Exotic decays of a charged Higgs boson through loop

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In collaboration with Jeonghyeon Song

Charged Higgs Day at KU, 2018.9.1

Charged Higgs

- For the SM, charged Goldstone boson is eaten by W boson.
- Many BSM which contains additional scalar sector show Charged Higgs.
- Popular models 2HDM, MSSM predict charged Higgs. They well fit the low energy SM constraints.

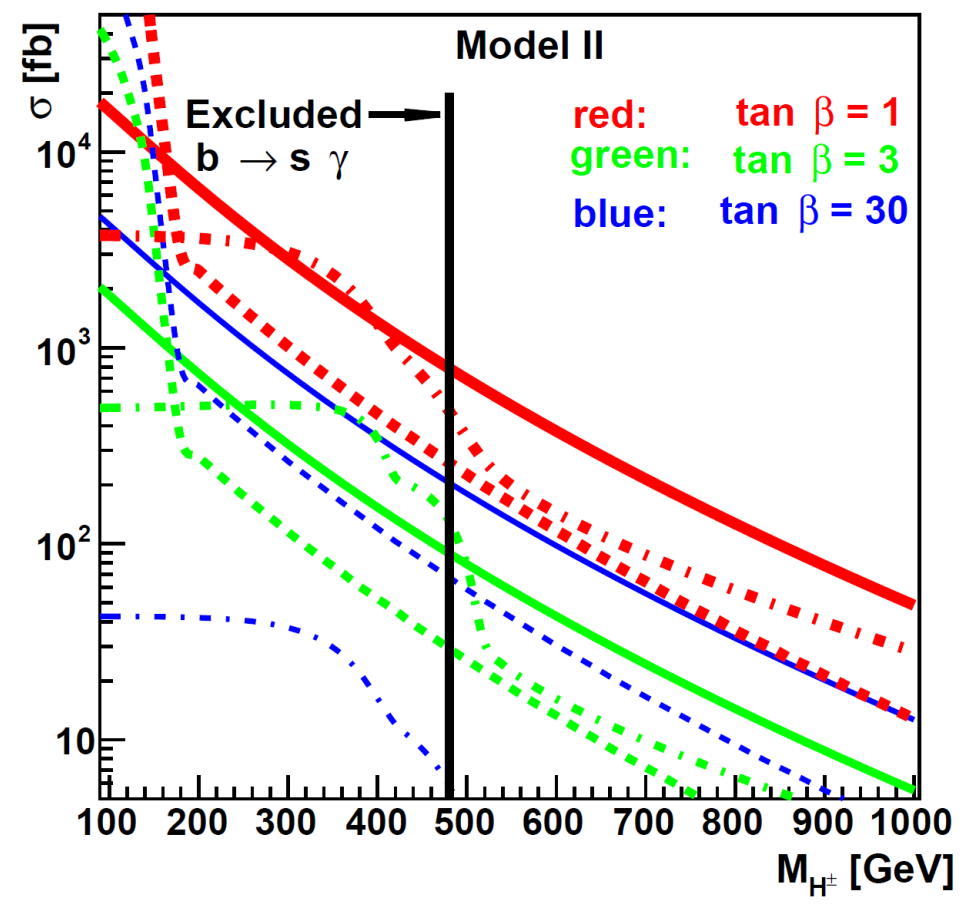
Charged Higgs in 2HDM

- 2HDM needs additional discrete (Z2) symmetry in order to avoid FCNC problem.

	Charged Higgs Yukawa Coupling	
	Left	Right
Type 1	$1/t_\beta$	$-1/t_\beta$
Type 2	$1/t_\beta$	t_β
Type X	$1/t_\beta$	$-1/t_\beta$
Type Y	$1/t_\beta$	t_β

