Benchmark Points for Type-I 2HDMs with a light h

William Klemm

Uppsala University & The University of Manchester

william.klemm@physics.uu.se

WG3 Benchmark Discussion

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Rikard Enberg, WK, Stefano Moretti, and Shoaib Munir [arXiv:1605.02498]
Abdesslam Arhrib, Rachid Benbrik, Rikard Enberg, WK, Stefano Moretti, and Shoaib Munir [arXiv:1706.01964]

Introduction

Scenario: Type-I 2HDM with $m_h < m_H = 125$ GeV

- Focus: Processes dominated by electroweak production (vs. gluon fusion)
- Parameter scans for points with interesting signatures
- 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
- Fermiophobia: $g_{hff} \sim \cos\alpha/\sin\beta \ll 1$ leads to enhancement of other decays, e.g. $h \to \gamma\gamma$

Proposed benchmarks:

- Resonant $pp \to Z \to hA$
- $pp \to H^\pm h \to W^{\pm(*)}hh \to W^{\pm(*)}\gamma\gamma\gamma\gamma$

Parameter scans

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]
- Z width
- DELPHI fermiophobic Higgs searches ($e^+e^- \to hA$)
- All BPs here checked against HiggsBounds-5.2

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. $m_H = 125$ GeV.

Benchmark Points

BP	m_h	m_H	m_A	$m_{H^\pm}$	$\sin(\beta-\alpha)$	m_{12}^2	$\tan\beta$	$\cos\alpha/\sin\beta$
1	54.2	125.0	33.0	95.9	-0.11590	118.3	9.0947	-6.7×10^{-3}
2	22.2	125.0	64.9	101.5	-0.046960	10.6	22.114	-1.8×10^{-3}
3	14.3	125.0	71.6	107.2	-0.061929	2.9	16.307	-7.2×10^{-4}
4	27.5	125.0	117.8	86.8	-0.14705	44.5	6.8946	-3.6×10^{-3}
5	63.3	125.0	129.2	148.0	-0.048763	173.1	20.660	-4.2×10^{-4}

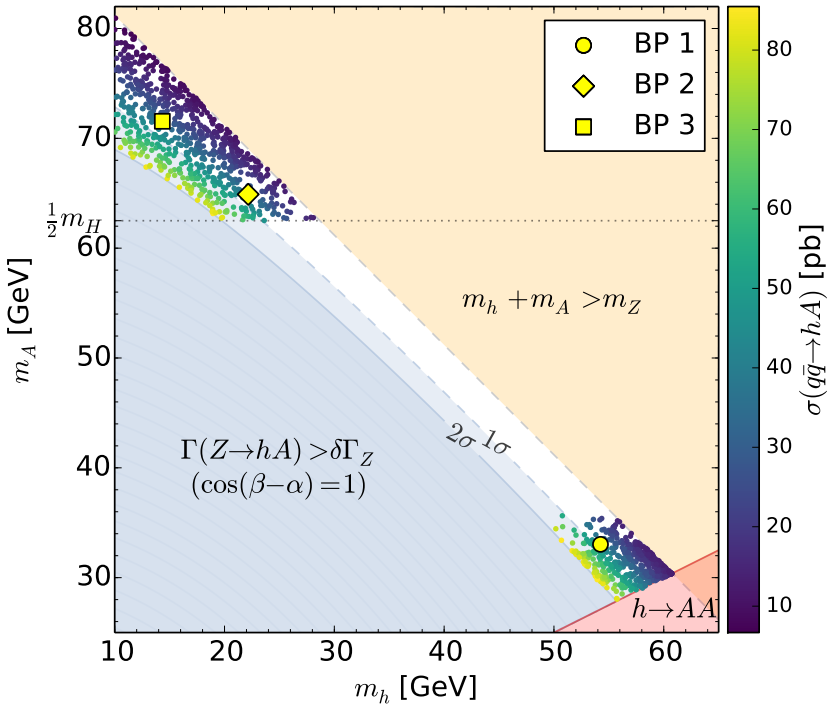
Parameters defining benchmark points in a Type-I 2HDM. All masses are in GeV.

