BSM 4 γ + X signatures

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Outlines

- Introduction and Motivation
- 2HDM overview
- Photon as a tool in BSM searches
  - $4\gamma + W^{\pm}$ signature for a light $H^{\pm}$ at the LHC Run II based on A.Arhrib, R.B, R. Enberg, W. Klemm, S. Moretti and S. Munir, Phys.Lett. B774 (2017) 591-598
  - 4γ production at the LHC Run-2 in progress arXiv.1712.XXXX. with A. Arhrib, R.B, S. Moretti, A. Rouchad, Q-S. Yan and X. Zhane
- Summary and perspectives

Introduction and Motivation:

Photon-based BSM analyses (based on the 8 TeV run-1 data):

- $\gamma + X$ resonnace searches
- $\gamma + X$ searches
- BSM through $H \to \gamma + X$

The mission of LHC Run II is:

- The improvement of the scalar boson mass and scalar boson coupling measurements.
- Find a clear hint of NP BSM
- Accurate measurements of the scalar boson couplings to SM particles would help to determine if the Higgs-like particle is the SM Higgs or a Higgs that belongs to a higher representations:
  more doublets, doublet & triplets, doublet & singlets
- Most of the High representations predicts: singly and/or doubly charged Higgs.

Extended Higgs sector: EWPT

mass terms:

$$\sum_i (D_\mu \Phi_i)^+ (D_\mu \Phi_i) \quad , \quad D_\mu = \partial_\mu + ig\,\vec{T}_a \vec{W}^a{}_\mu + ig' \frac{Y}{2} B_\mu$$

$$\rho = \frac{m_W^2}{c_W^2 m_Z^2} = \frac{\sum_i v_i^2 (I_i(I_i+1) - \frac{Y_i^2}{4})}{\sum_i v_i^2 \frac{Y_i^2}{2}} \approx 1.00037 \pm 0.00023$$

1. Doublets (I_i=1/2, Y_i=±1): tree ok but "rad. corrections"
2. $4I_i(I_i+1) = 3Y_i^2$: $I_i = 3$ and $Y_i = 4$, rather complicated
3. Triplet representation: tune the triplet vev. In type-II see-saw: $v_\Delta < 5 - 8$ GeV

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \phi_1^0 + i a_1) \end{pmatrix} ; \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \phi_2^0 + i a_2) \end{pmatrix} .$$

The most general potential for 2HDM:

$$\begin{aligned} V(\Phi_1, \Phi_2) &= m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 + (m_{12}^2 \Phi_1^\dagger \Phi_2 + \mathrm{h.c}) \\ &+ \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\ &+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ &+ \frac{1}{2}[\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + (\lambda_6 \Phi_1^\dagger \Phi_1 + \lambda_7 \Phi_2^\dagger \Phi_2)\Phi_1^\dagger \Phi_2 + \mathrm{h.c.}], \end{aligned}$$

- $\mathbb{Z}_2$: $\Phi_i \to (-)^i \Phi_i \Leftrightarrow \lambda_{6,7} = 0$
- No explicit CP violation: $Im(m_{12}^2 \lambda_{5,6,7}) = 0$

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \phi_1^0 + ia_1) \end{pmatrix}; \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \phi_2^0 + ia_2) \end{pmatrix}.$$

$$-\mathcal{L}_Y = \sum_{a=1,2} \left[\bar{Q}_L Y_d^a \Phi_a d_R + \bar{Q}_L Y_u^a \tilde{\Phi}_a u_R + \bar{L}_L Y_\ell^a \Phi_a \ell_R + \text{h.c.} \right],$$

leads to FCNCs at tree level.

• Classification of 2HDMs satisfying the Glashow-Weinberg condition which guarantees the absence of tree-level FCNC.

