Prospects of charged Higgs in two Higgs doublet model at the LHC

Prasenjit Sanyal

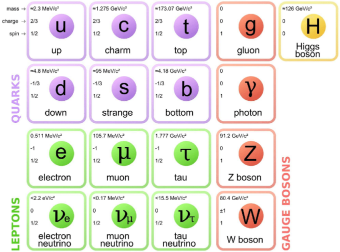
Asia Pacific Center for Theoretical Physics, Korea

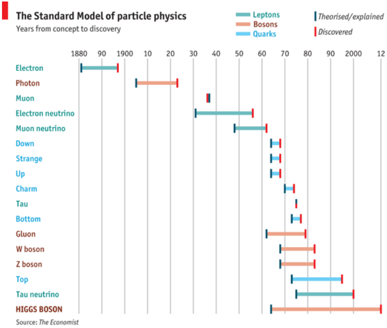
Outline

- Overview of two Higgs doublet model (2HDM).
- CMS results at 8TeV (19.5 fb^{-1}) and 13TeV (35.9 fb^{-1}) for the $\tau\nu$ and tb channels.
- Limits on the charged Higgs parameters ($m_{H^\pm} - \tan\beta$).
- Limits from the exotic decay channel $H^\pm \to AW^\pm$.
- 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.

Overview of two Higgs doublet model (2HDM)

- The Standard Model (SM) is the most successful model in explaining the fundamental particles of the Universe and their interactions.





- SM has theoretical and observational shortcomings.

- 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, $i = 1,\ 2$.

$$
\begin{aligned}
\Phi_i &= \begin{pmatrix} \phi_i^+ \\ \frac{v_i+\rho_i+i\eta_i}{\sqrt{2}} \end{pmatrix} \\
v_i = \langle \rho_i \rangle \quad v &= \sqrt{v_1^2 + v_2^2} = 246 \text{ GeV}
\end{aligned}
$$

- 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.

Model	Φ_1	Φ_2	u_R	d_R	l_R	Q_L, L_L
Type I	$+$	$-$	$-$	$-$	$-$	$+$
TypeII	$+$	$-$	$-$	$+$	$+$	$+$
Type X	$+$	$-$	$-$	$-$	$+$	$+$
Type Y	$+$	$-$	$-$	$+$	$-$	$+$

- Yukawa Lagrangian:

$$\mathcal{L}^{\text{2HDM}}_{\text{Yukawa}} = -\bar{Q}_L Y_u \tilde{\Phi}_u u_R - \bar{Q}_L Y_d \Phi_d d_R - \bar{L} Y_l \Phi_l l_R + h.c.$$

$\Phi_f (f = u, d$ or $l)$ is either Φ_1 or Φ_2 depending on the Types of 2HDM.

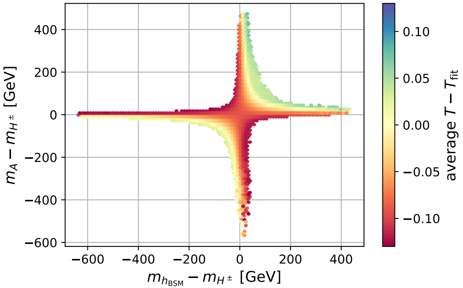
- The Yukawa interactions of $H^\pm$ with quarks and leptons take the form

$$\mathcal{L}^{H^\pm}_{\text{Yukawa}} = -\frac{\sqrt{2}}{v} H^+ \bar{u}[\xi_d V M_d P_R - \xi_u M_u V P_L] d - \frac{\sqrt{2}}{v} H^+ \xi_l \bar{\nu} M_l P_R l + h.c.$$

Model	ξ_d	ξ_u	ξ_l
Type I	$\cot\beta$	$\cot\beta$	$\cot\beta$
TypeII	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
Type X	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type Y	$-\tan\beta$	$\cot\beta$	$\cot\beta$

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

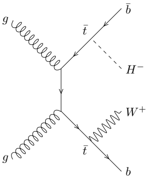
- The EWPO, T - parameter depends strongly on the mass spliting of the charged Higgs and the neutral scalars.