BP	Highlighted Channels
1	$hA \to Z^* AA \to Z^* b\bar{b}b\bar{b}$
2	$hA \to Z^* hh \to Z^* b\bar{b}b\bar{b}$
3	$hA \to Z^* hh \to Z^*(b\bar{b}b\bar{b}/b\bar{b}\gamma\gamma/\gamma\gamma\gamma\gamma)$
3,4,5	$H^\pm h \to W^{\pm(*)} hh \to W^{\pm(*)}\gamma\gamma\gamma\gamma$
3,4,5	$H^\pm A \to W^{\pm(*)} Z^{(*)} hh \to W^{\pm(*)} Z^{(*)}\gamma\gamma\gamma\gamma$

Resonant $pp \to Z \to hA$

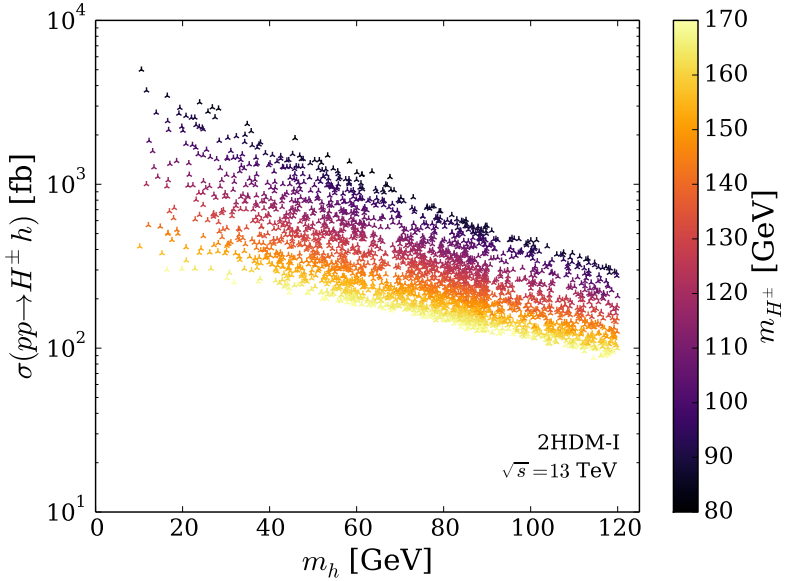
$q\bar{q}(gg) \to Z(Z^*) \to hA$ production dominated by $q\bar{q}$ due to Landau-Yang Theorem

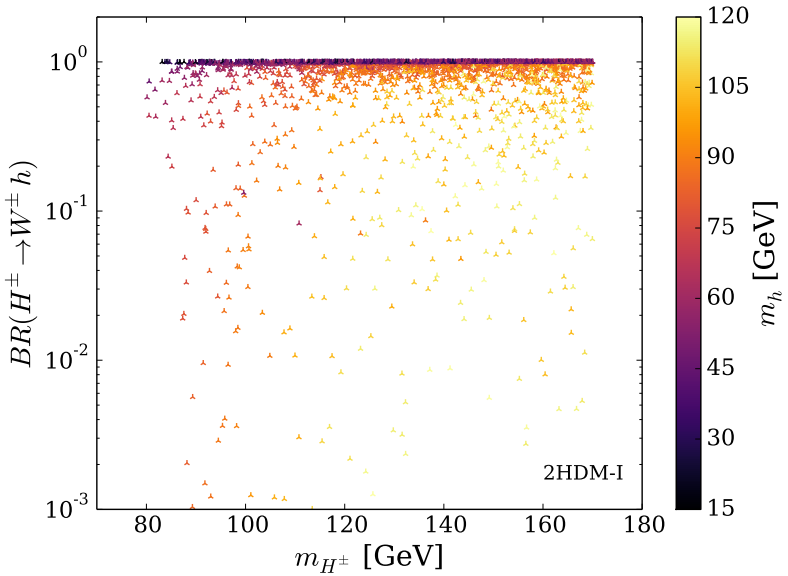
- 2HDM-I with $m_h + m_A < m_Z$
- Severely constrained by Γ_Z
- Limited by $H \to AA$, $h \to AA$
- Final states: $Z^*(b\bar{b}/\tau\tau)(b\bar{b}/\tau\tau)$
- BP3: $Z^*\gamma\gamma(\gamma\gamma/b\bar{b}/\tau\tau)$ possible