Type-I	$Y_{u,d}^1 = 0$, $Y_\ell^1 = 0$
Type-II	$Y_u^1 = Y_{d,\ell}^2 = 0$
Type-III (X)	$Y_{u,d}^1 = Y_\ell^2 = 0$
Type-IV (Y)	$Y_{u,\ell}^1 = Y_d^2 = 0$

CP conserving 2HDM: CP-even h,H, CP-odd A and $H^{\pm}$

The Yukawa Lagrangian:

$$-\mathcal{L}_{Yuk} = \sum_{\psi=u,d,l} \left(\frac{m_\psi}{v} \kappa_\psi^h \bar{\psi}\psi h^0 + \frac{m_\psi}{v} \kappa_\psi^H \bar{\psi}\psi H^0 - i \frac{m_\psi}{v} \kappa_\psi^A \bar{\psi}\gamma_5 \psi A^0 \right) +$$

$$\left(\frac{V_{ud}}{\sqrt{2}v} \bar{u}(m_u \kappa_u^A P_L + m_d \kappa_d^A P_R) d H^+ + \frac{m_l \kappa_l^A}{\sqrt{2}v} \bar{\nu}_L l_R H^+ + H.c. \right)$$

	κ_u^h	κ_d^h	κ_l^h	κ_u^A	κ_d^A	κ_l^A
Type-I	c_α/s_β	c_α/s_β	c_α/s_β	$\cot\beta$	$-\cot\beta$	$-\cot\beta$
Type-II	c_α/s_β	$-s_\alpha/c_\beta$	$-s_\alpha/c_\beta$	$\cot\beta$	$\tan\beta$	$\tan\beta$
Lepton-specific	c_α/s_β	c_α/s_β	$-s_\alpha/c_\beta$	$\cot\beta$	$-\cot\beta$	$\tan\beta$
Flipped	c_α/s_β	$-s_\alpha/c_\beta$	c_α/s_β	$\cot\beta$	$\tan\beta$	$-\cot\beta$

CP conserving 2HDM: CP-even: $h < H$, CP-odd A and $H^{\pm}$

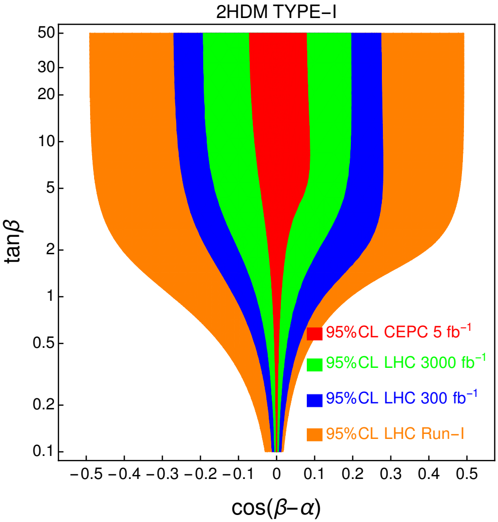
- Couplings:

$$hVV \propto \sin_{\beta-\alpha} \quad , \quad HVV \propto \cos_{\beta-\alpha} \quad , \quad AVV = 0$$
$$hH^{\pm}W^{\mp} \propto \cos_{\beta-\alpha} \quad , \quad HH^{\pm}W^{\mp} \propto \sin_{\beta-\alpha} \quad , \quad AH^{\pm}W^{\mp} \propto \frac{g}{2}$$
$$H^{\pm}W^{\mp}\gamma = 0 \ (e.m\ inv) \quad , \quad H^{\pm}W^{\mp}Z = 0 \ \ but \ \ loop\ mediated$$

- 2 alignment limits:
  - h=125 GeV SM-like: $\sin_{\beta-\alpha} = 1$ (Decoupling limit)
  - $h < H$=125 GeV SM-like: $\cos_{\beta-\alpha} = 1$:
    non-detected decays: $Br(H \to h^0 h^0, A^0 A^0) < 20 - 25\%$

$(\cos(\beta-\alpha) - \tan\beta)$ plan in 2HDM type-I

2σ fits:



Charged Higgs production

(See "Prospects for charged Higgs searches at the LHC," arXiv:1607.01320: A. Akeroyd et al)

