Prospects of same sign trilepton search in the Type I two Higgs doublet model at the LHC

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Outline

- Overview of Type I two Higgs doublet model (2HDM).
- Limits on the charged Higgs parameters ($m_{H^\pm} - \tan\beta$).
- Electro Weak production of charged Higgs.
- Fermiophobic nature of charged Higgs and heavy Higgs in Type I 2HDM.
- Signatures of same sign trilepton in Type I 2HDM.

- 2HDM is the minimal but phenomenologically rich extension of SM under the same gauge symmetry.

- The scalar sector of the 2HDM consists of two $SU(2)$ Higgs doublets Φ_i, $i = 1,\ 2$.

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ \frac{v_i+\rho_i+i\eta_i}{\sqrt{2}} \end{pmatrix}$$

$$v_i = \langle \rho_i \rangle \quad v = \sqrt{v_1^2 + v_2^2} = 246 \text{ GeV}$$

- Mostly studied: $\mathcal{CP}$ conserving 2HDM with softly broken $\mathcal{Z}_2$ (to avoid Higgs mediated FCNC) symmetry.

$$V_{\text{2HDM}} \supset m_{12}^2 \Phi_1^\dagger \Phi_2 + h.c.$$

- After EWSB, the scalar sector consists of two $\mathcal{CP}$ even Higgses (h and H), one $\mathcal{CP}$ odd scalar A and a pair of charged Higgs $H^\pm$.

- Parameters: $m_h^2,\ m_H^2,\ m_A^2,\ m_{H^\pm}^2,\ m_{12}^2,\ v,\ \tan\beta(= v_2/v_1),\ \sin(\beta-\alpha)$

- In 2HDM, h is identified as the observed 125 GeV Higgs boson.

- Based on the $\mathcal{Z}_2$ charge assignments for the fermions, there are four possible Yukawa structures – Type I, II, X and Y.

- After EW symmetry breaking the Yukawa Lagrangian in terms of the mass eigenstates is:

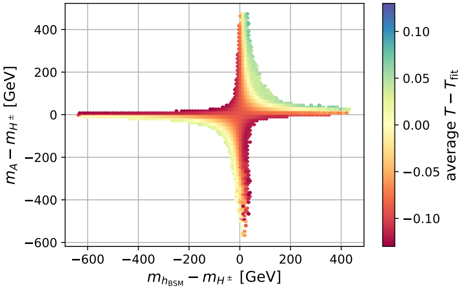
$$\begin{aligned}\mathcal{L}^{\rm 2HDM}_{\rm Yuk,\ I} &= -\sum_{f=u,d,\ell} \frac{m_f}{v}\left(\xi_h^f \bar{f} h f + \xi_H^f \bar{f} H f - i\xi_A^f \bar{f}\gamma_5 A f\right) \\ &- \left\{\frac{\sqrt{2}V_{ud}}{v}\bar{u}\left(\xi_A^u m_u P_L + \xi_A^d m_d P_R\right) H^+ d + \frac{\sqrt{2}m_l}{v}\xi_A^l \bar{v}_L H^+ l_R + \text{h.c.}\right\}\end{aligned}$$

ξ_h^u	ξ_h^d	ξ_h^ℓ	ξ_H^u	ξ_H^d	ξ_H^ℓ	ξ_A^u	ξ_A^d	ξ_A^ℓ
c_α/s_β	c_α/s_β	c_α/s_β	s_α/s_β	s_α/s_β	s_α/s_β	$\cot\beta$	$-\cot\beta$	$-\cot\beta$

- Other couplings:
  - (A) hVV : $\sin(\beta-\alpha)g^{\rm SM}_{hVV}$, HVV : $\cos(\beta-\alpha)g^{\rm SM}_{hVV}$, AVV : 0 where $V = Z,\ W^\pm$.
  - (B) hAZ_μ : $\frac{g}{2c_W}\cos(\beta-\alpha)(p+p')_\mu$, HAZ_μ : $-\frac{g}{2c_W}\sin(\beta-\alpha)(p+p')_\mu$
  - (C) $H^\pm h W^\mp_\mu$: $\mp i\frac{g}{2}\cos(\beta-\alpha)(p+p')_\mu$, $H^\pm H W^\mp_\mu$: $\pm i\frac{g}{2}\sin(\beta-\alpha)(p+p')_\mu$,
    $H^\pm A W^\mp_\mu$: $\frac{g}{2}(p+p')_\mu$

- Unitarity and vacuum stability bounds can be satisfied by proper choice of $m_{12}^2 \in [0, m_H^2 \sin\beta cos\beta]$.