BP	cross section[fb] $\sigma(q\bar{q} \to hA)$	$\sigma(gg \to hA)$	BR($h \to ...$) [%] Z^*A	$b\bar{b}$	$\gamma\gamma$	$\tau\tau$	BR($A \to ...$) [%] 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
3	31.6	1.1×10^{-2}	0	**60**	**24**	7	**90**	8	1

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

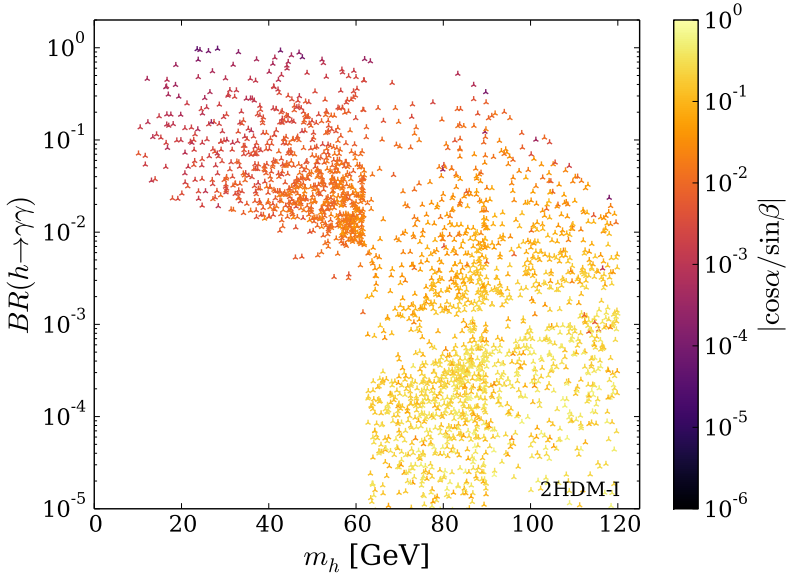




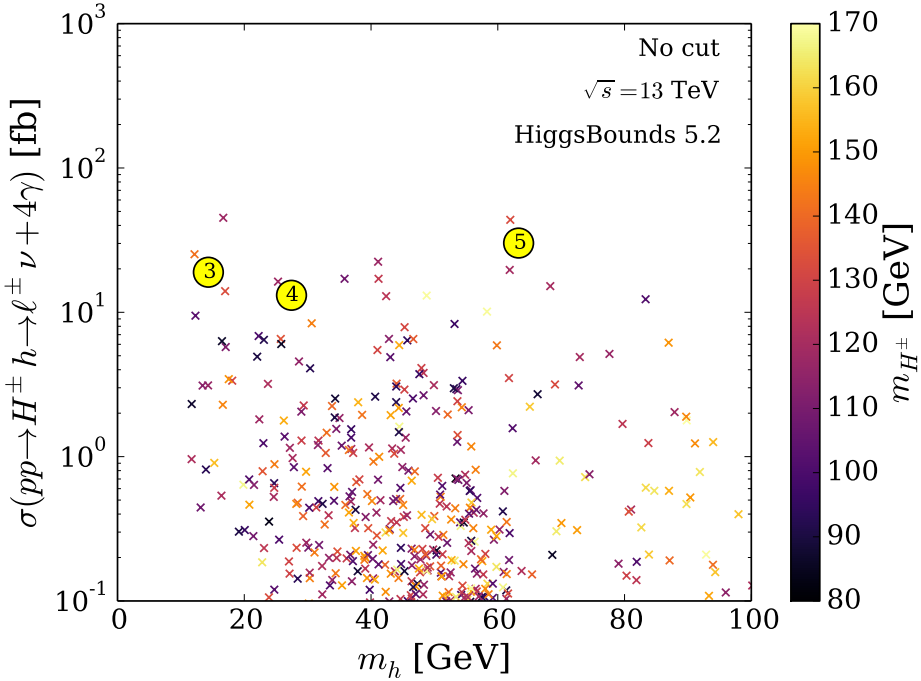
$hH^+W^- \propto \cos(\beta - \alpha) \approx 1$