- Light charged Higgs, i.e, with $m_{H\pm} \leq m_t - m_b$: are copiously produced from $t\bar{t}$ production $pp \to t\bar{t} \to t\bar{b}H^- + \text{c.c.}$
- various direct production modes:
  QCD: $gb \to tH^-$ and $gg \to t\bar{b}H^-$,
  $gg \to W^{\pm}H^{\mp}$ (loop),
  $b\bar{b} \to W^{\pm}H^{\mp}$
  $q\bar{q} \to \gamma, Z \to H^+H^-$,
  $gg \to H^+H^-$(loop)
  $q\bar{q}' \to W^* \to \phi H^{\pm}$ where $\phi = h^0, H^0, A^0$,
- Resonant production: $c\bar{s}, c\bar{b} \to H^+$
- $W - Higgs$ fusion : $qb \to q'H^+b$

A.A, K.M. Cheung, J.S.Lee and C. T. Lu'JHEP'2016

Charged Higgs decays

fermionic decays

- $H^{\pm} \to \tau\nu \quad , \quad cs \quad , \quad cb$
- $H^{\pm} \to tb$

bosonic decays

- $H^{\pm} \to W^{\pm}\phi^0 \quad , \quad \phi^0 = h^0, A^0, H^0$

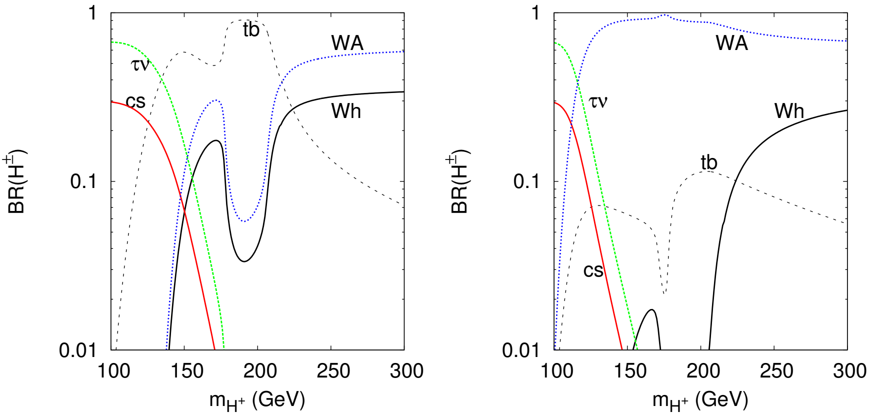
  A.Arhrib, R. B, S.Moretti, EPJC'17

- $H^{\pm} \to W^{\pm}\gamma, Z$: small loop mediated

  A.A, R. Benbrik, W.T. Chang and TC.Yuan, IJMP2007

- $H^{\pm} \to W^{\pm}Z$ exists at tree level in triplet models. (production through WZ fusion)

$H^{\pm}$ decays: $\tan\beta = 4.5$, $m_H = 300$ GeV, (left) $m_A = 125$ GeV (right) $m_A = 90$ GeV: 2HDM-I

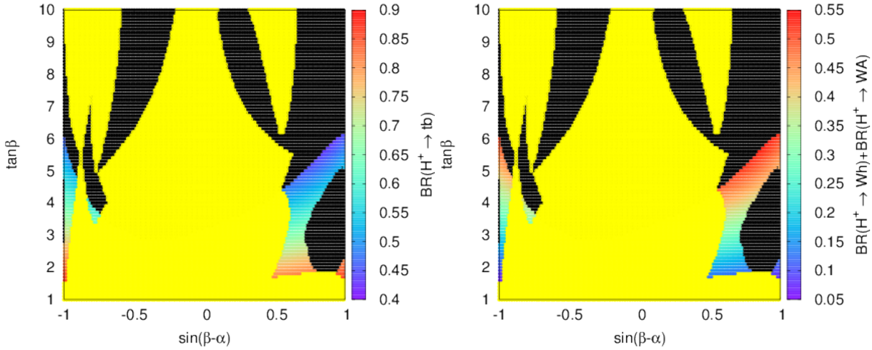


A.Arhrib, R. B and S. Moretti EPJC'17

$H^{\pm} \to tb$ vs $H^{\pm} \to W^{\pm}A^0/W^{\pm}h^0$: $m_H = 300$ GeV, $m_{h,A} = 125$ GeV, $m_{H^{\pm}} = 170$ GeV

