Limits on the Charged Higgs Parameters in the Two Higgs Doublet Model using CMS $\sqrt{s} = 13$ TeV Results

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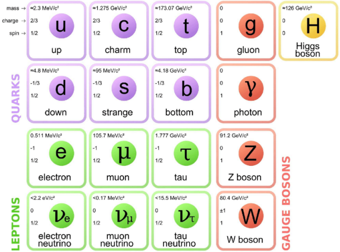
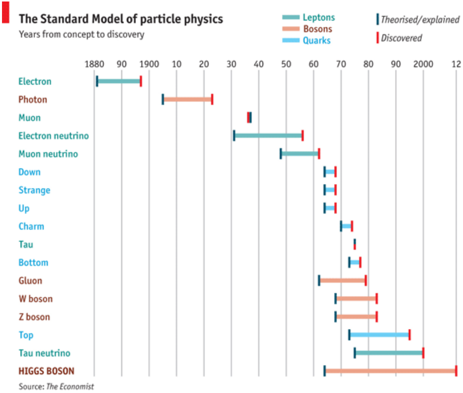
- The Standard Model (SM) is the most successful model in explaining the fundamental particles of the Universe and their interactions.



Particle Content of SM



Timeline of Discovery

Overview of Two Higgs Doublet Model (2HDM)

- Scalar Potential:

$$\begin{aligned}\mathcal{V}(\Phi_1,\Phi_2) &= m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - [m_{12}^2\Phi_1^\dagger\Phi_2 + h.c.] + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 \\ &+ \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ &+ [\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + h.c.]\end{aligned}$$

where

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

$\langle\Phi_1\rangle = v_1$, $\langle\Phi_2\rangle = v_2$, $\tan\beta = v_2/v_1$ and $v = \sqrt{v_1^2+v_2^2} \sim 246$ GeV.

- The physical mass eigenstates are given by

$$\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = R(\beta)\begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix}, \begin{pmatrix} G \\ A \end{pmatrix} = R(\beta)\begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix}, \begin{pmatrix} H \\ h \end{pmatrix} = R(\alpha)\begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix}$$

where

$$R(\theta) = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

- Yukawa Sector:

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

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

where $\Phi_f (f = u, d \text{ or } l)$ is either Φ_1 or Φ_2 depending on the Yukawa models of 2HDM.

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

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

Overview of Two Higgs Doublet Model (2HDM)

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	$-\tan\beta$	$\cot\beta$	$\cot\beta$

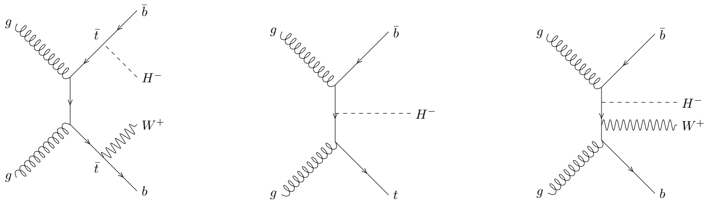
- Choice of parameter space:

$$\{m_{11}^2, m_{22}^2, m_{12}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5\}$$
$$\downarrow$$
$$\{M_h^2, M_H^2, M_A^2, M_{H^\pm}^2, m_{12}^2, v, \tan\beta, \sin(\beta-\alpha)\}$$

- Alignment limit: $\sin(\beta-\alpha) \to 1$ which implies h behaves as SM-Higgs boson (most favoured).