Charged Higgs Production

Akeroyd,et.al. 1607.01320



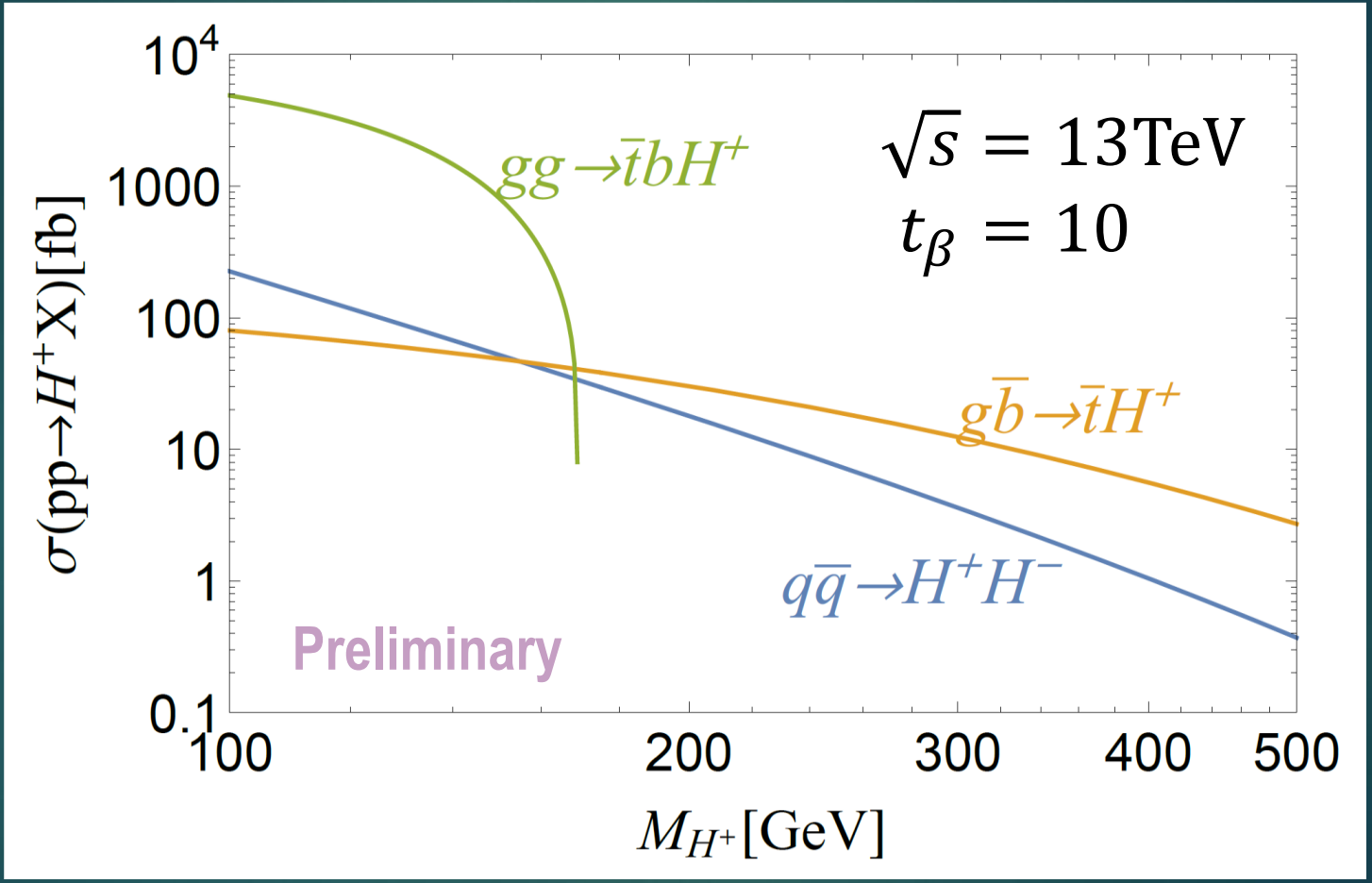
Solid: $g\bar{b} \to H^+\bar{t},$

Dotted: $gg \to H^+b\bar{t},$

Dot-dashed:

