New discovery modes for a light charged Higgs boson at the LHC

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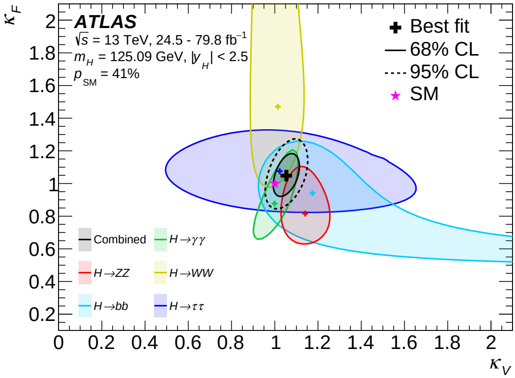
Based on A.A, R. Benbrik, M. Krab, B. Manaut, S. Moretti, Y. Wang and Q. S. Yan, JHEP **10** (2021) and JHEP **12** (2021)

Outlines

- Introduction
- Two Higgs doublet model (2HDM)
- Bosonic decays of charged Higgs: $H^{\pm} \to W^{\pm}A^0/W^{\pm}h^0$
- $W4\gamma$, $W4b$, $W2b2\tau$ signatures for a light $H^{\pm}$ at the LHC.
- Conclusions

Introduction:



Introduction:

After the Higgs-like discovery at $7 \oplus 8 \oplus 13$ TeV LHC, the mission of the LHC run at 13.6 TeV is:

- The improvement of the Higgs-like mass and Higgs-like coupling measurements.
- Find a clear hint of new physics beyond SM

Introduction:

After the Higgs-like discovery at $7 \oplus 8 \oplus 13$ TeV LHC, the mission of the LHC run at 13.6 TeV is:

- The improvement of the Higgs-like mass and Higgs-like coupling measurements.
- Find a clear hint of new physics beyond SM
- Accurate measurements of the Higgs-like 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:
- Most of the High representations predicts: singly and/or doubly charged Higgs

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

The most general potential for 2HDM:

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

2HDM: G. Branco et al Phys rep'2012

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

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

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

leads to FCNCs at tree level.

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

Type-I	$Y^1_{u,d} = 0$, $Y^1_\ell = 0$
Type-II	$Y^1_u = Y^2_{d,\ell} = 0$
Type-III (X)	$Y^1_{u,d} = Y^2_\ell = 0$
Type-IV (Y)	$Y^1_{u,\ell} = Y^2_d = 0$

$$\mathcal{L}_{H_i\bar{f}f} = -\frac{gm_f}{2m_W}\,\bar{f}\left(Y^S_{i,f} + i\,Y^P_{i,f}\,\gamma_5\right) f\, H_i\,,$$

$$\mathcal{L}_{H^\pm tb} = +\frac{gm_b}{\sqrt{2}m_W}\,\bar{b}\,(c_L\,P_L + c_R\,P_R)\,t\,H^- \;+\; \text{h.c.}\,,$$

$$\mathcal{L}_{H_iVV} = -\frac{gm_V}{2c_W}\,\underbrace{(\cos\beta\, O_{\phi_2 i} + \sin\beta\, O_{\phi_1 i})}_{H_iVV}\,g_{\mu\nu}\,V^\mu V^\nu$$

$$\mathcal{L}_{H_iH^\pm W^\pm} = -\frac{g}{2}\,(S_i + iP_i)\left[H^-\left(i\,\overset{\leftrightarrow}{\partial}_\mu\right)H_i\right]\,W^{+\mu} \;+\; \text{h.c.}\,,$$

$$S_i = c_\beta\, O_{\phi_2 i} - s_\beta\, O_{\phi_1 i}\,,\quad P_i = O_{ai}$$

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Sum rules:

- $\Sigma_i(H_iVV)^2 = 1$

- $(H_iVV)^2 + |H^\pm W^\mp H_i|^2 = 1$ for $i = 1,2,3$
- 2HDM+S : $(H_iVV)^2 + |H^\pm W^\mp H_i|^2 + S_{i3}^2 = 1$ for $i = 1,2,3$

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	$-s_\alpha/c_\beta$	$-s_\alpha/c_\beta$	$\cot\beta$	$\tan\beta$	$\tan\beta$
Type-III	c_α/s_β	c_α/s_β	$-s_\alpha/c_\beta$	$\cot\beta$	$-\cot\beta$	$\tan\beta$
Type-IV	c_α/s_β	$-s_\alpha/c_\beta$	c_α/s_β	$\cot\beta$	$\tan\beta$	$-\cot\beta$

Constraints

- Stability of the 2HDM potential requires that it should be bounded from below, i.e. that there is no direction in field space along which the potential becomes negatif.

Deshpande and E. Ma, PRD18'1978

$$\lambda_1 > 0 \quad , \quad \lambda_2 > 0$$
$$\lambda_3 > -\sqrt{\lambda_1 \lambda_2}$$
$$\lambda_3 + min(0, \lambda_4 - \mid \lambda_5 \mid) > -\sqrt{\lambda_1 \lambda_2}$$

- The vacuum of the model is global one if and only if:
$m_{12}^2(m_{11}^2 - k^2 m_{22}^2)(\tan\beta - k) > 0 \quad ; \quad k = \sqrt[4]{\frac{\lambda_1}{\lambda_2}}$

A. Barroso et al JHEP**06** (2013)

- Perturbative unitarity: $V_L^+ V_L^- \to V_L^+ V_L^-$, $h_i\ h_j \to h_i\ h_j$ ...