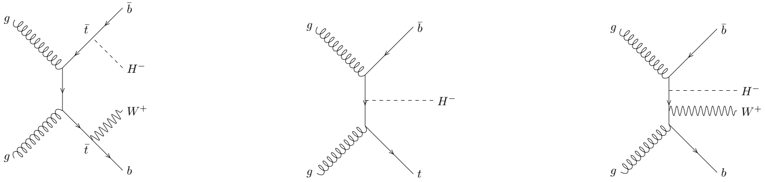
- The EWPO, T - parameter depends strongly on the mass spliting of the charged Higgs and the neutral scalars.



Henning Bahl, Tim Stefaniak, Jonas Wittbrodt, JHEP 06 (2021) 183

- Alignment limit: $\sin(\beta - \alpha) \to 1$ implies that the couplings of h is like SM Higgs boson.

$H^{\pm}$ production and decay channels



- The QCD induced production of charged Higgs depends on its mass with respect to top quark and can be divided into
  - (A) Light Scenario: $m_{H^{\pm}} \lesssim 160$ GeV
  - (B) Heavy Scenario: ($m_{H^{\pm}} \gtrsim 200$ GeV)
  - (C) Intermediate Scenario: ($m_{H^{\pm}} \sim m_t$)
- In Type I 2HDM, the strong production of charged Higgs is $\tan\beta$ suppressed.

Conventional decay channels:

(A) $H^+ \to \tau^+ \nu$

(B) $H^+ \to t\bar{b}$

(C) $H^+ \to c\bar{s}$

(D) $H^+ \to c\bar{b}$

Exotic decay channels:

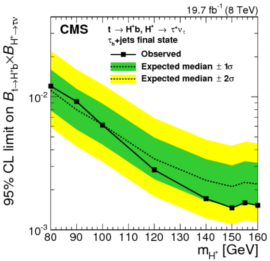
(A) $H^{\pm} \to hW^{\pm} : \frac{\mp ig}{2} \cos(\beta - \alpha)(p_\mu - p_\mu^{\mp})$

(B) $H^{\pm} \to HW^{\pm} : \frac{\mp ig}{2} \sin(\beta - \alpha)(p_\mu - p_\mu^{\mp})$

(C) $H^{\pm} \to AW^{\pm} : \frac{g}{2}(p_\mu - p_\mu^{\mp})$

CMS 8 TeV and 13 TeV results: ($\tau\nu$ and *tb* channels)

JHEP11(2015) 018,[1508.07774]



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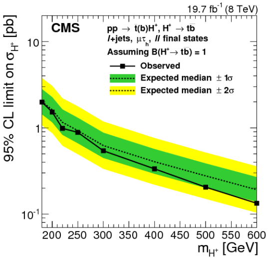
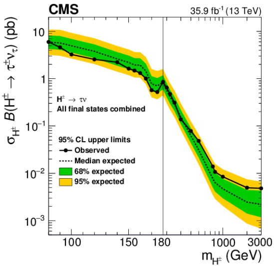


JHEP 07 (2019) 142,[1903.04560]



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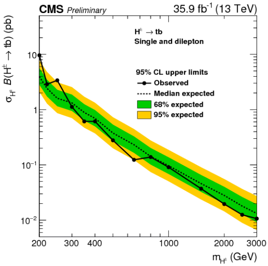
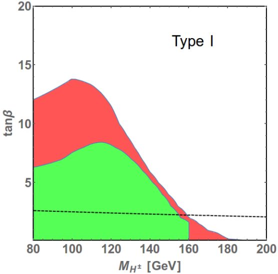
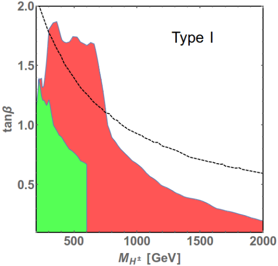


Constraints on charged Higgs parameter space





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- Exclusions:

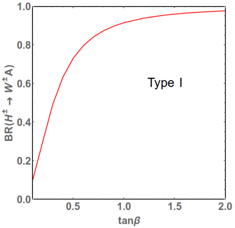
  (A) Green Region $\longrightarrow$ 8 TeV CMS results

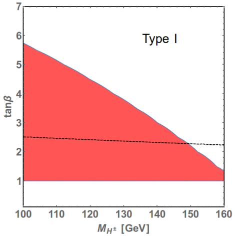
  (B) Red Region $\longrightarrow$ 13 TeV CMS results

  (C) Dashed Line $\longrightarrow$ $\mathcal{BR}(B \to X_s\gamma)$

Charged Higgs exotic decay channel ($H^\pm \to W^\pm A$)

- Minimal mass splitting together with alignment limit restricts the exotic decay channels $H^\pm \to h/H/AW^\pm$.
- But once open, $H^\pm$ can dominantly decay to these channels.
- CMS collaboration put upper bounds on $\mathcal{BR}(t \to H^+ b)$ at 95% CL assuming $\mathcal{BR}(H^+ \to W^+ A) \to 1$ and $\mathcal{BR}(A \to \mu^+\mu^-) \to 3 \times 10^{-4}$.
- Mass difference $m_{H^\pm} - m_A = 85$ GeV with $m_{H^\pm} \in [100 - 160]$ GeV is considered by CMS group.
- T - parameter is satisfied by choosing $m_{H^\pm} \sim m_H$.
- In Type I scenario, $\mathcal{BR}(H^\pm \to W^\pm A) \to 1$ for $\tan\beta \gtrsim 1$ and $\mathcal{BR}(A \to \mu^+\mu^-) \sim 2.6 \times 10^{-4}$ for $m_A \in [15 - 75]$ GeV.