- $pp \to W^{\pm *} \to H^{\pm} h$ 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



$pp \to H^{\pm}h \to W^{\pm} + 4\gamma$ & $pp \to H^{\pm}A \to W^{\pm}Z + 4\gamma$



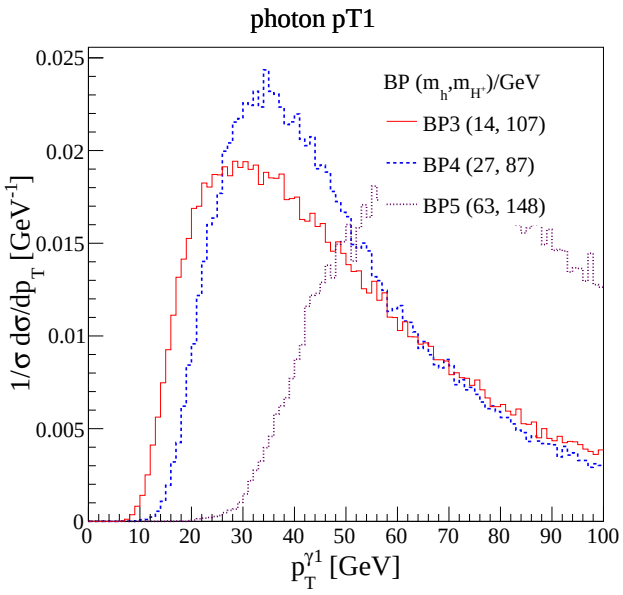
Nearly background free
$\sigma_{SM}(\ell^{\pm} + 4\gamma) < 10^{-6} pb$ for
$p_T^{(\ell,\gamma)} > 10$ GeV

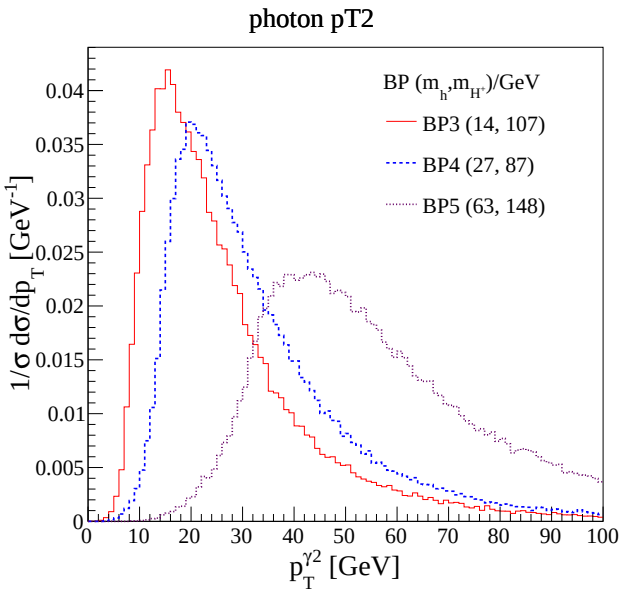
Soft objects suggest multi-object triggers, e.g. 3γ with $p_T > 15 GeV$ used in ATLAS 3γ search [arXiv:1509.05051]