Constraints

- 2HDM-Calculator linked to SuperIso
- In 2HDM-II and IV: $m_{H\pm} > 800$ GeV for any $\tan\beta > 1$

  [Misiak et al EPJC'2017, JHEP'20]
- In 2HDM-I there is no limit on $H^{\pm}$ for $\tan\beta \geq 2$
- HiggsBounds and HiggsSignal

Charged Higgs production

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

- light $H^{\pm}$: $m_{H^{\pm}} \leq m_t - m_b$: are copiously produced from $t\bar{t}$ production $pp \to t\bar{t}^* \to t\bar{b}H^- + \text{c.c.}$

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- various direct production modes:
  QCD: $gb \to tH^-$ and $gg \to t\bar{b}H^-$,
- $gg \to W^\pm H^\mp$ (loop) , $b\bar{b} \to h^*, H^*, A^* \to W^\pm H^\mp$
  $q\bar{q} \to \gamma^*, Z^* \to H^+H^-$, $gg \to H^+H^-$(loop)
  $q\bar{q}' \to W^* \to \phi H^\pm$ where $\phi = h, H, A$,

Charged Higgs decays

Fermionic decays

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

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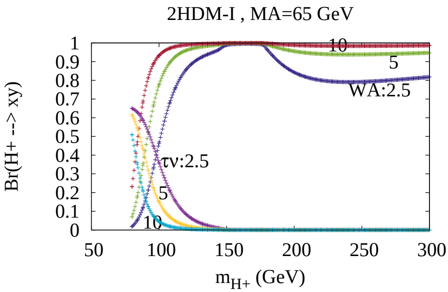
Fermionic decays

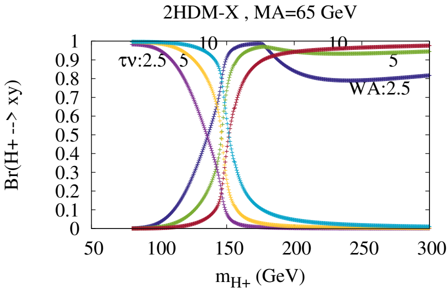
- $H^{\pm} \to \tau\nu \quad , \quad cs \quad , \quad cb$
- $H^{\pm} \to tb$

Bosonic decays

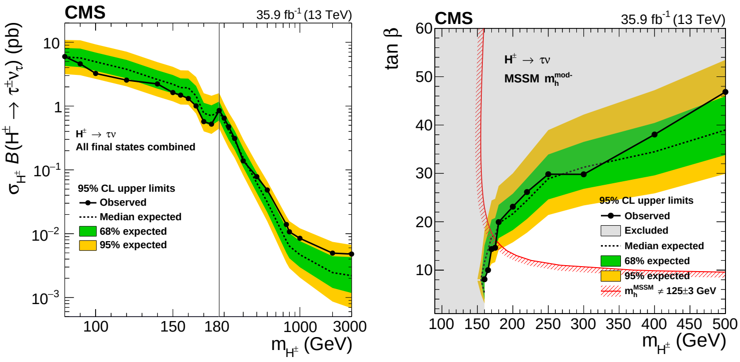
- $H^{\pm} \to W^{\pm}\phi^{0} \quad , \quad \phi^{0} = h^{0}, H^{0}, A^{0}$
- $H^{\pm} \to W^{\pm}\gamma, W^{\pm}Z$: small because loop mediated