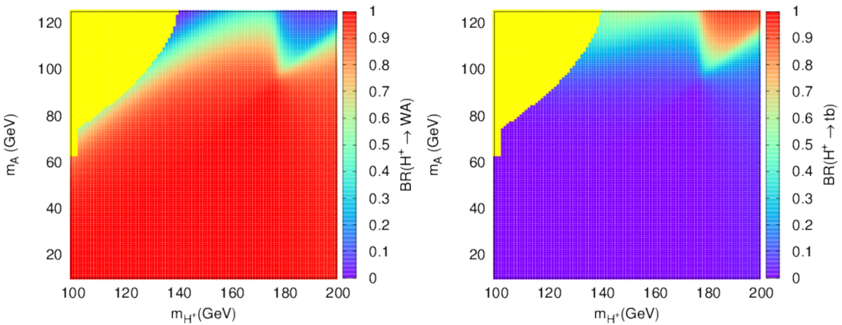
A.A, R. Benbrik and S. Moretti, EPJC'17

Yellow excluded by data, black by theoretical constraints

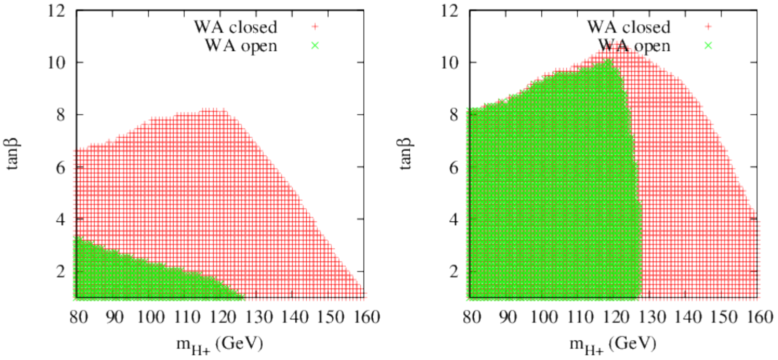


$$W^{\pm}H^{\mp}A \propto \frac{g}{2}\ ,\ W^{\pm}H^{\mp}h \propto \frac{g}{2}\cos(\beta-\alpha),\ W^{\pm}H^{\mp}H \propto \frac{g}{2}\sin(\beta-\alpha)$$

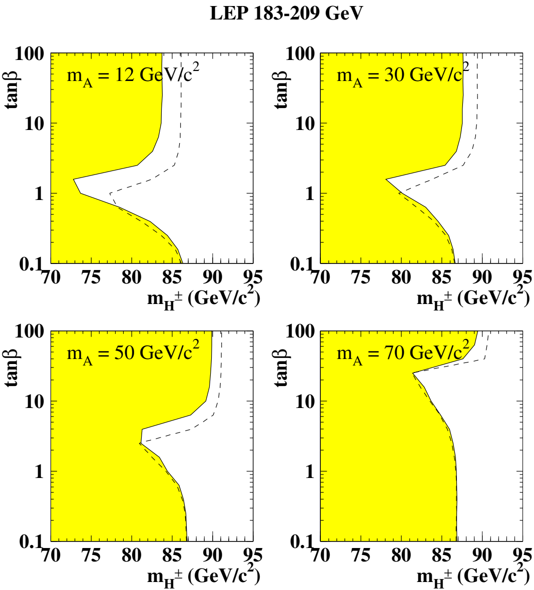
very light A^0: $\tan\beta = 5$, $m_H = 300$ GeV, $\sin(\beta - \alpha) = 1$



Implication for 2HDM: (left) 2HDM-I, (right) Lepton-specific, WA open for $m_A = 40$ GeV