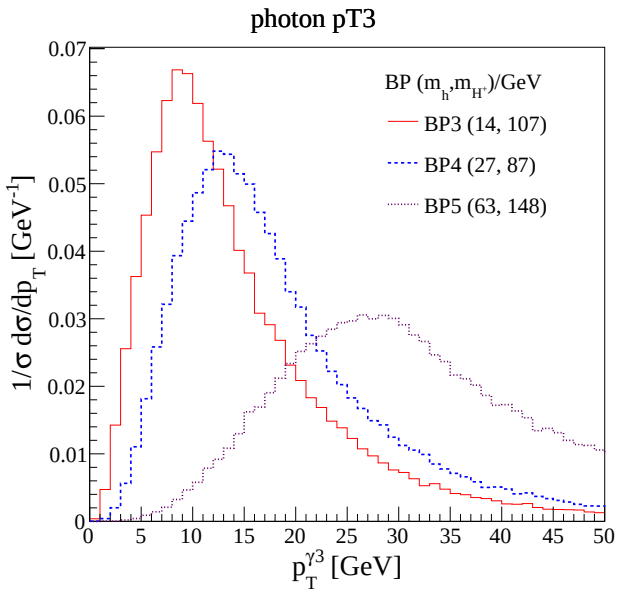
BP	$\sigma(W^{\pm} + 4\gamma)$	$\sigma(W^{\pm}Z + 4\gamma)$	$H^{\pm} \to W^{\pm}h$	$h \to \gamma\gamma$	$A \to Zh$
3	88.8	26.8	1.00	0.24	0.90
4	61.5	7.4	0.98	0.16	0.94
5	141.4	55.7	1.00	0.71	0.98

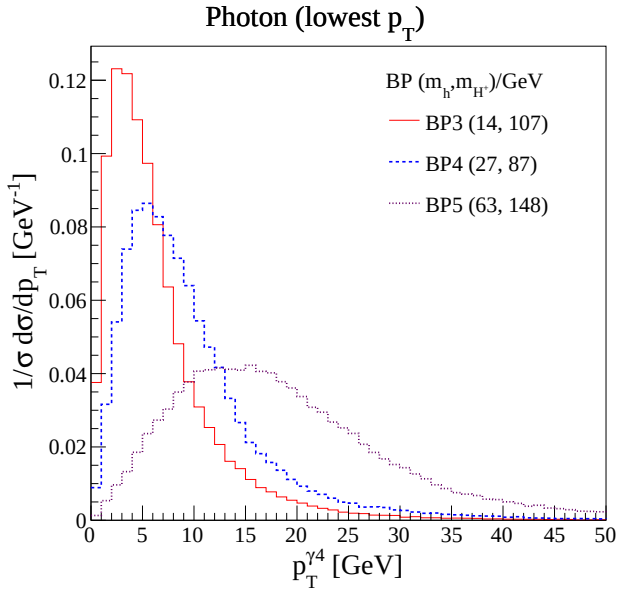
Cross sections (in fb) and relevant BRs of $H^{\pm}$, h, and A for the BPs.