2HDM-I , MA=65 GeV
Br(H+ --> xy)
m$_{H+}$ (GeV)
10
5
WA:2.5
τν:2.5
5
10

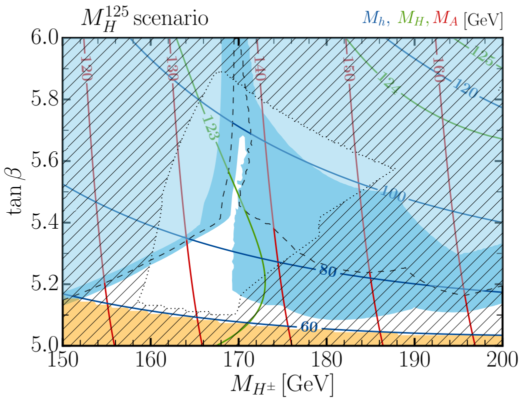


2HDM-X , MA=65 GeV
Br(H+ --> xy)
m$_{H+}$ (GeV)
τν:2.5
5
10
10
5
WA:2.5

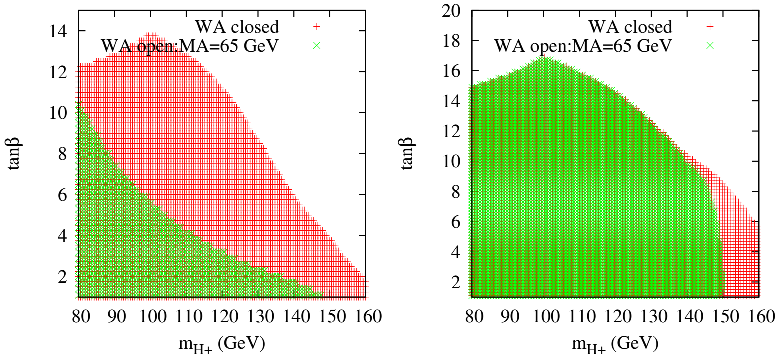

CMS
35.9 fb-1 (13 TeV)
H± → τν
All final states combined
95% CL upper limits
Observed
Median expected
68% expected
95% expected
mH± (GeV)
CMS
35.9 fb-1 (13 TeV)
tan β
H± → τν
MSSM mh mod-
95% CL upper limits
Observed
Excluded
Median expected
68% expected
95% expected
mh MSSM ≠ 125±3 GeV
mH± (GeV)

MSSM with $m_h < m_H = 125$ GeV:

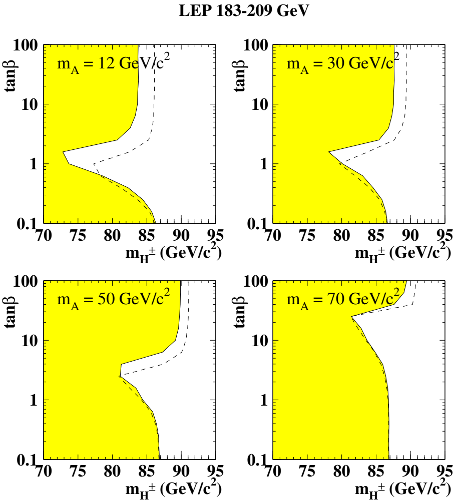
E. Bagnaschi et al EPJC'18 hep-ph/ arXiv:1808.07542



left: 2HDM-I, right: 2HDM-III



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



CMS searches: $H^\pm \to HW^\pm$ hep-ex/2207.01046
$H^\pm \to AW \to \mu^+\mu^- W$ with $B(A \to \mu^+\mu^-) = 1$ hep-ex/1905.07453

very light a_1 in the NMSSM: [A.Akeroyd, A.A and Q.S. Yan EPJC'07]

$H^{\pm}W^{\mp}a_1 \propto \cos\theta_A$: θ_A is the doublet-singlet mixing.

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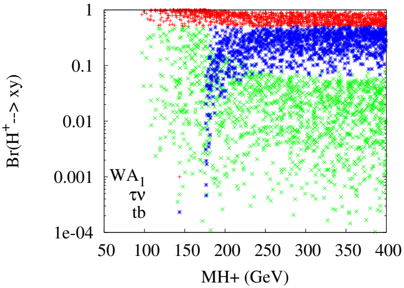
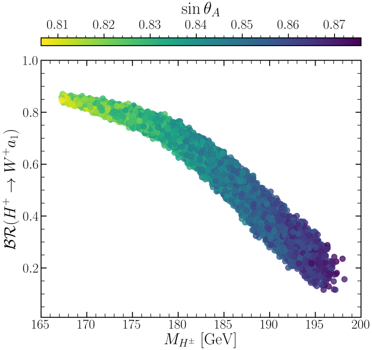
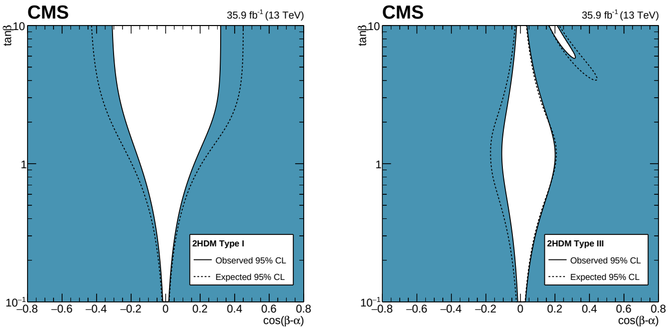




CP conserving 2HDM



- 2 alignment limits:
  - h=125 GeV SM-like: $\sin_{\beta-\alpha} = 1$ (Decoupling limit)
  - $h < H$=125 GeV SM-like: $\cos_{\beta-\alpha} = 1$:

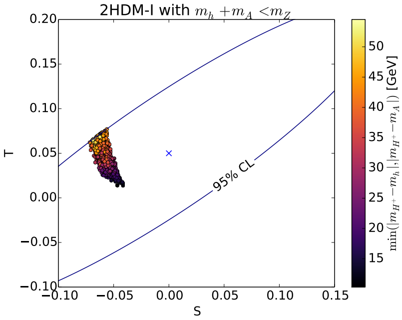
H^0-SM like ; $m_h < m_H = 125$ GeV

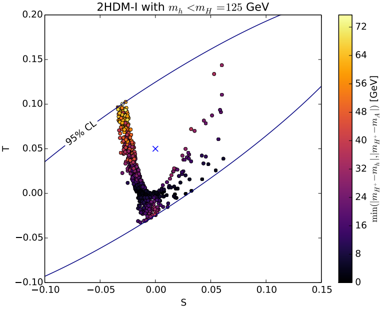
In the alignment limit $\cos(\beta-\alpha) \approx 1$, the heavy CP-even Higgs H^0 completely mimics the SM Higgs:

$$
\begin{aligned}
H^0 f\bar{f} &= \frac{\sin\alpha}{\sin\beta} \approx 1 \quad , \quad h^0 f\bar{f} = \frac{\cos\alpha}{\sin\beta} \\
H^0 VV &= \cos(\beta-\alpha) \approx 1 \quad , \quad h^0 VV = \sin(\beta-\alpha) \approx 0 \qquad (1)
\end{aligned}
$$