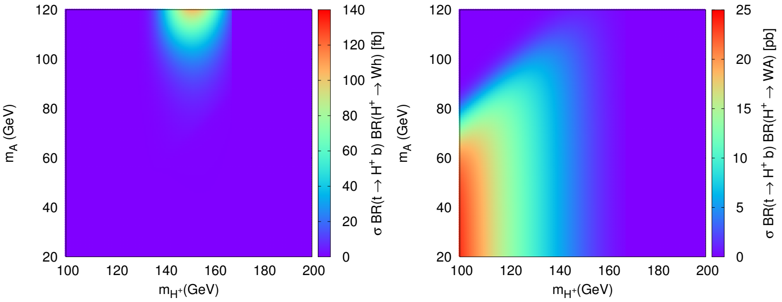
Search for $H^\pm \to W^\pm A^0$ at LEP-II



$\sigma(pp \to t\bar{t}) \times \mathrm{BR}(t \to H^{\pm}b) \times \mathrm{BR}(H^{\pm} \to W^{\pm*}\phi)$, $\phi = A, h = 125$ GeV

In the alignment limit $\cos(\beta - \alpha) \approx 1$, the heavy CP-even Higgs H^0 completely mimics the SM Higgs:

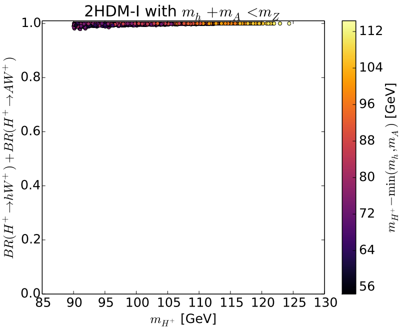
$$H^0 f\bar{f} = \frac{\sin\alpha}{\sin\beta} \approx 1$$
$$H^0 VV = \cos(\beta - \alpha) \approx 1 \quad (1)$$

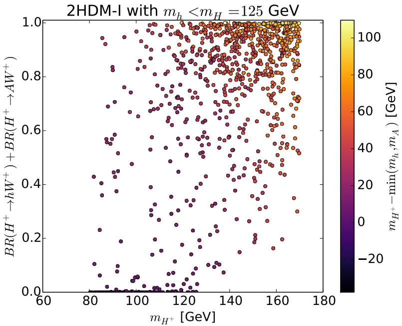


Fermiophobic h^0

- In 2HDM-I, $h^0 f\bar{f} \propto \frac{\cos\alpha}{\sin\beta} = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$
  For negative $\sin(\beta-\alpha)$ and positive $\cos(\beta-\alpha)$,
  it is clear that $\cos\alpha \to 0$. h^0 becomes fermiophobic.
- $h^0 VV \propto \sin_{\beta-\alpha} \approx 0$; $h^0 \to \{VV^*, V^*V^*\}$ very suppressed;
  $h^0 \to \gamma\gamma$ could reach 100%
- $H^\pm W^\mp h^0 \propto \cos(\beta-\alpha) \approx 1$
- light charged Higgs can be produced from $t \to bH^+$ and also
  $pp \to W^* \to H^\pm h^0$
- with h^0 close to fermiophobic,
  $pp \to t\bar{t} \to bWbH^+ \to 2b2Wh^0 \to 2b + 2W + 2\gamma$;
  $pp \to H^\pm h^0 \to Wh^0h^0 \to 4\gamma + W$