$H^{\pm}$ Production Modes

- The production cross section of charged Higgs depends on its mass with respect to top quark. Also $\sigma^{H^{\pm}}_{\text{Type I}} = \sigma^{H^{\pm}}_{\text{Type X}}$, $\sigma^{H^{\pm}}_{\text{Type II}} = \sigma^{H^{\pm}}_{\text{Type Y}}$ and $\sigma_{H^{\pm}} = \sigma_{H^{+}} + \sigma_{H^{-}}$.
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGMSSMCharged



- Light Scenario: The double resonant (left diagram) top pair production is the dominant process for light $H^{\pm}$ ($M_{H^{\pm}} \lesssim 150$ GeV).
- Heavy Scenario: The single resonant (middle diagram) top production is the dominant process for $H^{\pm}$ production ($M_{H^{\pm}} \gtrsim 200$ GeV).
- Intermediate Scenario: Both of these channels, left and middle, along with the non-resonant top quark production (right diagram) are taken into account ($M_{H^{\pm}} \sim M_t$).

- $H^{\pm}$ decay to fermion-antifermion:

$$\begin{array}{lcll} H^{+} & \longrightarrow & c\bar{s} & \text{depends on types} \\ H^{+} & \longrightarrow & c\bar{b} & \text{of Yukawa interaction} \\ H^{+} & \longrightarrow & t\bar{b} & \text{and CKM matrix element} \\ H^{+} & \longrightarrow & \tau^{+}\nu & \end{array}$$

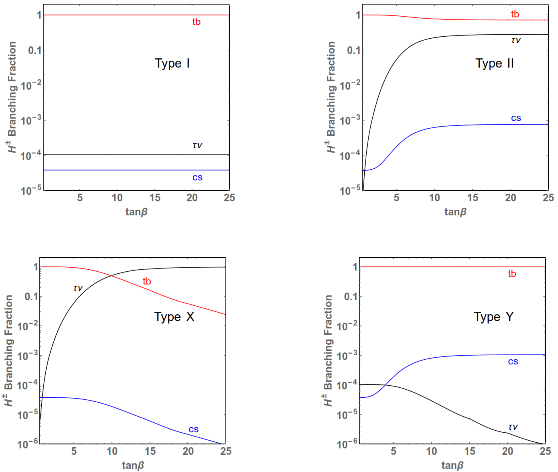
- $H^{\pm}$ decay to gauge bosons:

$$\begin{array}{lcll} H^{+} & \longrightarrow & W^{+}\gamma & \text{loop} \\ H^{+} & \longrightarrow & W^{+}Z & \text{suppressed} \end{array}$$

- $H^{\pm}$ decay to neutral bosons:

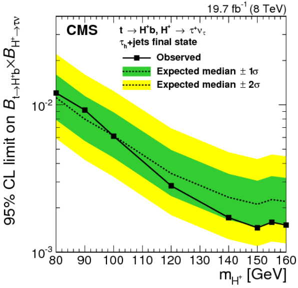
$$\begin{array}{lcl} H^{+} & \longrightarrow & hW^{+} : \frac{\mp ig}{2}\cos(\beta-\alpha)(p_{\mu}-p_{\mu}^{\mp}) \\ H^{+} & \longrightarrow & HW^{+} : \frac{\mp ig}{2}\sin(\beta-\alpha)(p_{\mu}-p_{\mu}^{\mp}) \\ H^{+} & \longrightarrow & AW^{+} : \frac{g}{2}(p_{\mu}-p_{\mu}^{\mp}) \end{array}$$

$H^{\pm}$ Decay Modes

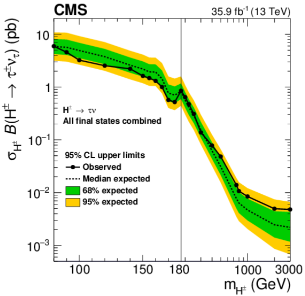


- $H^{\pm}$ branching ratio for $M_{H^{\pm}} = 250$ GeV. Alignment limit ie. $\sin(\beta - \alpha) = 1$ and minimal mass splitting of $M_{H^{\pm}}$, M_H and M_A are considered. P. Sanyal, Eur.Phys.J. C79 (2019) no.11, 913

CMS 8TeV and 13 TeV results ($\tau\nu$ channel)