- $m_h \le m_H = 125$ GeV: $H^0 \to h^0 h^0; A^0 A^0; ZA^0$ might be open: $Br(H^0 \to h^0 h^0) + Br(H^0 \to A^0 A^0) + Br(H^0 \to ZA^0) \le 10\%$
- if h^0 and A^0 too light: $Z \to h^0 A^0 \propto \cos^2(\beta-\alpha)$
- For $m_h \le 125$ GeV and $m_H = 125$ GeV: EWPT imply that $H^\pm$ and A^0 would be also light.

EWPT: S and T


2HDM-I with $m_h + m_A < m_Z$
95% CL
T
S
$\min(|m_{H^+} - m_h|, |m_{H^+} - m_A|)$ [GeV]


2HDM-I with $m_h < m_H = 125$ GeV
95% CL
T
S
$\min(|m_{H^+} - m_h|, |m_{H^+} - m_A|)$ [GeV]

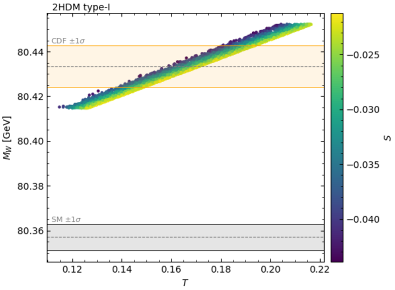
$$M_W^{\text{CDF}} = 80.4435 \pm 0.0094 \ \mathrm{GeV}.$$ [CDF collaboration ' Science 2022]

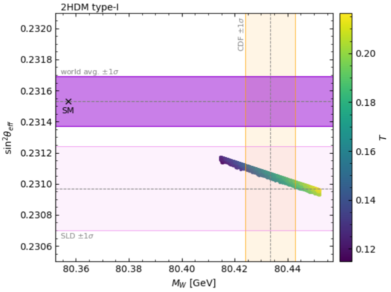
$$M_W^{\text{SM}} = 80.357 \pm 0.006 \ \ \mathrm{GeV}.$$ [Review of Particle Physics ' 2020]

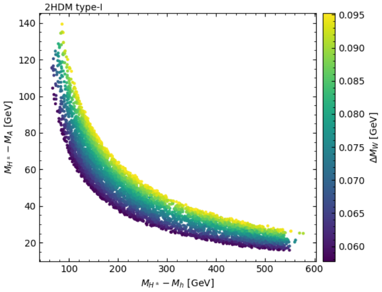
M_W^{CDF} presents a deviation from M_W^{SM} with a significance of 7.0 σ.

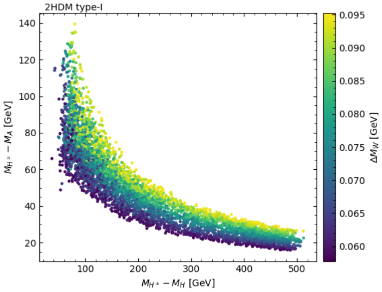
$$(M_W^{2HDM})^2 - (M_W^{SM})^2 = \frac{\alpha_0 c_W^2 M_Z^2}{c_W^2 - s_W^2}\left[-\frac{1}{2}S + c_W^2 T + \frac{c_W^2 - s_W^2}{4 s_W^2} U\right],$$

$$\Delta \sin^2\theta_{\text{eff}} = \frac{\alpha_0}{c_W^2 - s_W^2}\left[\frac{1}{4}S - s_W^2 c_W^2 T\right].$$


2HDM type-I
CDF ±1σ
SM ±1σ
M_W [GeV]
T
S


2HDM type-I
CDF ±1σ
world avg. ±1σ
SM
SLD ±1σ
$\sin^2\theta_{eff}$
M_W [GeV]
T


2HDM type-I
$M_{H^\pm} - M_A$ [GeV]
$M_{H^\pm} - M_h$ [GeV]
ΔM_W [GeV]


2HDM type-I
$M_{H^\pm} - M_A$ [GeV]
$M_{H^\pm} - M_H$ [GeV]
ΔM_W [GeV]

Can h^0 be Fermiophobic ?