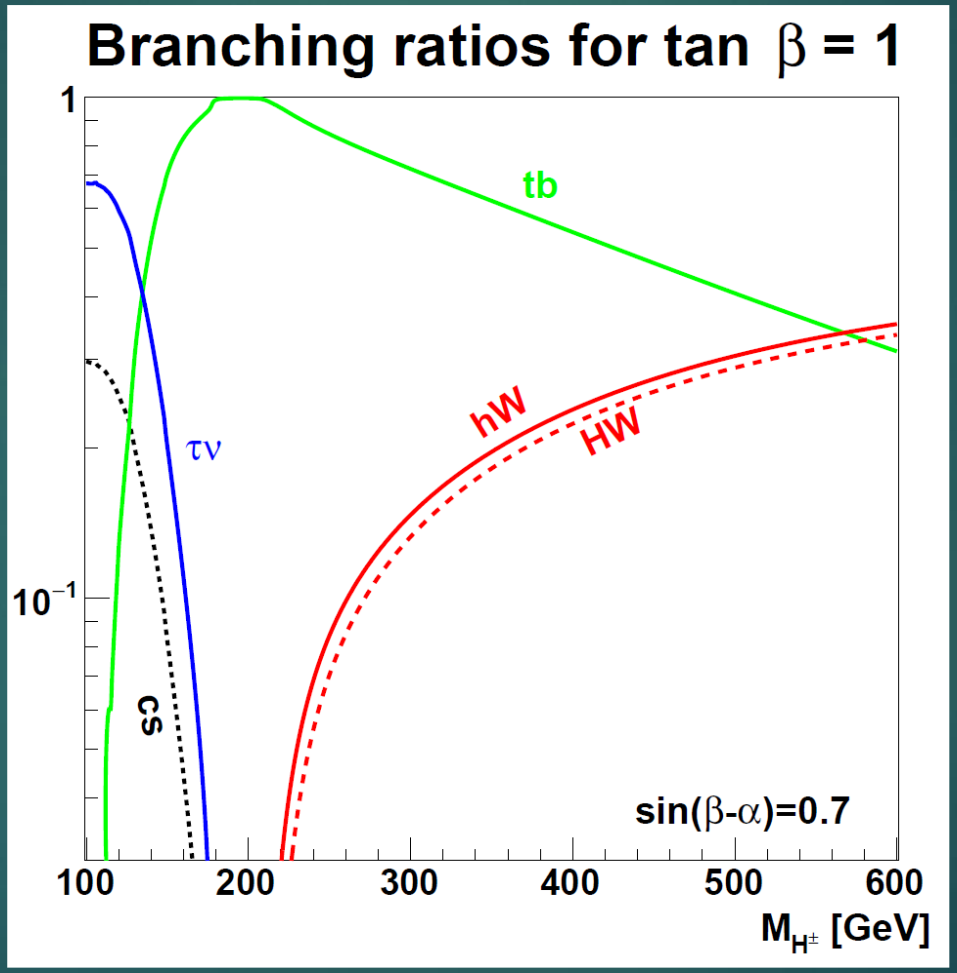
$gg \to H_j \to H^+W^-$

Charged Higgs Production



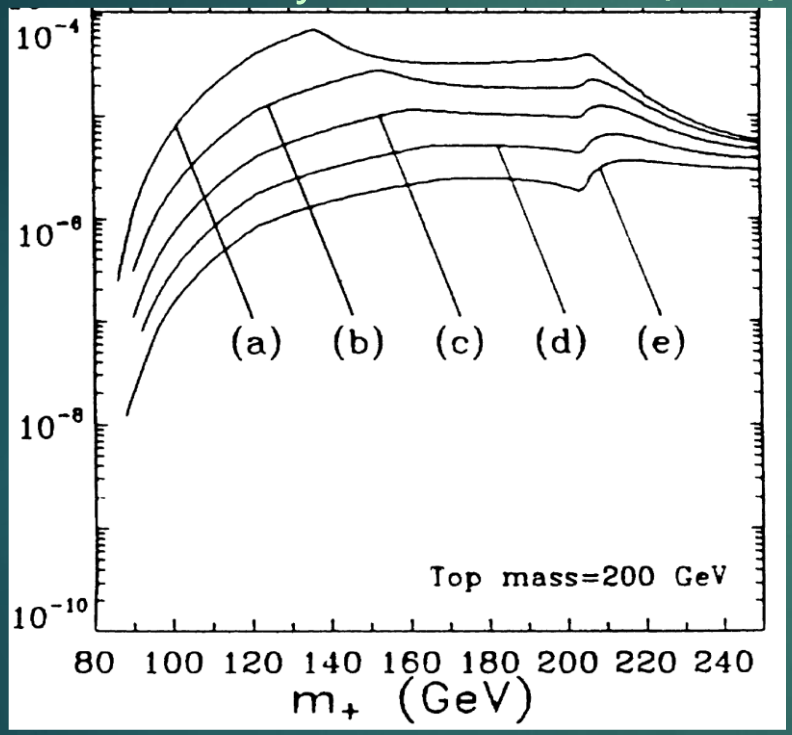
Charged Higgs Decays

Akeroyd,et.al. 1607.01320

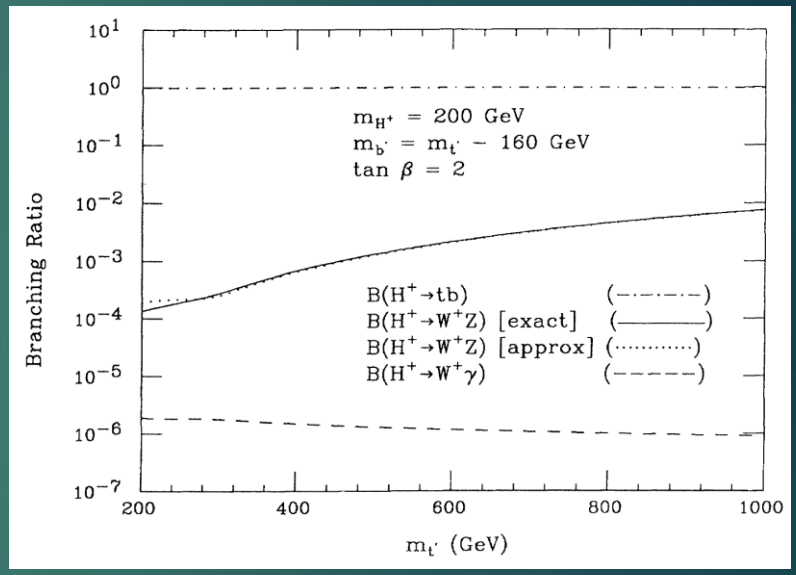


Loop Induced Charged Higgs Decays in 2HDM

Raychaudhuri, PRD(1994)



Peyranere,Haber,Irulegui, PRD(1991)



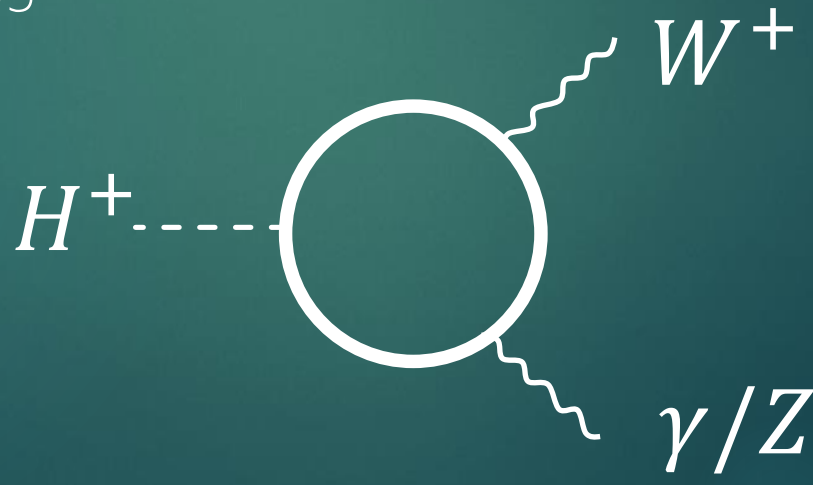
$$\mathrm{Br}(H^+ \to W\gamma) \sim 10^{-5}$$

The Model we are studying is

2HDM+VLF

Vectorlike Fermion(VLF) is motivated by

- String Theory
- Top-quark seesaw model
- Warped extra dimension
- Composite Higgs
- Little Higgs
- SUSY