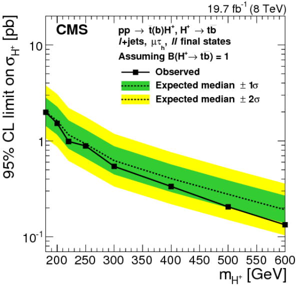


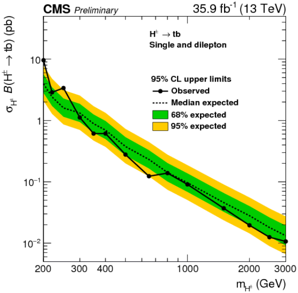
Expected and observed 95% CL model independent upper limits on $\mathcal{BR}(t \to H^+ b)\mathcal{BR}(H^+ \to \tau^+ \nu)$ for $\sqrt{s} = 8$ TeV at a luminosity of 19.5 fb^{-1} in the $\tau_h +$ jets final states.JHEP 11(2015) 018,[1508.07774]



Expected and observed 95% CL model independent upper limits on $\sigma_{H^\pm} \mathcal{BR}(H^\pm \to \tau^\pm \nu)$ for $\sqrt{s} = 13$ TeV at a luminosity of 35.9 fb^{-1} with all final states combined. arxiv:1903.04560

CMS 8TeV and 13 TeV results ($t\bar{b}$ channel)





Expected and observed 95% CL model independent upper limits on $\sigma_{H\pm}$ assuming $\mathcal{BR}(H^+ \rightarrow t\bar{b}) = 1$ for $\sqrt{s} = 8$ TeV at a luminosity of 19.5 fb^{-1} for the combination of $\mu\tau_h$, l+jets and ll' final states.
JHEP 11(2015) 018,[1508.07774]

Expected and observed 95% CL model independent upper limits on $\sigma_{H\pm}\,\mathcal{BR}(H^+ \rightarrow t\bar{b})$ for $\sqrt{s} = 13$ TeV at a luminosity of 35.9 fb^{-1} for the combination of l+jets and ll' final states.
Available on the CERN CDS information server CMS PAS HIG-18-004

Flavour Physics Constraints

- B meson decays put strong constraints on $(M_{H^\pm} - \tan\beta)$ space.

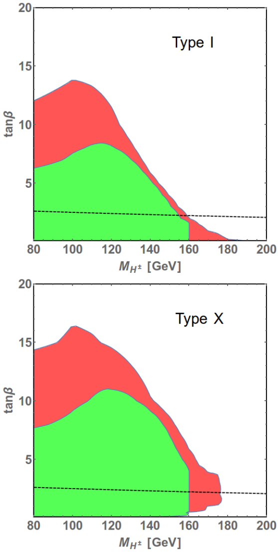
Observable	Experiment	SM prediction
$\mathrm{BR}(B \to X_s\gamma)$	$(3.32 \pm 0.15) \times 10^{-4}$	$(3.34 \pm 0.22) \times 10^{-4}$
$\mathrm{BR}(B_s \to \mu^+\mu^-)$	$(3.0 \pm 0.6 \pm 0.25) \times 10^{-9}$	$(3.54 \pm 0.27) \times 10^{-9}$

Weak radiative decays of the B meson and bounds on $M_{H^\pm}$ in the Two-Higgs-DoubletModel,Eur. Phys. J.C77 (2017) 201,[1702.04571]

- $B \to X_s\gamma$ rules out Type II and Type Y 2HDMs for $M_{H^\pm} \lesssim 580$ GeV independently of $\tan\beta$.

- For $M_{H^\pm} \gtrsim 600$ GeV, in Type II and Type Y, $\mathcal{BR}(B_s \to \mu^+\mu^-)$ puts stronger constraint than $\mathcal{BR}(B \to X_s\gamma)$.

Constraints on 2HDM Parameter Space ($\tau\nu$ channel)



- For $M_{H^\pm} \in (80 - 160)$GeV, the most important constraint comes from $H^\pm \to \tau^\pm \nu$ channel.
- Exclusion regions are shown in Type I and Type X 2HDMs.