- 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%

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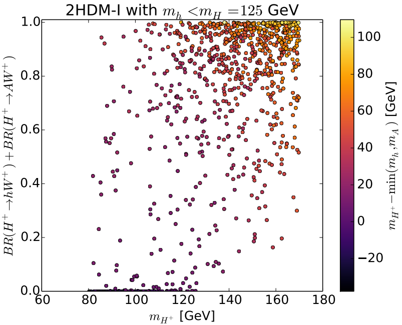
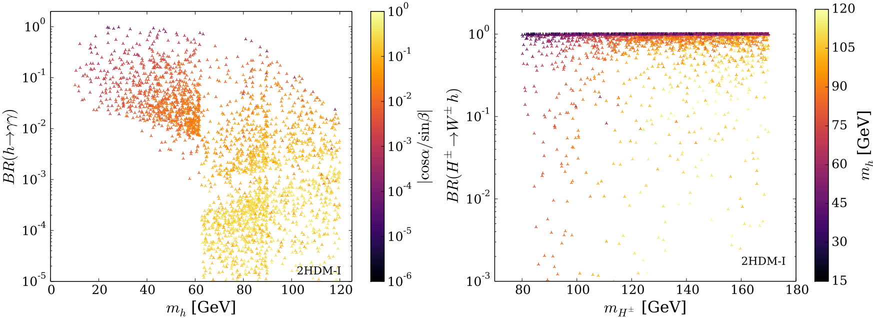
  $h^0 \to \gamma\gamma$ could reach 100%
- $H^\pm W^\mp h^0 \propto \cos(\beta-\alpha) \approx 1$
- light $H^\pm$ can be produced from $t \to bH^+$ and also
  $pp \to W^* \to \{H^\pm h^0, H^\pm A^0\}$; $pp \to \gamma^*, Z^* \to H^\pm H^\mp$
- with h^0 close to fermiophobic,
  $pp \to t\bar{t} \to bWbH^+ \to 2b2Wh^0 \to 2b + 2W + 2\gamma$;
  $pp \to H^\pm h^0 \to Wh^0h^0 \to 4\gamma + W$

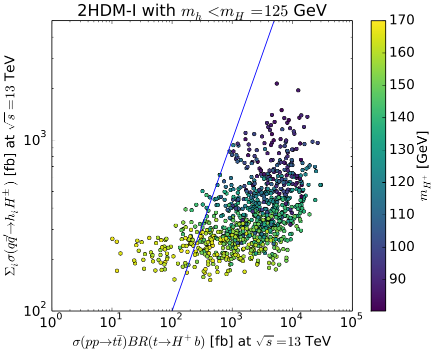
Br($H^\pm \to W^\pm S$)



$Br(h^0 \to \gamma\gamma)$ and $Br(H^\pm \to W^\pm h^0)$

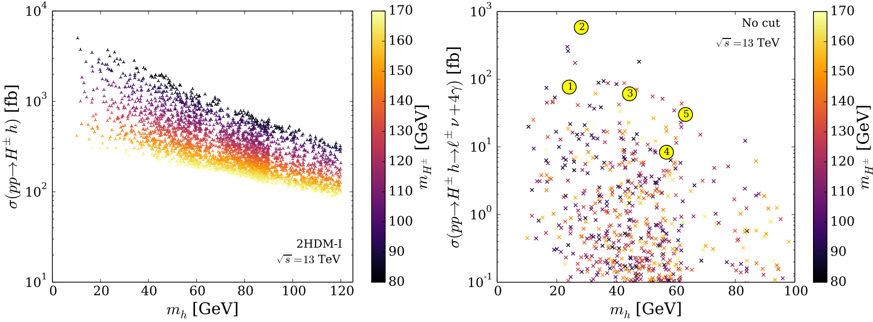


Comparison: $\sigma(pp \to t\bar{t}) \times BR(t \to H^+ b)$ vs. $\Sigma_i \sigma(q\bar{q}' \to H^\pm h_i)$



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

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.

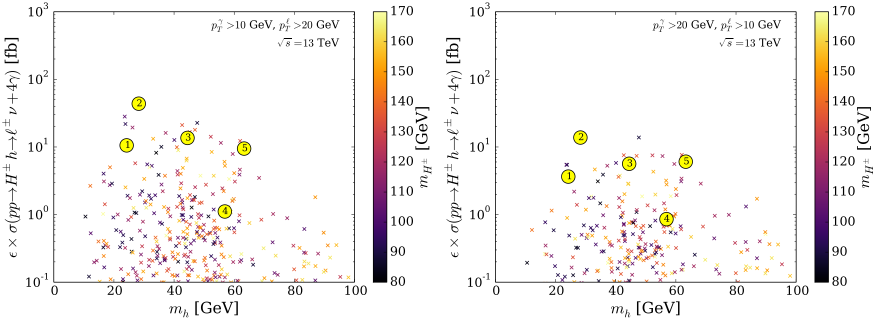
- The irreducible SM W+4γ Background $< 10^{-6}$ pb.

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

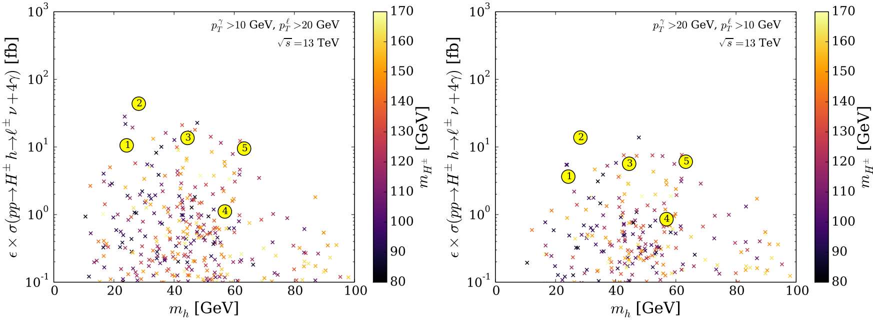
p_T^γ >10 GeV, p_T^ℓ >20 GeV

$m_{H^+} \backslash m_h$	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



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



A full Monte Carlo (MC) analysis at the detector level shows that $W4\gamma$ signal is very promising, at the LHC with 300 fb^{-1} luminosity.