The Model details

Yukawa couplings are as follows

$$\text{VLQ doublet}: \quad Q_L = \begin{pmatrix} U_L \\ D_L \end{pmatrix}, \; Q_R = \begin{pmatrix} U_R \\ D_R \end{pmatrix}$$

$$\text{VLQ singlets}: \quad \begin{matrix} u_R & u_L \\ d_R & d_L \end{matrix} .$$

Yukawa couplings are as follows

$$\begin{aligned} \mathcal{L}_{\text{Yuk}} = & -M_Q \overline{Q} Q - M_U \overline{u} u - M_D \overline{d} d \\ & - \Big[\overline{Q}_R (Y^L_{D_1} H_1 + Y^L_{D_2} H_2) d_L + \overline{Q}_L (Y^R_{D_1} H_1 + Y^R_{D_2} H_2) d_R \\ & + \overline{Q}_R (Y^L_{U_1} \widetilde{H}_1 + Y^L_{U_2} \widetilde{H}_2) u_L + \overline{Q}_L (Y^R_{U_1} \widetilde{H}_1 + Y^R_{U_2} \widetilde{H}_2) u_R + \text{h.c.} \Big] . \end{aligned}$$

Free parameters: M_Q, M_U, M_D, Y_U, Y_D

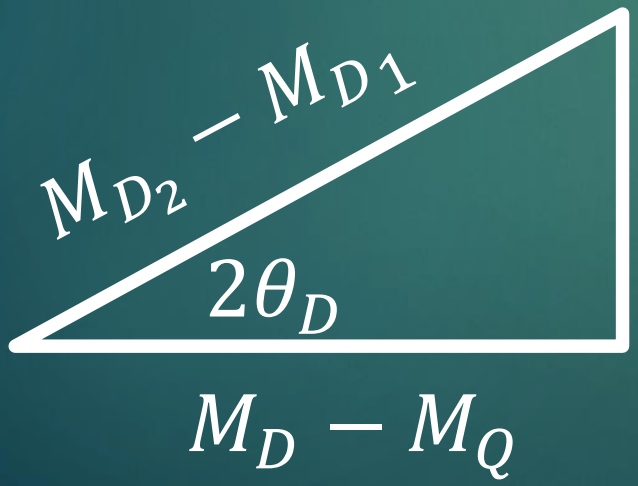
The Model details

Mass Matrix for Down-type:

$$\mathbb{M}_D = \begin{pmatrix} M_Q & \frac{1}{\sqrt{2}} Y_D v_1 \\ \frac{1}{\sqrt{2}} Y_D v_1 & M_D \end{pmatrix}$$

After mass diagonalization

$$V_D = \begin{pmatrix} \cos\theta_D & -\sin\theta_D \\ \sin\theta_D & \cos\theta_D \end{pmatrix}, \quad V_D \mathbb{M}_D V_D^\dagger = \begin{pmatrix} M_{D,1} & 0 \\ 0 & M_{D,2} \end{pmatrix}$$



$$\sin 2\theta_D = \frac{\sqrt{2} Y_D v_1}{M_{D,2} - M_{D,1}}$$

The Model details

$$\mathcal{L}_{\text{Yuk}} =$$

$$-\sum_{ij=1,2}\left[y_{hD_iD_j}h\overline{D}_iD_j + y_{hU_iU_j}h\overline{U}_iU_j + y_{HD_iD_j}H\overline{D}_iD_j + y_{HU_iU_j}H\overline{U}_iU_j\right]$$

$$-\sum_{ij=1,2}\left[y^L_{H^+D_iU_j}H^+\overline{U}_{i,R}D_{j,L} + y^R_{H^+D_iU_j}H^+\overline{U}_{i,L}D_{j,R} + \text{h.c.}\right].$$

$$\mathcal{L}_{\text{Gauge}} = +\frac{g}{\sqrt{2}}\left[g_{WD_iU_j}W^-_\mu\bar{D}_i\gamma^\mu U_j + \text{h.c.}\right]$$

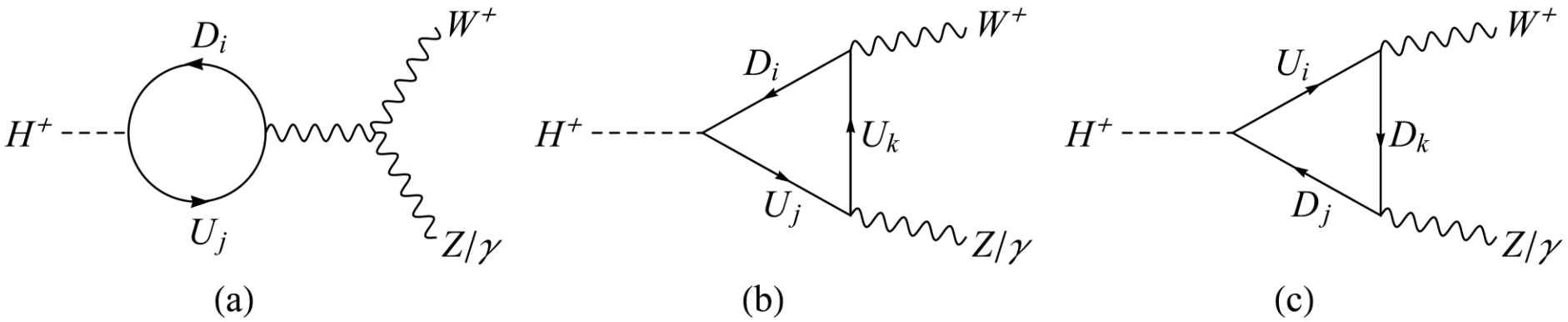
Both Diagonal couplings and Non-diagonal couplings arise