Green Region	$\longrightarrow$	8TeV CMS results
Red Region	$\longrightarrow$	13TeV CMS results
Bellow Dashed line	$\longrightarrow$	$\mathcal{BR}(B \to X_s\gamma)$

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Constraints on 2HDM Parameter Space ($t\bar{b}$ channel)

- For $M_{H^\pm} \gtrsim M_t$, the most important constraint comes from the $H^+ \to t\bar{b}$ channel.
- Exclusion regions are shown in Type I and Type II 2HDMs.

Green Region	$\longrightarrow$	8TeV CMS results
Red Region	$\longrightarrow$	13TeV CMS results
Bellow Dashed line	$\longrightarrow$	$\mathcal{BR}(B \to X_s\gamma)$
Bellow Continuous line	$\longrightarrow$	$\mathcal{BR}(B_s \to \mu^+\mu^-)$

- The Type X result is equivalent to Type I and Type Y result is equivalent to Type II.

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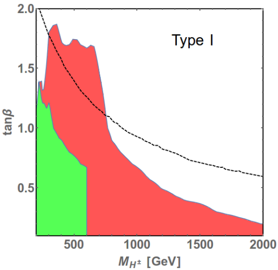
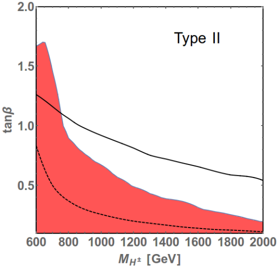
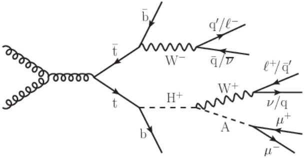
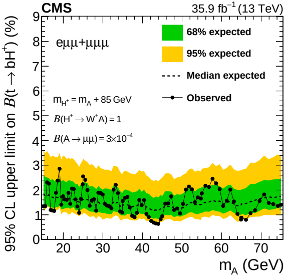




Charged Higgs Exotic Decay $H^{\pm} \to W^{\pm} A$

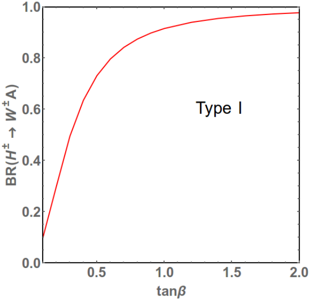
- The minimal mass splitting of $H^{\pm}$, H and A is prefered to satisfy the Electro Weak Precision Observables (EWPOs) S, T and U (specially T).
- Minimal mass splitting together with alignment limit restricts the exotic decay channels $H^{\pm} \to h/H/AW^{\pm}$.
- But once open, $H^{\pm}$ can dominantly 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.
- EWPOs can still be satisfied in this mass range by proper choice of m_{12}^2 and $M_H \sim M_{H^{\pm}}$.