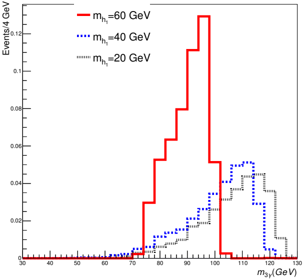
Is $h \to \gamma\gamma$ ruled out?

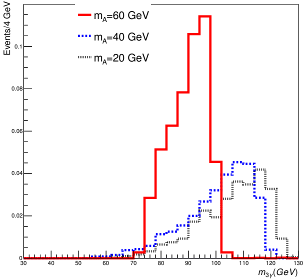
- ATLAS searched for new phenomena in events with at least three photons at 8 TeV and with an integrated luminosity of 20.3 fb^{-1}. [ATLAS ; hep-ex/1509.05051] based on $pp \to H \to AA \to 4\gamma$
- $pp \to H \to hh \to 4\gamma$: [A.A et al JHEP 07 (2018) 007]

- $gg \to H \to hh \to 4\gamma$ and $gg \to H \to AA \to 4\gamma$ have the same differential cross section,
- The matrix elements can be put as

$$\begin{aligned}\mathcal{M}^h &= C(k_1 \cdot k_2 \eta^{\mu\nu} - k_2^{\mu} k_1^{\nu}) \epsilon_{\mu}^*(k_1) \epsilon_{\nu}^*(k_2) (k_3 \cdot k_4 \eta^{\rho\sigma} - k_4^{\rho} k_3^{\sigma}) \\ &\quad \times \epsilon_{\rho}^*(k_3) \epsilon_{\sigma}^*(k_4) \delta^{ab} \epsilon(p_1) \cdot \epsilon(p_2)\,, \\ \mathcal{M}^A &= D \epsilon_{\alpha}^*(k_1) \epsilon_{\beta}^*(k_2) \epsilon^{\alpha\beta\mu\nu} k_{\mu}^1 k_{\nu}^2 \epsilon_{\rho}^*(k_3) \epsilon_{\sigma}^*(k_4) \epsilon^{\rho\sigma\gamma\delta} k_{\gamma}^3 k_{\delta}^4 \delta^{ab} \epsilon_{p_1} . \epsilon_{p_2}\end{aligned}$$

  p_1 and p_2 is the momentum of the initial gluons, $k_1 - k_4$ are momentum of 4 photons in the final state.
- $\mid \mathcal{M}^{h,A} \mid^2 \propto \{C^2, D^2\}(k_1.k_2)^2 (k_3.k_4)^2$

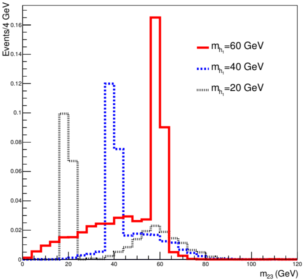


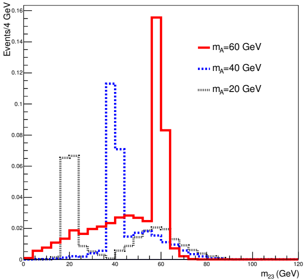


Distributions at detector level: (a) $m_{3\gamma}$ for $gg \to H \to hh \to 4\gamma$, (b) $m_{3\gamma}$ for $gg \to H \to AA \to 4\gamma$,

$m_{3\gamma}$: the invariant mass of the 3 leading P_T-ordered photons

$gg \to H \to hh \to 4\gamma$ vs $gg \to H \to AA \to 4\gamma$





Distributions at detector level: (a) m_{23} for $gg \to H \to hh \to 4\gamma$ and (b) m_{23} for $gg \to H \to AA \to 4\gamma$.

m_{23}: the invariant mass of the 2nd and 3rd P_T-ordered photons.

Projection from 8 TeV to 14 TeV sensitivity

- In order to project the sensitivity of the future LHC run at $\sqrt{s} = 14$ TeV, we have to rescale 8 TeV results.
- The 'boost factors', for both signal and background processes is calculated using MC tools: (MadGraph 5, PYTHIA: simulate showering, hadonisation and decays and PGS to perform the fast detector simulations).