$$
\begin{aligned}
y_{hD_1D_1} &= -Y_D \xi_h^D s_{2D}/\sqrt{2}\,, & y_{hU_1U_1} &= -Y_U \xi_h^U s_{2U}/\sqrt{2}\,,\\
y_{hD_1D_2} &= Y_D \xi_h^D c_{2D}/\sqrt{2}\,, & y_{hU_1U_2} &= Y_U \xi_h^U c_{2U}/\sqrt{2}\,,\\
y_{hD_2D_1} &= Y_D \xi_h^D c_{2D}/\sqrt{2}\,, & y_{hU_2U_1} &= Y_U \xi_h^U c_{2U}/\sqrt{2}\,,\\
y_{hD_2D_2} &= Y_D \xi_h^D s_{2D}/\sqrt{2}\,, & y_{hU_2U_2} &= Y_U \xi_h^U s_{2U}/\sqrt{2}\,.
\end{aligned}
$$

$$
\begin{aligned}
y^L_{H^+D_1U_1} &= y^R_{H^+D_1U_1} = Y_U \xi_A^U c_D s_U + Y_D \xi_A^D s_D c_U\,,\\
y^L_{H^+D_1U_2} &= y^R_{H^+D_1U_2} = -Y_U \xi_A^U c_D c_U + Y_D \xi_A^D s_D s_U\,,\\
y^L_{H^+D_2U_1} &= y^R_{H^+D_2U_1} = Y_U \xi_A^U s_D s_U - Y_D \xi_A^D c_D c_U\,,\\
y^L_{H^+D_2U_2} &= y^R_{H^+D_2U_2} = -Y_U \xi_A^U s_D c_U - Y_D \xi_A^D c_D s_U\,.
\end{aligned}
$$

	ξ_h^D	ξ_h^U	ξ_H^D	ξ_H^U	ξ_A^D	ξ_A^U
Type I	c_α	c_α	s_α	s_α	$-c_\beta$	c_β
Type II	$-s_\alpha$	c_α	c_α	s_α	s_β	c_β

Loop induced Decays



No tree level processes.

UV div. are canceled in a non-trivial manner.

We use LoopTools notation for loop functions

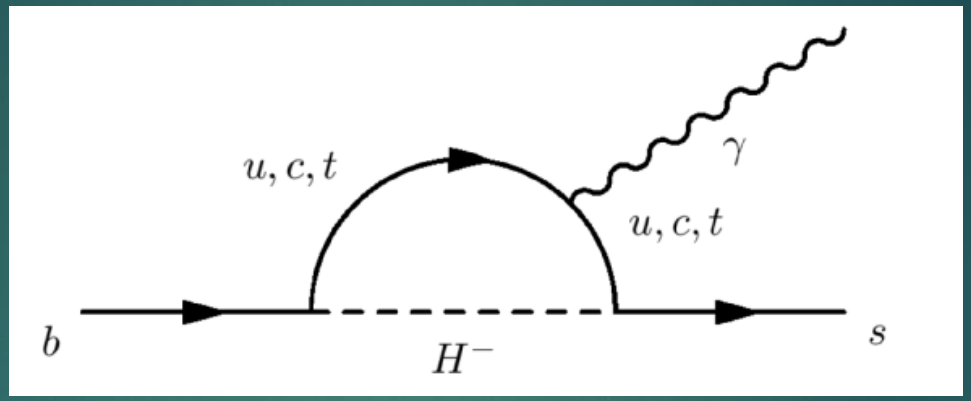
Loop induced Decays

$$\Gamma(H^+ \to W^+\gamma) = \frac{M_{H^+}}{32\pi}\left(1 - \frac{m_W^2}{M_{H^+}^2}\right)^3 \left[\,|\mathcal{M}_2|^2 + |\mathcal{M}_3|^2\,\right].$$

$$\Gamma(H^+ \to W^+Z) = \frac{\beta M_{H^+}}{32\pi}\left[\left(6 + \frac{\beta^2 M_{H^+}^4}{2m_W^2 m_Z^2}\right)|\mathcal{M}_1|^2 + \frac{\beta^4 M_{H^-}^4}{8m_W^2 m_Z^2}|\mathcal{M}_2|^2 + \beta^2|\mathcal{M}_3|^2 + \frac{\beta^2}{2}\left(\frac{M_{H^+}^4}{m_W^2 m_Z^2} - \frac{M_{H^+}^2}{m_W^2} - \frac{M_{H^+}^2}{m_Z^2}\right)\mathrm{Re}(\mathcal{M}_1\mathcal{M}_2^*)\right],$$

Longitudinal Enhancement terms arise for WZ decay YWY, Kingman, Kang, Song 1705.05486

Constraints from $b \to s\gamma$



Charged Higgs Yukawa Coupling

	Left	Right	
Type 1	$1/t_\beta$	$-1/t_\beta$	→ Contribution suppressed by t_β^2
Type 2	$1/t_\beta$	t_β	→ Contribution regardless of t_β

Constraints from $b \to s\gamma$

Misiak, Steinhauser EPJC(2017)