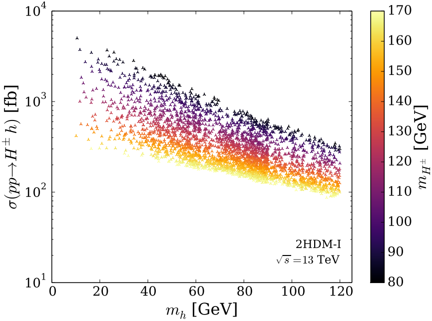
$\mathrm{Br}(H^\pm \to W^\pm S)$

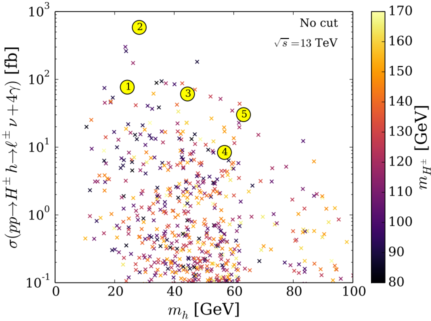




$\sigma(q\bar{q}' \to H^{\pm}h^0)$; $\sigma(q\bar{q}' \to l\nu 4\gamma)$

BP	m_h	$m_{H^\pm}$	m_A	$\sin_{\beta-\alpha}$	$\tan\beta$	$\sigma_{W^\pm 4\gamma}$[fb]	$Br(h^0 \to \gamma\gamma)$
1	24.2	152.2	111.1	-0.048	20.9	359	0.94
2	28.3	83.7	109.1	-0.050	20.2	2740	0.97
3	44.5	123.1	119.9	-0.090	10.9	285	0.70
4	56.9	97.0	120.3	-0.174	5.9	39	0.22
5	63.3	148.0	129.2	-0.049	20.7	141	0.71





Cuts and selection efficiencies

We require pseudorapidity $|\eta| < 2.5$ for the lepton and photons, and an isolation $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.4$ for all objects.

(i) all photons: $p_T^\gamma > 10$ GeV; charged lepton: $p_T^\ell > 20$ GeV,

(ii) imposes that $p_T^\gamma > 20$ GeV and $p_T^\ell > 10$ GeV.

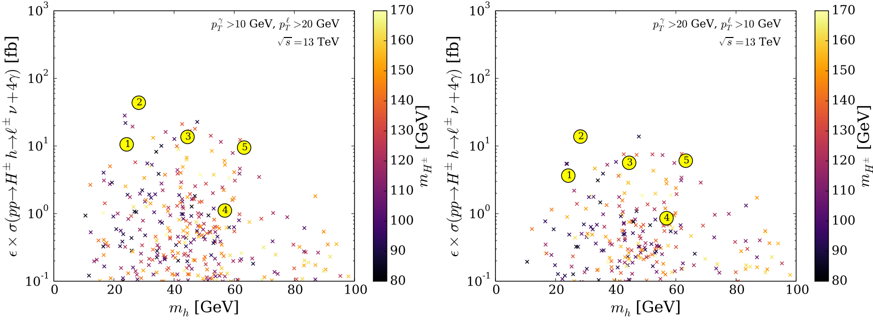
- The irreducible SM $W4 + \gamma$ Background $< 10^{-6}$ pb.

- The selection efficiencies: $\epsilon = \sigma(\text{cuts})/\sigma(\text{no cuts})$.

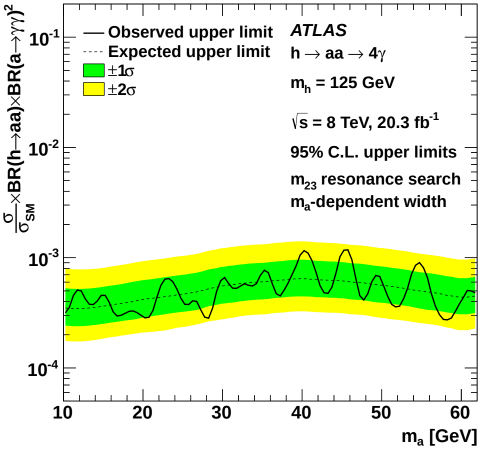
p_T^γ >10 GeV, p_T^ℓ >20 GeV

$m_{H^+} \backslash m_h$	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

$\sigma(q\bar{q}' \to H^{\pm}h \to l\nu + 4\gamma)$ with cuts



ATLAS: fermiophobic Higgs searches from SM-like: $\sigma_{ren}(pp \to H) \times BR(H \to AA) \times BR(A \to \gamma\gamma)^2$