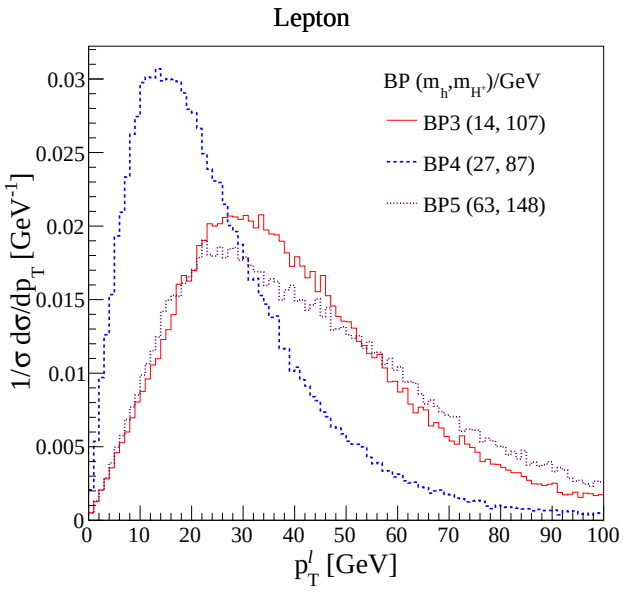
$W + 4\gamma$ kinematic distributions











BP	m_h	$m_{H\pm}$
3	14	107
4	27	87
5	63	148

Masses in GeV

Summary

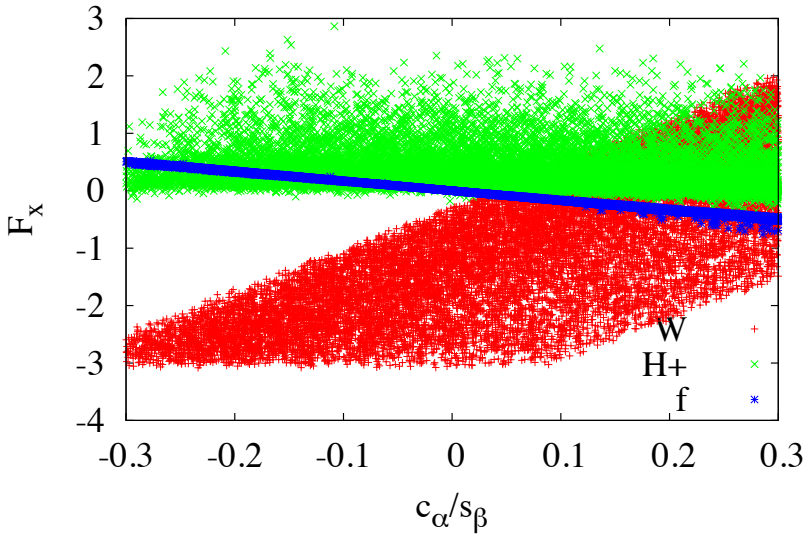
- BP1 and BP2 have large resonant $q\bar{q} \to Z \to hA$ production cross sections, giving possible $Z^* + 4f$ signatures.
- BP3 has strong hA and $W^{\pm} + 4\gamma$ signals. It has a large $m_{H^{\pm}} - m_h$ difference, which should lead to a harder spectrum for a lepton from $W^{\pm}$ decay in the $W^{\pm} + 4\gamma$ signature.
- BP4 has a very light $H^{\pm}$, whose decay products will include a very off-shell W^*. This BP is challenging as all final state objects tend to be soft.
- Unlike the other benchmark points shown in this note, which evade LEP-II constraints through non-standard decays, BP5 lies near the upper CM energies at LEP-II for hA and $hH^{\pm}$ production. It has the hardest p_T distributions in $W + 4\gamma$ production.

Backup

Fermiophobic h in the 2HDM-I

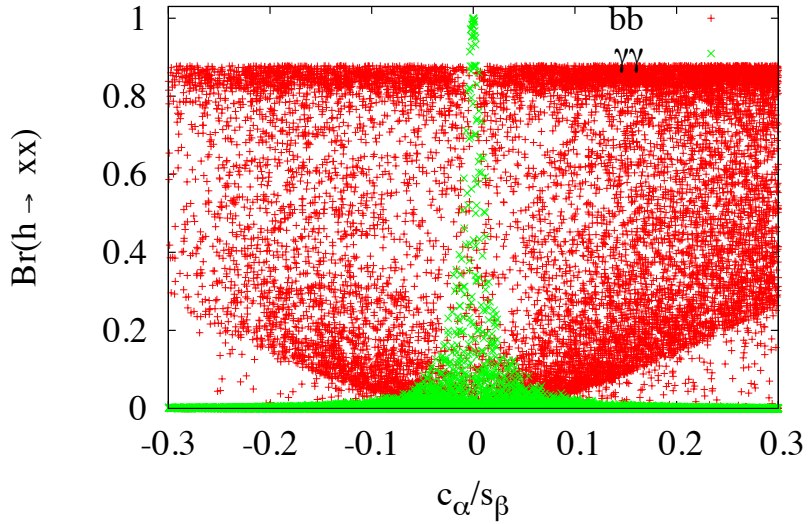
h couplings:
$hf\bar{f} \propto \cos\alpha/\sin\beta$
$hVV \propto \sin(\beta-\alpha) \approx 0$ (SM-like H)
$hH^+H^- \sim$ potential parameters

