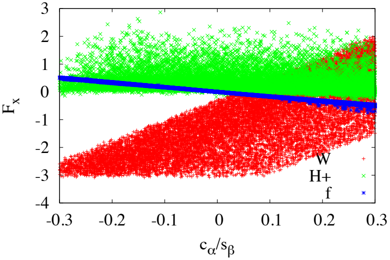
Scanned ranges of the 2HDM-I parameters.

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

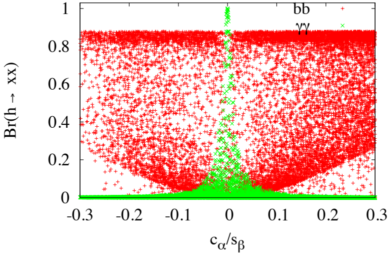
# Fermiophobic $h$ in the 2HDM-I

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

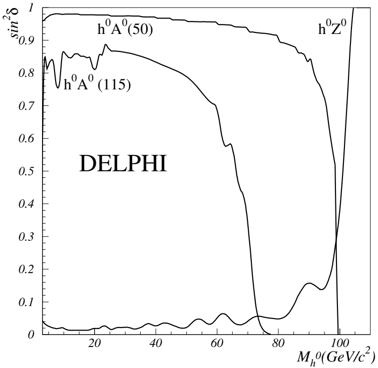
# Constraints on Fermiophobic Models

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:

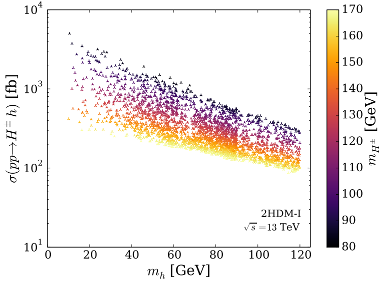
- $e^+e^-/pp \to hA$ $(ZhA \propto \cos(\beta - \alpha))$

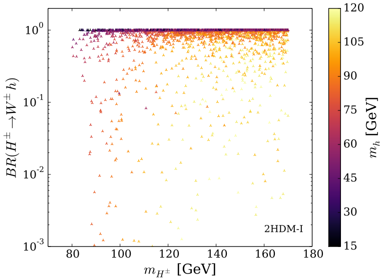



DELPHI $hA + Zh$ combination excludes most $(m_h, m_A)$ accessible at LEP-II energies for exactly fermiophobic models [hep-ex/0406012].

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

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

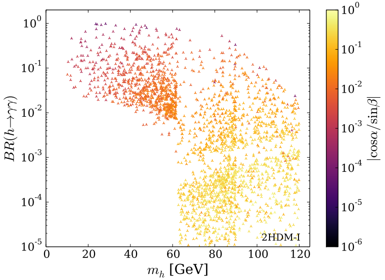


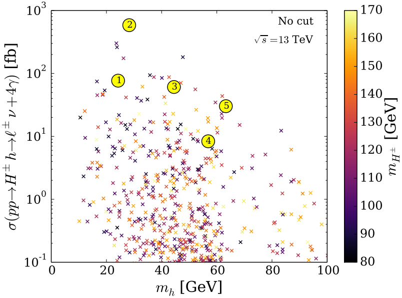

$hH^+W^- \propto \cos(\beta - \alpha) \approx 1$

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

$BR(h \to \gamma\gamma) \to 1$ 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 |

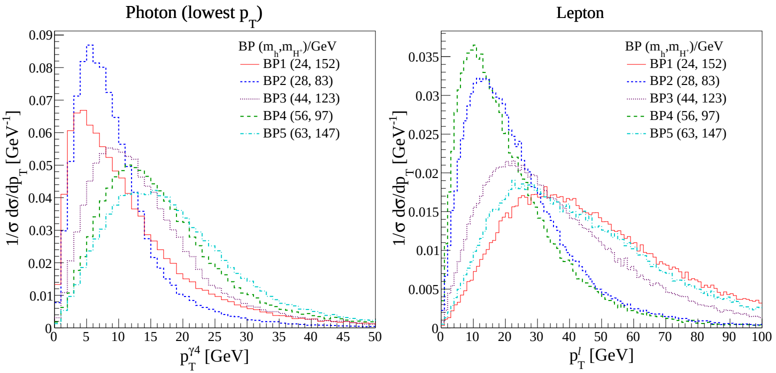
Branching Ratios ↑

| 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 $\sigma(\ell^\pm + 4\gamma) < 10^{-6} pb$ 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.