Including full dataset of Belle (Belle Collaboration) 1608.02344

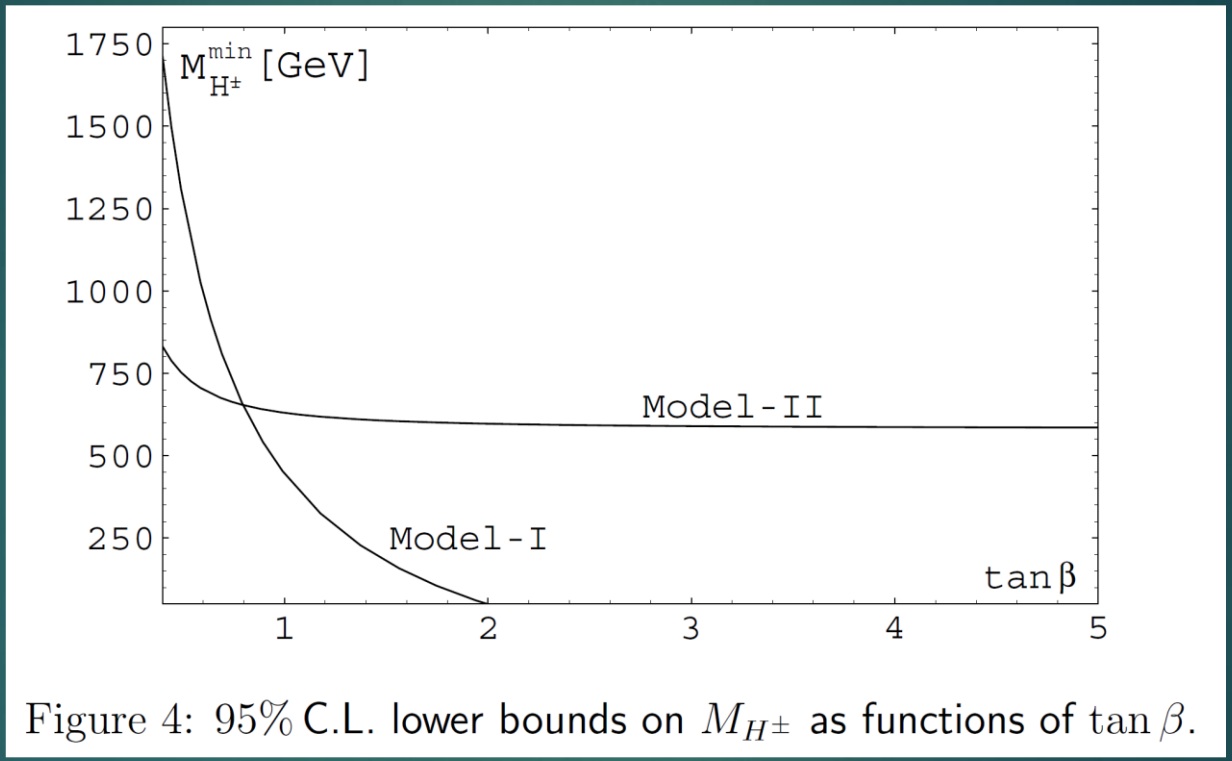
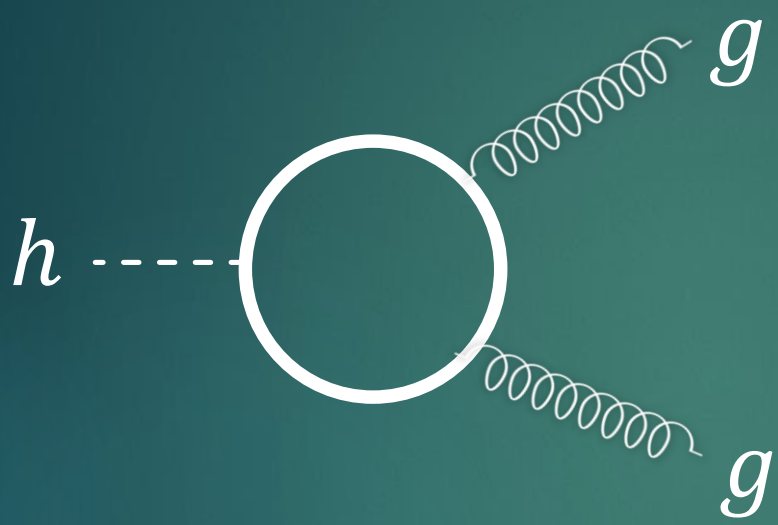


Figure 4: 95% C.L. lower bounds on $M_{H^\pm}$ as functions of $\tan\beta$.

$M_{H^+} > 570$ GeV for Type 2

Constraints from Higgs precision



$$0.6 < \kappa_g < 0.12$$

ATLAS+CMS 1606.02266

$$y_{hD_1D_1} = -Y_D \xi_h^D s_{2D}/\sqrt{2}\,,$$
$$y_{hD_2D_2} = Y_D \xi_h^D s_{2D}/\sqrt{2}\,.$$

→ Significant Cancellation

Constraints from EW precision

Oblique parameters

S, T, U

$$S \approx \frac{1}{6\pi} ,$$

$$T \approx \frac{1}{12\pi s^2 c^2} \left[\frac{(\Delta m)^2}{m_Z^2} \right] ,$$

$$U \approx \frac{2}{15\pi} \left[\frac{(\Delta m)^2}{m_N^2} \right] .$$

Peskin, Takeuchi, PRD (1992)

Constraints from EW precision

Cynolter, Lendvai, EPJC (2008)