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



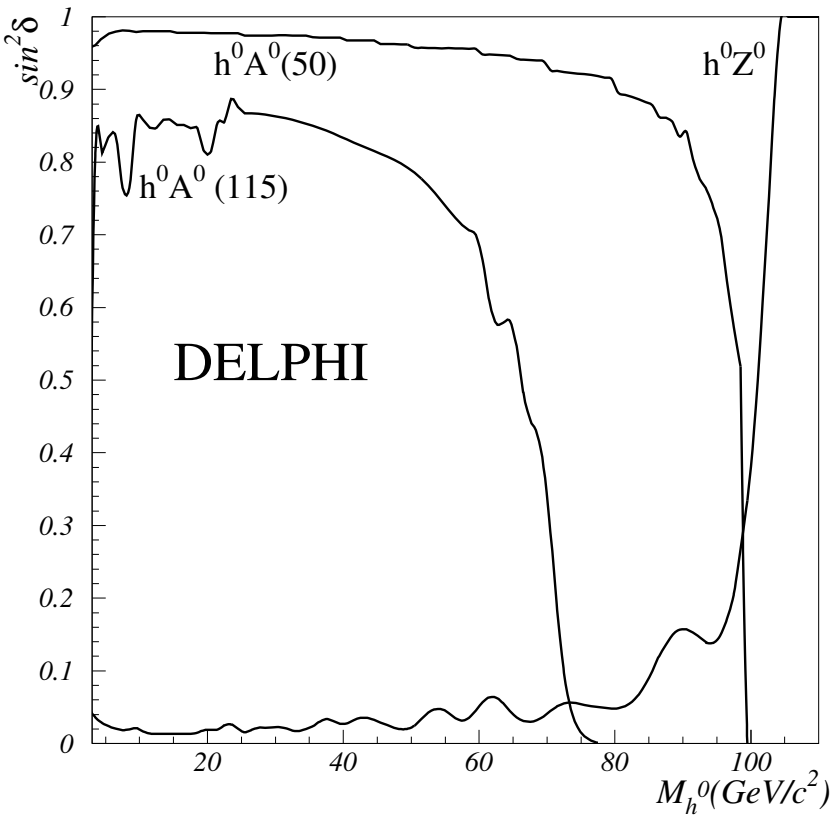
- If $\cos\alpha$ vanishes, $h \to \gamma\gamma$ can be large, dominated by H^+ loop
- $h \to f\bar{f}/gg$ suppressed by $\cos\alpha$
- $h \to VV$ suppressed by $\sin(\beta-\alpha)$ and kinematics

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



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 $182 < \sqrt{s} < 207$ 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.