Projection from 8 TeV to 14 TeV sensitivity

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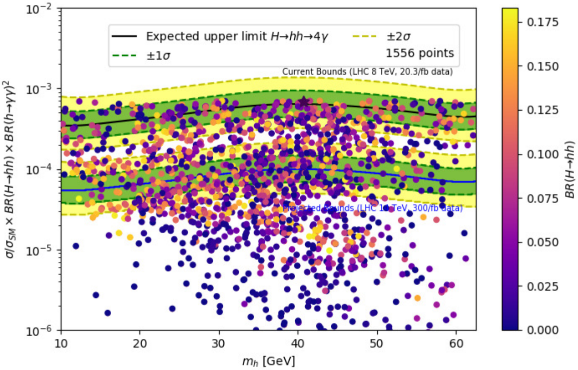
- The 'boost factors', for both signal and background processes is calculated using MC tools: (MadGraph 5, PYTHIA: simulate showering, hadonisation and decays and PGS to perform the fast detector simulations).
- we adopt the same selection cuts of the ATLAS collaboration,
  i) $n_\gamma \geq 3$: we consider inclusive 3 photon events.
  ii) The two leading photons should have a $P_t(\gamma) > 22$ GeV and the third one should have a $P_t(\gamma) > 17$ GeV
  iii) The photons should be resolved in the range $|\eta| < 2.37$ and do not fall in the end-cap region $1.37 < |\eta| < 1.52$.
  iv) $\Delta R(\gamma\gamma) > 0.4$.



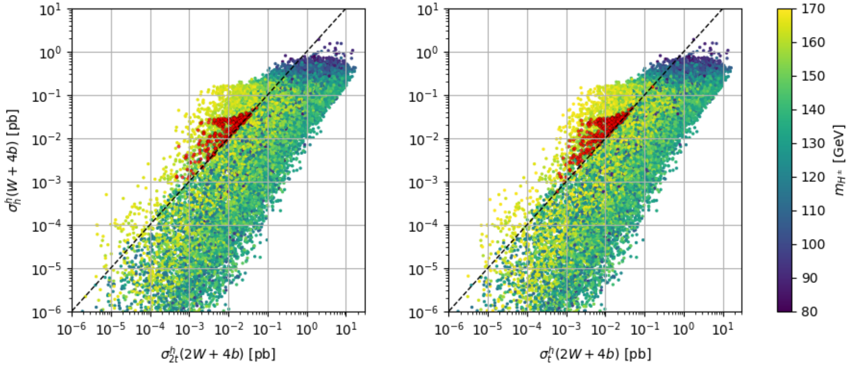
Expected upper limit H→hh→4γ
±2σ
±1σ
1556 points
Current Bounds (LHC 8 TeV, 20.3/fb data)
Projected Bounds (LHC 14 TeV, 300/fb data)
σ/σSM × BR(H→hh) × BR(h→γγ)²
mh [GeV]
BR(H→hh)

fermionic decays of h^0 and A^0

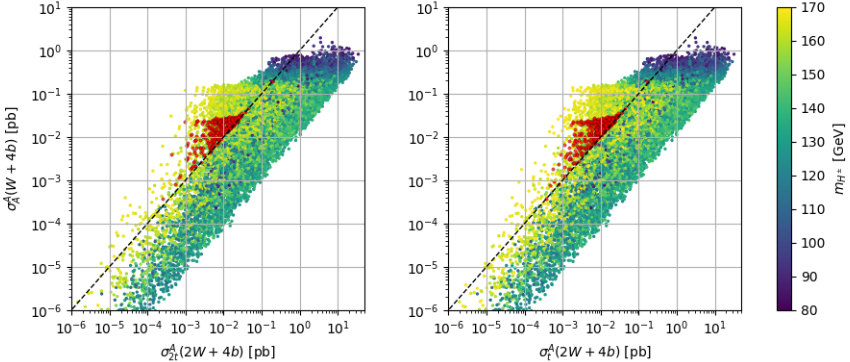
	production and decay chain
$\sigma^{h_i}_{2t}(2W2b2f)$	$2\ \sigma_{t\bar{t}} \times \mathrm{BR}(t \to bH^+) \times \mathrm{BR}(\bar{t} \to \bar{b}W) \times \mathrm{BR}(H^\pm \to Wh_i) \times \mathrm{BR}(h_i \to f\bar{f})$
$\sigma^{h_i}_{t}(2W2b2f)$	$\sigma(pp \to t\bar{b}H^-) \times \mathrm{BR}(t \to bW) \times \mathrm{BR}(H^\pm \to Wh_i) \times \mathrm{BR}(h_i \to f\bar{f})$

	Di-Higgs production and decay chain
$\sigma^{h_i}_{h_j}(2W2f2f')$	$\sigma(H^+H^-) \times \mathrm{BR}(H^\pm \to W^\pm h_i) \times \mathrm{BR}(H^\pm \to W^\pm h_j) \times (\mathrm{BR}(h_i \to f\bar{f}) \times \mathrm{BR}(h_j \to f'\bar{f}') + h_i \longleftrightarrow h_j)\ \frac{1}{1+\delta_{ff'}}$
$\sigma^{h_i}_{h_j}(W2f2f')$	$\frac{1}{1+\delta_{ff'}}\ \sigma(H^\pm h_i) \times \mathrm{BR}(H^\pm \to W^\pm h_j) \times (\mathrm{BR}(h_i \to f\bar{f}) \times \mathrm{BR}(h_j \to f'\bar{f}') + h_i \longleftrightarrow h_j)$