# Discovery potential

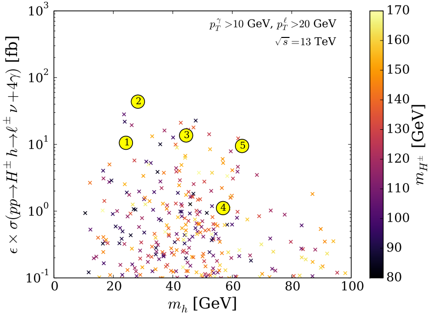
$p_T^\gamma > 10$ GeV, $p_T^\ell > 20$ GeV

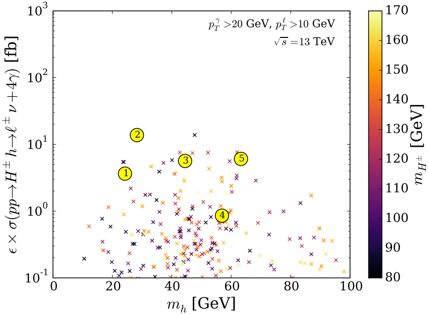
| $m_{H^+} \backslash m_h$ | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
|---|---|---|---|---|---|---|---|---|---|
| 80 | 0.04 | 0.08 | 0.10 | 0.08 | 0.05 | <0.01 | | | |
| 90 | 0.05 | 0.10 | 0.13 | 0.13 | 0.10 | 0.06 | <0.01 | | |
| 100 | 0.05 | 0.14 | 0.16 | 0.16 | 0.13 | 0.11 | 0.06 | <0.01 | |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

$p_T^\gamma > 20$ 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 |

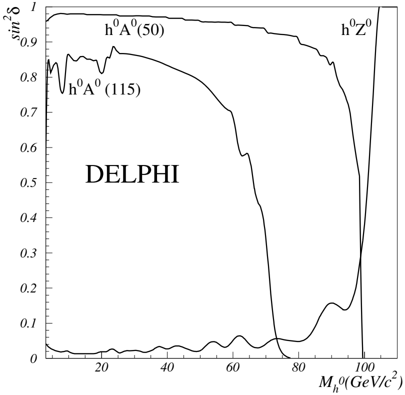
Efficiencies, $\epsilon = \sigma(\text{cuts})/\sigma(\text{no cuts})$ ↑ ↓ Cross sections after cuts



# 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 $(m_h, m_A)$




$\delta = \beta - \alpha$

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

- Assume that selection efficiency has only small variation with $m_h$,$m_A$, and $182 < \sqrt{s} < 207\ \mathrm{GeV}$
- Translate limits on $\sin(\beta - \alpha)$ for fermiophobic model into number of expected signal events (before selection) using known $\sigma \times BR$ for fermiophobic Higgs.

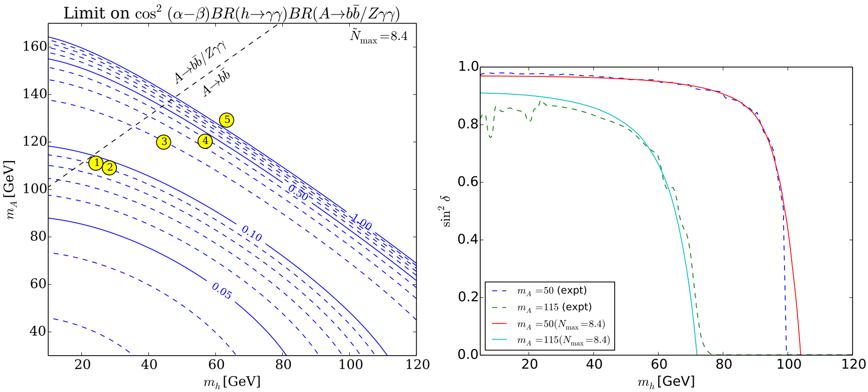
$$\tilde{N}_{\max}(m_h, m_A) = N_0(m_h, m_A)(1 - (s^{\mathrm{lim}}_{\beta\alpha}(m_h, m_A))^2) \times \mathrm{BR}(h_f \to \gamma\gamma).$$

$$N_0(m_h, m_A) = \sum_{\{s\}} \sigma_0(s, m_h, m_A) \times \mathcal{L}(s) \qquad (\cos(\beta - \alpha) = 1)$$