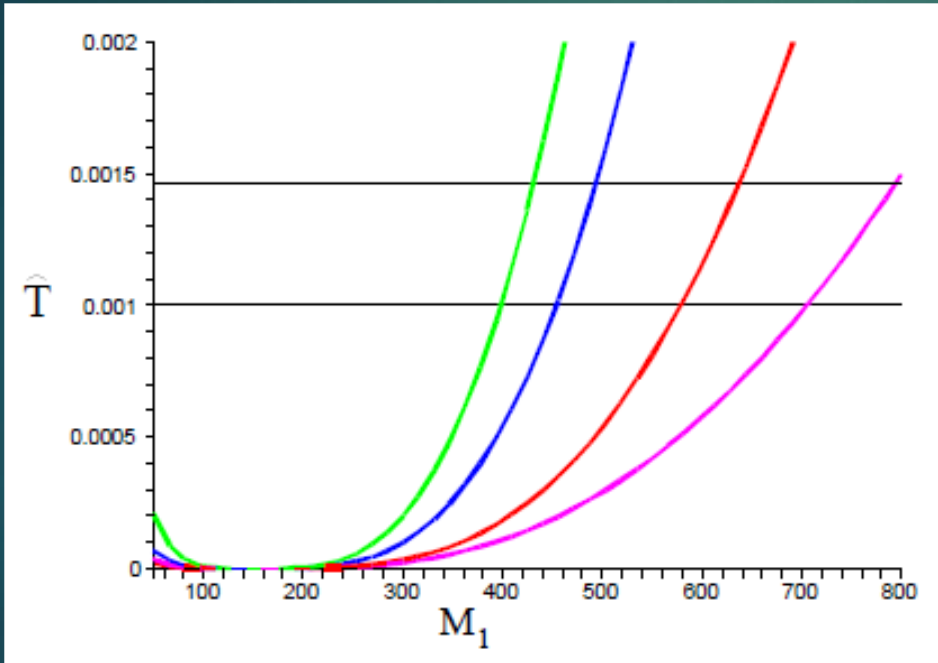


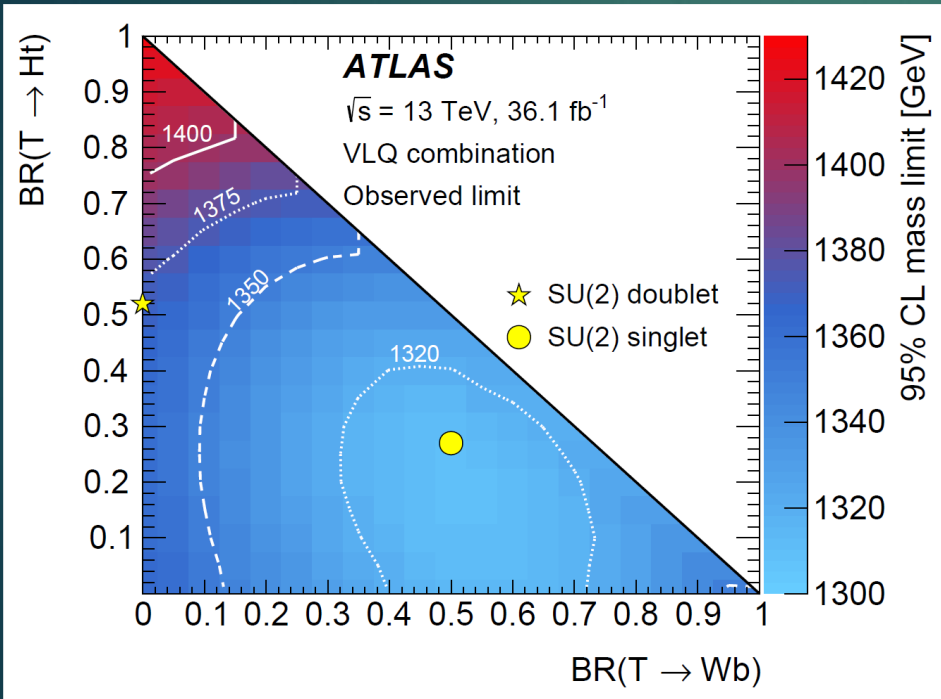
Fig. 2 The $\hat{T}$ parameter versus M_1 for $M_2 = 150$ GeV for $c^2 = 0.9, 0.1, 0.2, 0.55$ from the bottom upwards; the *horizontal lines* are the 1σ and 1.6σ experimental upper bounds

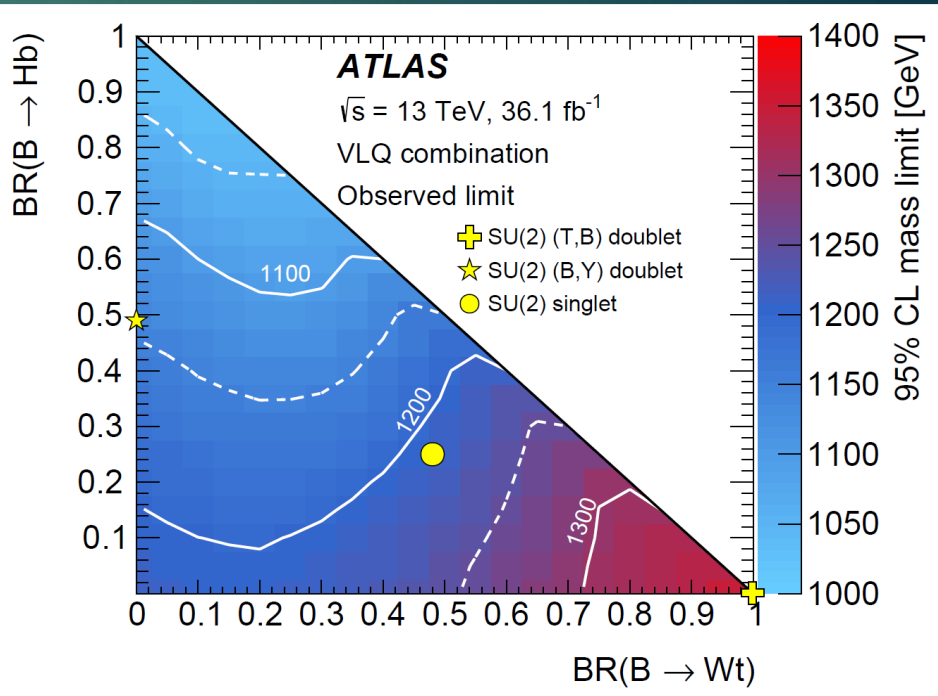
→ Result with both double and singlet VLQs