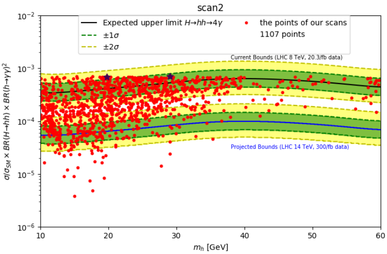
$\sigma_{4\gamma} = \sigma(pp \to H) \times BR(H \to hh) \times BR(h \to 2\gamma)^2$ at 13 TeV

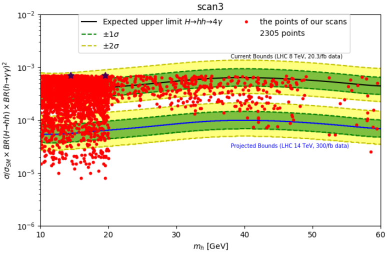
We use 2HDM type-I with the following scans:

parameters	scan2	scan3
m_H (SM-like)	125	125
m_h	$[10, 60]$	$[10, 60]$
m_A	$[60, 150]$	$[62.5, 200]$
$m_{H^\pm}$	$[100, 150]$	$[100, 170]$
$\tan\beta$	$[2, 50]$	$[2, 50]$
$\sin(\beta-\alpha)$ & α	$\alpha=\frac{\pi}{2}-\delta$	$\alpha=\frac{\pi}{2}$
m_{12}^2	$[0, 100]$	$[0, 150]$
$\lambda_6 = \lambda_7$	0	0

- 2HDMC
- HB5 and HS2
- Additional constraints from ATALS and Z width.

$\sigma_{4\gamma} = \sigma(pp \to H) \times BR(H \to hh) \times BR(h \to 2\gamma)^2$ at 13 TeV





$\sigma_{4\gamma} = \sigma(pp \to H) \times BR(H \to hh) \times BR(h \to 2\gamma)^2$ at 13 TeV

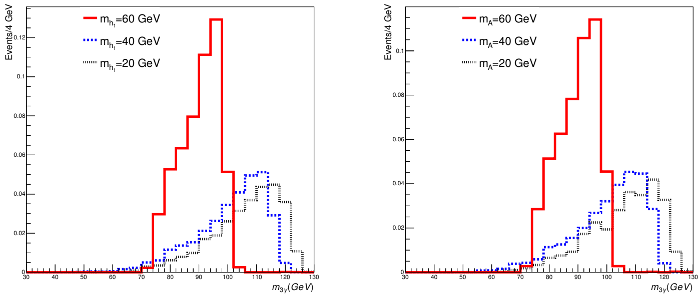


Figure: Distributions of important observables at detector level: (a) $m_{3\gamma}$ for $gg \to hh \to 4\gamma$, (b) $m_{3\gamma}$ for $gg \to AA \to 4\gamma$.

Summary and perspectives

- In 2HDM-I there is regions of the parameter space compliant with theoretical and experimental constraints yielding substantial BRs for $H^{\pm} \to W^{\pm *}h/W^{\pm *}A$ in which the $m_{H^{\pm}} < m_t - m_b$, wherein $W^{\pm *} \to l\nu$ $(l = e, \mu)$.
- $\sigma(pp \to t\bar{t} \to tbH^{+} \to tbWA^{0})$ could be sizeable
- light $H^{\pm}$ in the 80–160 GeV mass range, still being consistent with all LHC, LEP Tevatron and B-physics data.
- If $m_h < m_H = 125$ GeV, EWPT imply that $H^{\pm}$ is rather light and decay to $W^{\pm}h^{0}$ with $h^{0} \to \gamma\gamma$
- $pp \to H^{\pm}h^{0} \to W^{\pm} + 4\gamma$ and $pp \to H \to hh \to 4\gamma$ with significant events.
- After reasonable cuts of the photons and the lepton, $\sigma_{W^{\pm}4\gamma}$ and $\sigma_{4\gamma}$ can still enjoy a cross section of the order 10 fb and 100 fb respectively.

Thank You