- This value varies slowly in relevant region - take $\tilde{N}_{\max}$ as a single parameter and fit to each curve to approximate limit:

$$\cos^2(\beta - \alpha) \times \mathrm{BR}(h \to \gamma\gamma) \times \mathrm{BR}(A \to X) \leq \frac{\tilde{N}_{\max}}{N_0(m_h, m_A)}$$

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

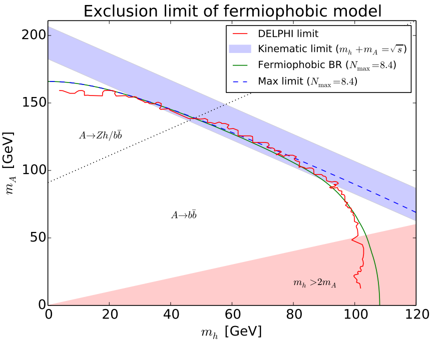


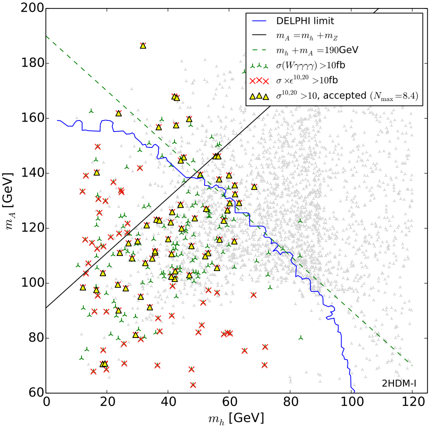

(Left)Estimated limits on $\cos^2(\beta-\alpha)\times \mathrm{BR}(h\to\gamma\gamma)\times \mathrm{BR}(A\to b\bar{b}/Z\gamma\gamma)$ with $\tilde{N}_{\max}=8.4$. BPs are indicated in yellow circles. The dashed line indicates where $m_A = m_h + m_Z$, above which the on-shell $A \to Zh$ decay is possible. (Right) Fit to DELPHI fermiophobic $hA$ limits.

# Summary

- The nearly fermiophobic 2HDM-I still alive.
- There is potentially a large, clean $W^{\pm} + 4\gamma$ signal to be seen at the LHC.
- We encourage LHC experiments to consider multi-object triggers that would allow this sort of study.

Backup


Exclusion limit of fermiophobic model
DELPHI limit
Kinematic limit ($m_h + m_A = \sqrt{s}$)
Fermiophobic BR ($N_{max}$=8.4)
Max limit ($N_{max}$=8.4)
$A \to Zh/b\bar{b}$
$A \to b\bar{b}$
$m_h > 2m_A$
$m_A$ [GeV]
$m_h$ [GeV]


DELPHI limit
$m_A = m_h + m_Z$
$m_h + m_A$ = 190GeV
$\sigma(W\gamma\gamma\gamma\gamma)$ > 10fb
$\sigma \times \epsilon^{10,20}$ > 10fb
$\sigma^{10,20}$ > 10, accepted ($N_{max}$=8.4)
2HDM-I
$m_A$ [GeV]
$m_h$ [GeV]

The loop factors are defined as

$$
\begin{aligned}
F_f &= \sum_i \frac{-2}{\tau_f^2} N_f Q_f^2 \xi_f^h (\tau_f + (\tau_f - 1) I(\tau_f)), \\
F_{H\pm} &= \frac{g_{hH\pm H\mp}}{\tau_{H\pm}^2} \frac{m_W^2}{m_{H\pm}^2} (\tau_{H\pm} - I(\tau_{H\pm})), \\
F_W &= \frac{\sin(\beta - \alpha)}{\tau_W^2} (2\tau_W^2 + 3\tau_W + 3(2\tau_W - 1) I(\tau_W)),
\end{aligned}
$$

where

$$
g_{hH\pm H\mp} = \frac{1}{2m_W^2}((2m_{H\pm}^2 - m_h^2)\sin(\beta - \alpha) + \frac{\cos(\beta - \alpha)}{\sin\beta^2 \cos\beta^2}(m_h^2 \sin\beta \cos\beta - m_{12}^2))
$$

$\tau_x = m_h^2/(4m_x^2)$, and the scalar function $I(x)$ is given by (from, e.g.,hep-ph/0503173, but using the opposite sign convention)

$$
I(x) = \begin{cases} [\sin^{-1}(\sqrt{x})]^2, & x \leq 1 \\ -\frac{1}{4}[\ln(\frac{\sqrt{x}+\sqrt{x-1}}{\sqrt{x}-\sqrt{x-1}}) - i\pi]^2, & x > 1 \end{cases} .
$$