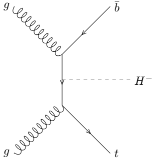


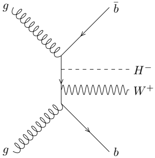
Henning Bahl, Tim Stefaniak, Jonas Wittbrodt, arXiv:2103.07484

- 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 production cross section of charged Higgs depends on its mass with respect to top quark.

  (A) Light Scenario: The double resonant (top diagram) top pair production is the dominant process for light $H^{\pm}$ ($m_{H^{\pm}} \lesssim 160$ GeV).

  (B) Heavy Scenario: The single resonant (middle diagram) top production is the dominant process for $H^{\pm}$ production ($m_{H^{\pm}} \gtrsim 200$ GeV).

  (C) Intermediate Scenario: Both of these channels, top and middle, along with the non-resonant top quark production (bottom diagram) are taken into account ($m_{H^{\pm}} \sim m_t$).

- $\sigma^{H^{\pm}}_{\text{Type I}} = \sigma^{H^{\pm}}_{\text{Type X}}$ and $\sigma^{H^{\pm}}_{\text{Type II}} = \sigma^{H^{\pm}}_{\text{Type Y}}$.

Conventional decay channels:

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

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

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

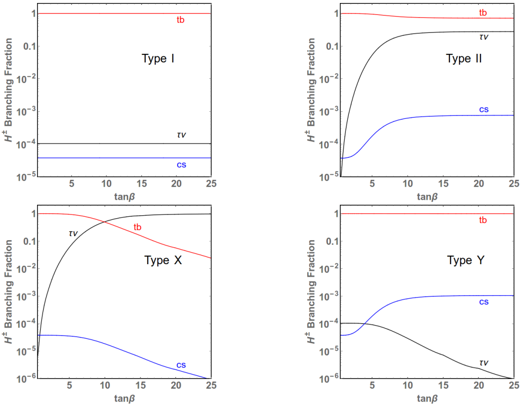
(D) $H^+ \to c\bar{b}$

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

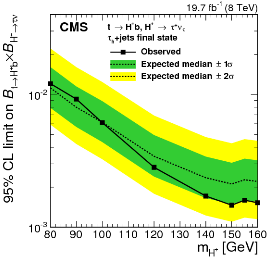


$H^\pm$ branching ratio for $m_{H^\pm} = 250$ GeV with $m_{H^\pm} = m_H = m_A$.

P.Sanyal, Eur.Phys.J.C 79 (2019) 11, 913

Constraints on charged Higgs parameter space ($\tau\nu$ channel)

JHEP11(2015) 018,[1508.07774]



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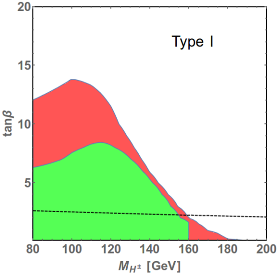
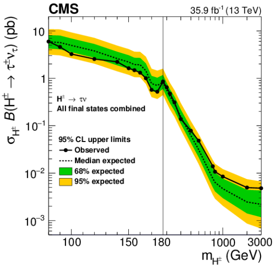


JHEP 07 (2019) 142,[1903.04560]



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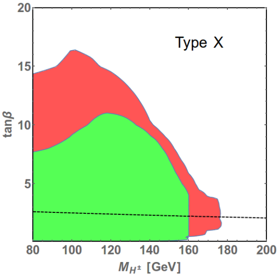
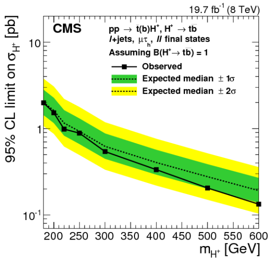


Constraints on charged Higgs parameter space (*tb* channel)

JHEP11(2015) 018,[1508.07774]