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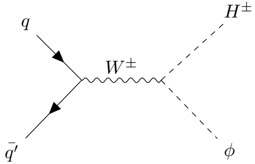
Same sign trilepton search at the LHC in Type I 2HDM

- For large $\tan\beta$ the cross section $pp \to W^{*\pm} \to H^{\pm}\phi$ dominates over the $pp \to H^{\pm}tb$ channel in Type I 2HDM.



- For close to the alignment limit $\phi \neq h_{SM}$.

- Signal:

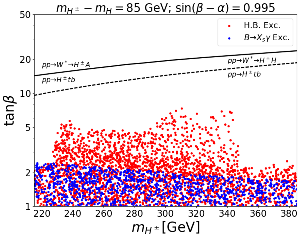
  (A) $pp \to W^{*\pm} \to H^{\pm}H \to (W^{\pm}H)(W^{+}W^{-}) \to (W^{\pm}W^{+}W^{-})(W^{+}W^{-}) \to 3\ell^{\pm}\not{E}_T + X$

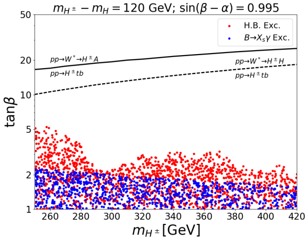
  (B) $pp \to W^{*\pm} \to H^{\pm}A \to (W^{\pm}H)(ZH) \to (W^{\pm}W^{+}W^{-})(ZW^{+}W^{-}) \to 3\ell^{\pm}\not{E}_T + X$

- SM backgrounds: $WZ+$ jets, $Z\ell^{+}\ell^{-}+$ jets and $t\bar{t}W+$ jets.

- Parameter Choice: $m_{H^{\pm}} - m_H = 85$, 120 GeV, $m_H \in [130 - 300]$GeV, $m_{H^{\pm}} \approx m_A$, $\tan\beta \in [1, 50]$, $\sin(\beta - \alpha) = 0.995$ and $m_{12}^2 \in [0, m_H^2 \sin\beta\cos\beta]$.

Current Limits in Type I 2HDM





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- Red Region: Exclusion regions from the LHC $\sqrt{s}$ =7, 8, 13 TeV constraints on neutral Higgses and charged Higgs.

- Channels:

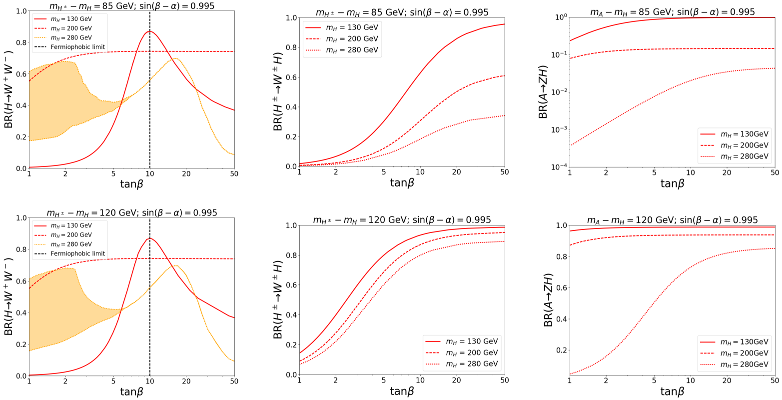
(1) $H/A \to \tau\tau$ (4) $A \to HZ$

(2) $H/A \to \gamma\gamma$ (5) $A \to hZ$

(3) $H \to VV$ $(V = W^\pm, Z)$ (6) $H^\pm \to tb$

- Blue Region: Exclusion region coming from the $\mathcal{BR}(B \to X_s\gamma)$ constraint.