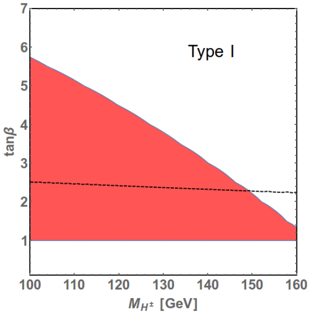




arxiv: 1905.07453

Charged Higgs Exotic Decay $H^\pm \to W^\pm A$





- In Type I scenario $\mathcal{BR}(H^\pm \to W^\pm A) \to 1$ is obtained for $\tan\beta \gtrsim 1$.
  Also $\mathcal{BR}(A \to \mu^+\mu^-) \sim 2.4 \times 10^{-4}$ for $M_A \in (15 - 75)$ GeV.
- Red region shows the excluded parameter space in Type I scenario.
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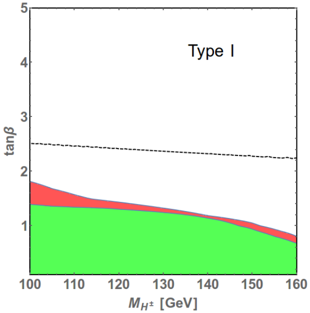
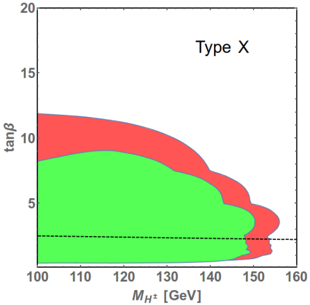
- Unlike Type I where all the fermionic couplings of A is proportional to $\cot\beta$, in Type X the coupling of A to the leptons is proportional to $\tan\beta$ whereas its coupling to the quarks is proportional to $\cot\beta$. Thus the BR($A \to \mu^+\mu^-$) increases with $\tan\beta$.
- In Type X $\mathcal{BR}(A \to \mu^+\mu^-) \to 3 \times 10^{-4}$ for $\tan\beta \approx 1$ and BR($t \to H^+ b$) is above the CMS upper bound.
- Type II and Y are not considered as in this mass range they are ruled out by $B \to X_s\gamma$ constraint.





- Under the same CMS assumption of mass difference between $H^{\pm}$ and A,
  ie. $(M_{H^{\pm}} - M_A) = 85$ GeV.
  The constraint from $\tau\nu$ channel will be less restrictive.
- Exclusion regions are shown in Type I and Type X 2HDMs.

Green Region $\longrightarrow$ 8TeV CMS results
Red Region $\longrightarrow$ 13TeV CMS results
Bellow Dashed line $\longrightarrow$ $\mathcal{BR}(B \to X_s\gamma)$

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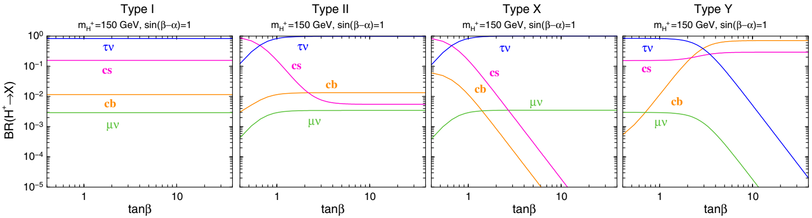
Conclusions

- 2HDM is the simplest model containing charged Higgs.
- Two most dominant decay modes $H^{\pm} \to \tau^{\pm}\nu$ and $H^{+} \to t\bar{b}$ are studied using recent 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.
- Exclusion bounds from B meson decays are also compared for completeness.
- Comment: Latest results from collider experiments are excluding a large parameter space of 2HDMs, specially for charged Higgs mass lighter than top quark.

Thank You



Branching ratios of $H^{\pm}$ in four different models of 2HDM as a function of $\tan\beta$ for $M_{H^{\pm}} = 150$GeV.

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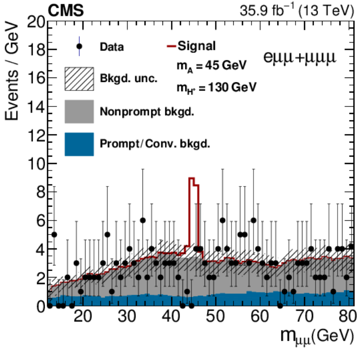
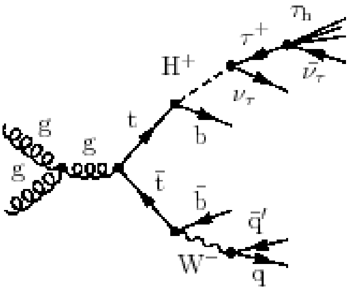


Invariant mass distribution of muon pair $m_{\mu\mu}$ produced from pseudoscalar decay A.



Feynman diagram for $\tau\nu$ signal