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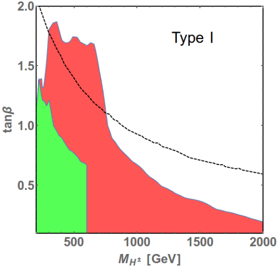
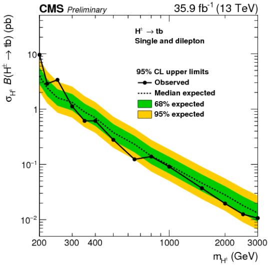


CMS PAS HIG-18-004



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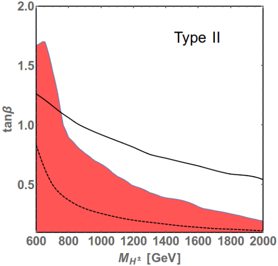
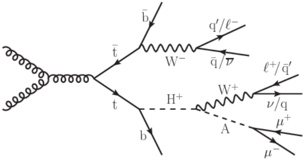
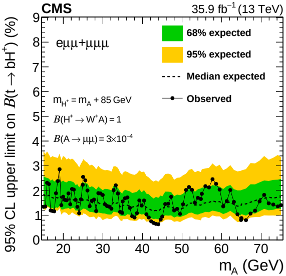


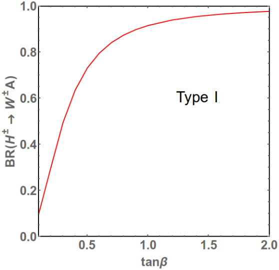
Charged Higgs exotic decay channel ($H^{\pm} \to W^{\pm}A$)

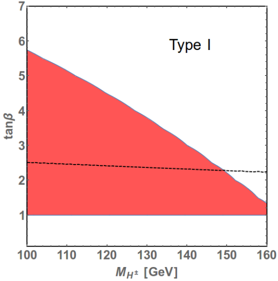
- Minimal mass splitting together with alignment limit restricts the exotic decay channels $H^{\pm} \to h/H/AW^{\pm}$.
- But once open, $H^{\pm}$ can dominantly decay to these channels.
- CMS collaboration put upper bounds on $\mathcal{BR}(t \to H^{+}b)$ at 95% CL assuming $\mathcal{BR}(H^{+} \to W^{+}A) \to 1$ 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 $m_{H^{\pm}} \sim m_{H}$.



Phys. Rev. Lett. 123, 131802 (2019)







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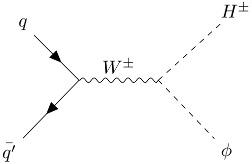
- In Type I scenario, $\mathcal{BR}(H^\pm \to W^\pm A) \to 1$ is obtained for $\tan\beta \gtrsim 1$ and $\mathcal{BR}(A \to \mu^+\mu^-) \sim 2.6 \times 10^{-4}$ for $m_A \in [15 - 75]$ GeV.
- Red region shows the excluded parameter space in Type I scenario.
- Unlike Type I where all the fermionic couplings of A is proportional to $\cot\beta$, in Type X the coupling of A to the leptons is proportional to $\tan\beta$ whereas its coupling to the quarks is proportional to $\cot\beta$. Thus the $\mathcal{BR}(A \to \mu^+\mu^-)$ increases with $\tan\beta$.
- In Type X, $\mathcal{BR}(A \to \mu^+\mu^-) \to 3 \times 10^{-4}$ for $\tan\beta \approx 1$ and $\mathcal{BR}(t \to H^+ b)$ is above the CMS upper bound.

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:

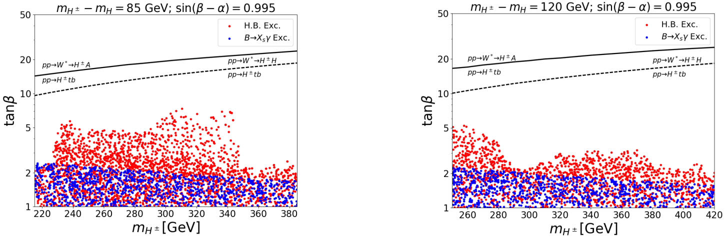
  (A) $pp \to W^{*\pm} \to H^{\pm}H \to (W^{\pm}H)(W^{+}W^{-}) \to (W^{\pm}W^{+}W^{-})(W^{+}W^{-}) \to 3\ell^{\pm}\not{E}_T + X$