Bosonic decay modes of Higgs bosons



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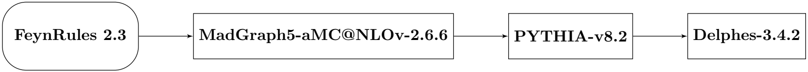
(A) $\mathcal{BR}(H \to W^+W^-)$ $\quad$ $HW^+W^-: \cos(\beta-\alpha) g_{hVV}^{SM}$

(B) $\mathcal{BR}(H^\pm \to W^\pm H)$ $\quad$ $H^\pm H W_\mu^\mp : \pm i \frac{g}{2} \sin(\beta-\alpha)(p_\mu + p'_\mu)$

(C) $\mathcal{BR}(A \to ZH)$ $\quad$ $AHZ: -\frac{g}{2c_w} \sin(\beta-\alpha)(p_\mu + p'_\mu)$

Collider Analysis



- Selection cuts:

  (1) SS3L: Three isolated leading leptons (e, μ) with same sign.

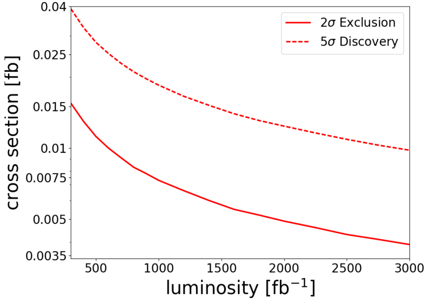
  (2) Momentum p_T cuts: $p_T(\ell_1) > 30$ GeV, $p_T(\ell_2) > 30$ GeV, $p_T(\ell_3) > 20$ respectively and $\not{E}_T > 30$ GeV.

  (3) Lepton and jet separation cuts: Lepton-lepton separation, $\Delta R_{\ell\ell} > 0.4$ and lepton-jet separation cuts, $\Delta R_{\ell j} > 0.4$ where $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$.

  (4) Z-veto: Veto events with additional leptons oppositely charged to the tagged SS3L with same flavor satisfying the condition $80 < m_{\ell^+\ell^-} < 100$ GeV.

  (5) b-veto: Veto events if there are any tagged b-jets.

Background cross sections at $\sqrt{s} = 13$ TeV			
Selection cuts	$WZ+$ jets [fb]	$Z\ell^+\ell^-+$ jets [fb]	$t\bar{t}W+$ jets [fb]
MG5	1360.80	246.550	62.570
SS3L	0.0543	0.00991	0.0878
Lepton p_T & $\not{E}_T$	0.0122	0.00122	0.0118
$\Delta R_{\ell\ell}$ & $\Delta R_{\ell j}$	0.0073	0.00083	0.0103
Z-veto	0.0065	0.00065	0.0103
b-veto	0.0061	0.00061	0.0018



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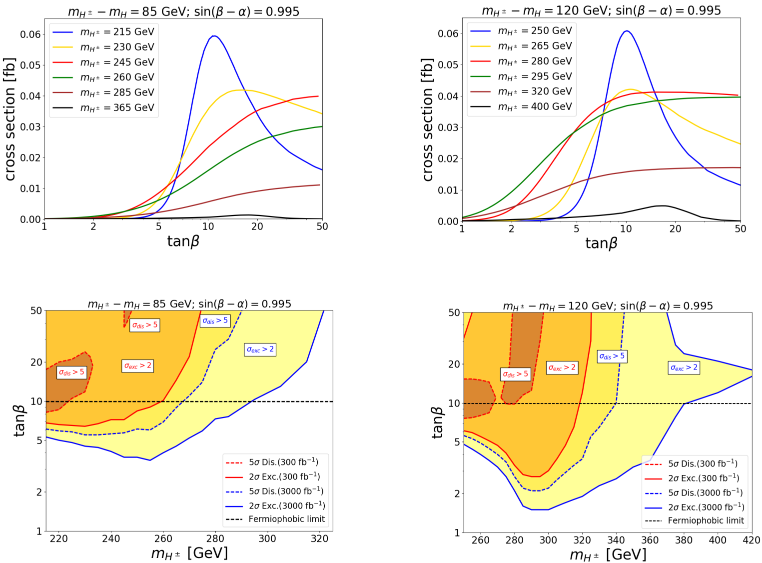
Results



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Conclusions

- Large $\tan\beta$ regions in Type I 2HDM are allowed due to the fermiophobic nature of BSM Higgses.
- Two most conventional decay modes $H^{\pm} \to \tau^{\pm}\nu$ and $H^{+} \to t\bar{b}$ are studied using the CMS 13 TeV results and compared with 8 TeV results.
- CMS collaboration for the first time studied the exotic channel, $H^{\pm} \to W^{\pm}A$, $A \to \mu^{+}\mu^{-}$ to put upper limits on $\mathcal{BR}(t \to H^{\pm}b)$.
- The EW production of charged Higgs dominates over the strong production in Type I scenario for large $\tan\beta$.
- Mass splitting of $H^{\pm}$ and H along with the fermiophobic limit of H in Type I scenario are used to study the same sign trilepton final state at the LHC.
- The exclusion and discovery limits are discussed for 300fb^{-1} and 3000fb^{-1} luminosities at $\sqrt{s} = 13$TeV.

Thank You

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