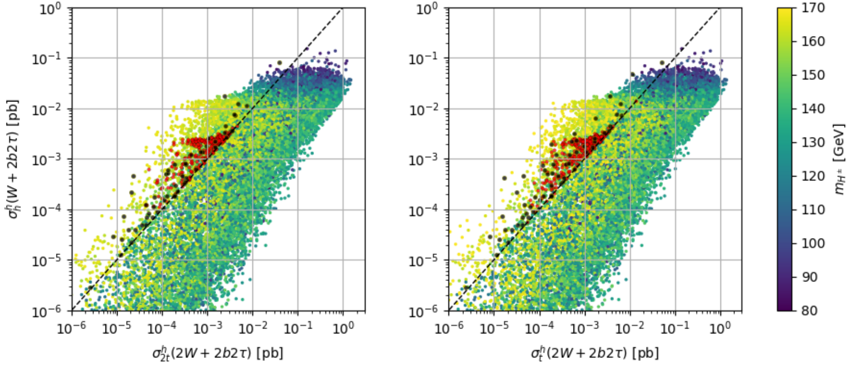
Table: $i, j = 1, 2$ and have $h_1 = h$ and $h_2 = A$; $f(f') = b$ or τ.



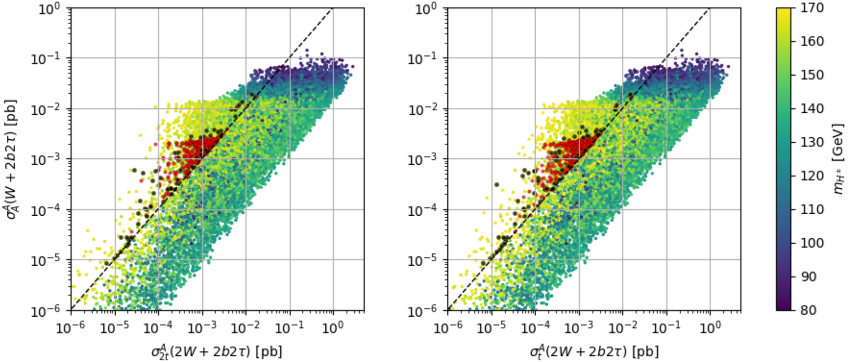
$\sigma(pp \to H^\pm h) \times \mathrm{BR}(H^\pm \to W^\pm h) \times \mathrm{BR}(h \to b\bar{b})^2$ compared to 2 σ_{2t} (left) and σ_t^h (right). Red points identify: $\sigma(H^+H^-) \times \mathrm{BR}(H^\pm \to W^\pm h)^2 \times \mathrm{BR}(h \to b\bar{b})^2$ in 2HDM-I.



$\sigma(pp \to H^\pm A) \times \mathrm{BR}(H^\pm \to W^\pm A) \times \mathrm{BR}(A \to b\bar{b})^2$ compared to σ_{2t}^A (left) and σ_t^A (right). Red points identify: $\sigma(H^+H^-) \times \mathrm{BR}(H^\pm \to W^\pm A)^2 \times \mathrm{BR}(A \to b\bar{b})^2$ in 2HDM-I.



$2\sigma(pp \to H^\pm h) \times \mathrm{BR}(H^\pm \to Wh) \times \mathrm{BR}(h \to b\bar{b}) \times \mathrm{BR}(h \to \tau^+\tau^-)$ compared to σ_{2t}^h (left) and σ_t^h (right). The red points identify $\sigma(H^+H^-)x\mathrm{BR}(H^\pm \to Wh)^2 x\mathrm{BR}(h \to b\bar{b})x\mathrm{BR}(h \to \tau^+\tau^-)$ for 2HDM-I while the black points are for 2HDM-X rates: $\sigma(pp \to H^\pm h) \times \mathrm{BR}(H^\pm \to W^\pm h) \times \mathrm{BR}(h \to \tau^+\tau^-)^2$.



$2\sigma(pp \to H^\pm A)x\mathrm{BR}(H^\pm \to WA)x\mathrm{BR}(A \to b\bar{b})x\mathrm{BR}(A \to \tau^+\tau^-)$ compared to σ_{2t}^A (left) and σ_t^A (right). The red points identify $\sigma(H^+H^-)x\mathrm{BR}(H^\pm \to WA)^2x\mathrm{BR}(A \to b\bar{b})x\mathrm{BR}(A \to \tau^+\tau^-)$ for 2HDM-I while the black points are for 2HDM-X rates: $\sigma(pp \to H^\pm A) \times \mathrm{BR}(H^\pm \to W^\pm A) \times \mathrm{BR}(A \to \tau^+\tau^-)^2$.

Conclusions

- In 2HDM-I there is regions of the parameter space compliant with all constraints yielding substantial BRs for $H^\pm \to W^{\pm *} h / W^{\pm *} A$ in which the $m_{H^\pm} < m_t - m_b$.
- $\sigma(pp \to t\bar{t} \to tbH^+ \to tbWA^0)$ and/or $pp \to H^\pm h / H^\pm A / H^\pm H^\mp$ 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.

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- light $H^\pm$ in the 80–160 GeV mass range, still being consistent with all LHC, LEP Tevatron and B-physics data.
- $pp \to H^\pm h^0 \to W^\pm + 4\gamma$ with significant events.
- $pp \to H^\pm h^0 \to W^\pm + 4f$ could be much larger than events from $pp \to t\bar{t}$ or $pp \to tbH^+$.