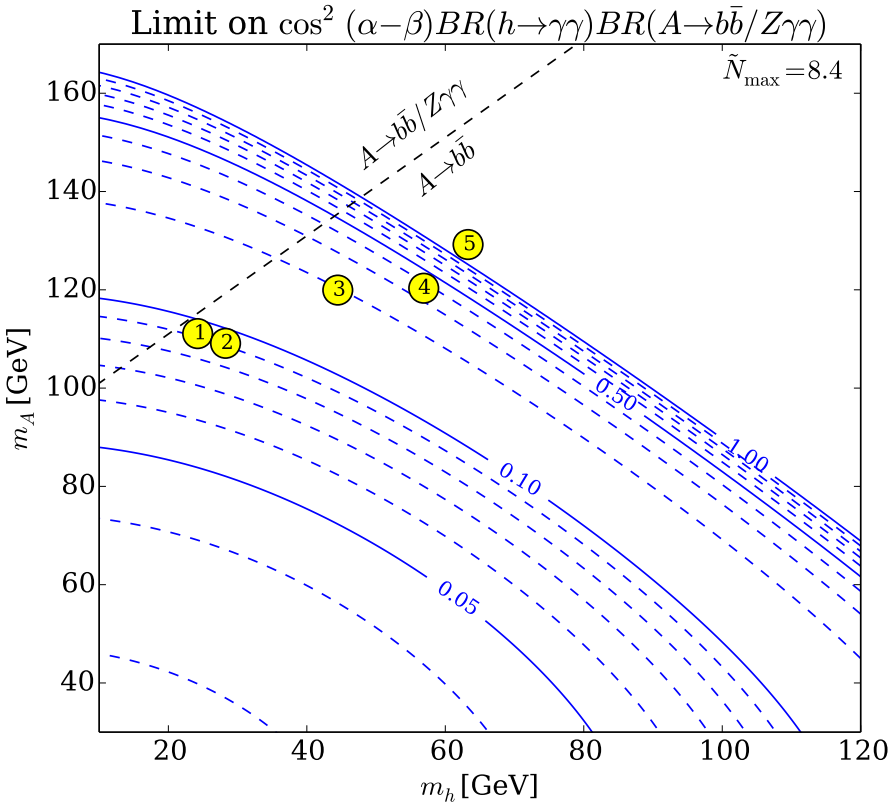
$$\tilde{N}_{\text{max}}(m_h, m_A) = N_0(m_h, m_A)(1 - (s^{\lim}_{\beta\alpha}(m_h, m_A))^2) \times \text{BR}(h_f \to \gamma\gamma).$$

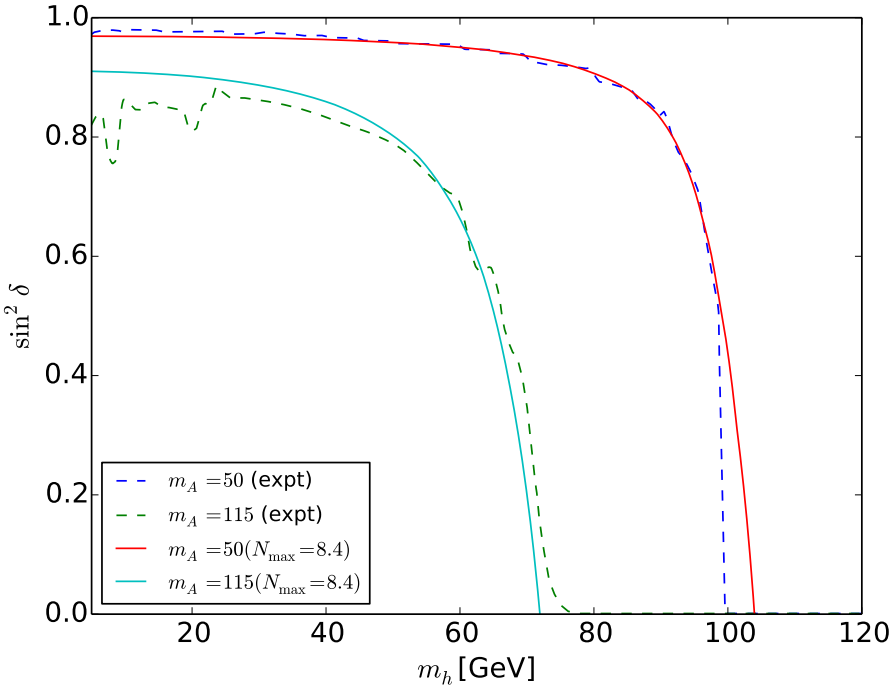
$$N_0(m_h, m_A) = \sum_{\{s\}} \sigma_0(s, m_h, m_A) \times \mathcal{L}(s) \qquad (\cos(\beta - \alpha) = 1)$$

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

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

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 $\tilde{N}_{\max}=8.4$. **NOTE: BPs shown here are from the original text, not the BPs put forth in this presentation**. 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.