  (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



T. Mondal and P. Sanyal, arXiv:2109.05682

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

- Channels:

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

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

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

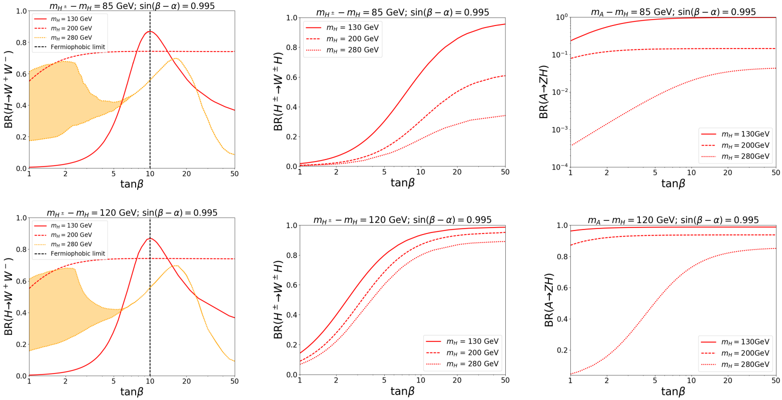
(4) $A \to HZ$

(5) $A \to hZ$

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

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

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

Collider Analysis

FeynRules 2.3 $\rightarrow$ **MadGraph5-aMC@NLOv-2.6.6** $\rightarrow$ **PYTHIA-v8.2** $\rightarrow$ **Delphes-3.4.2**

- <u>Selection cuts</u>:

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

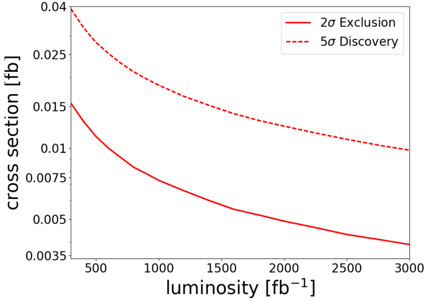
  (2) Momentum p_T cuts: $p_T(\ell_1) > 30$ GeV, $p_T(\ell_2) > 30$ GeV, $p_T(\ell_3) > 20$ respectively and $\not{E}_T > 30$ GeV.

  (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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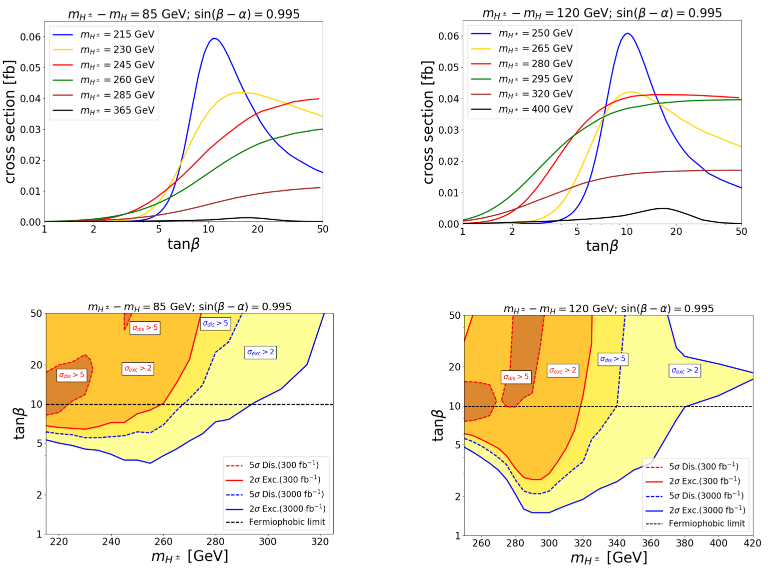
Results



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Conclusions

- 2HDM is the simplest model containing charged Higgs.
- 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 $\mathcal{BR}(t \to H^{\pm}b)$. These results exclude significant parameter space not excluded by $\tau\nu$ channel.
- 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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