Constraints from the Direct Searches

ATLAS, 1808.02343

Constrains on VLQ mass



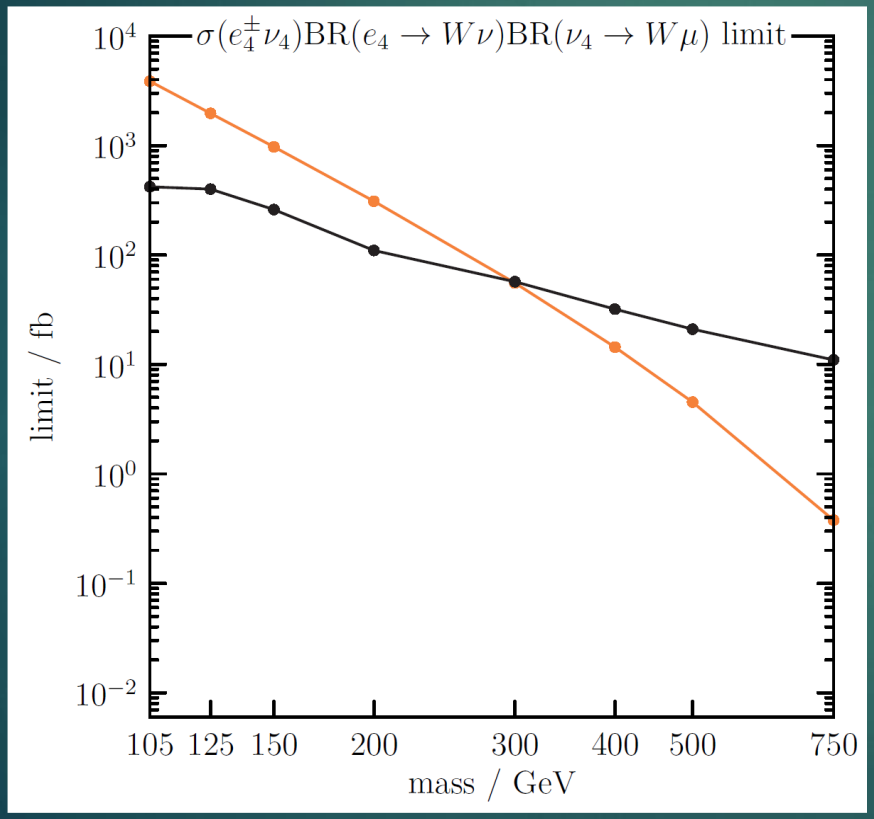


$M_T > 1.31\text{TeV}$

$M_B > 1.03\text{TeV}$

Constraints from the Direct Searches

Dermisek, Hall, Lunghi, Shin, 1408.3123

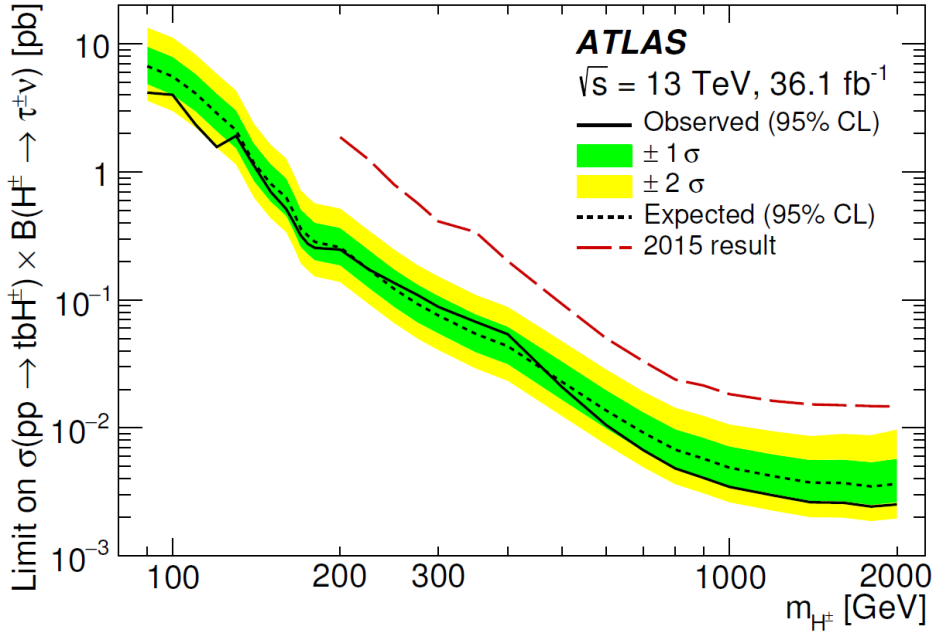


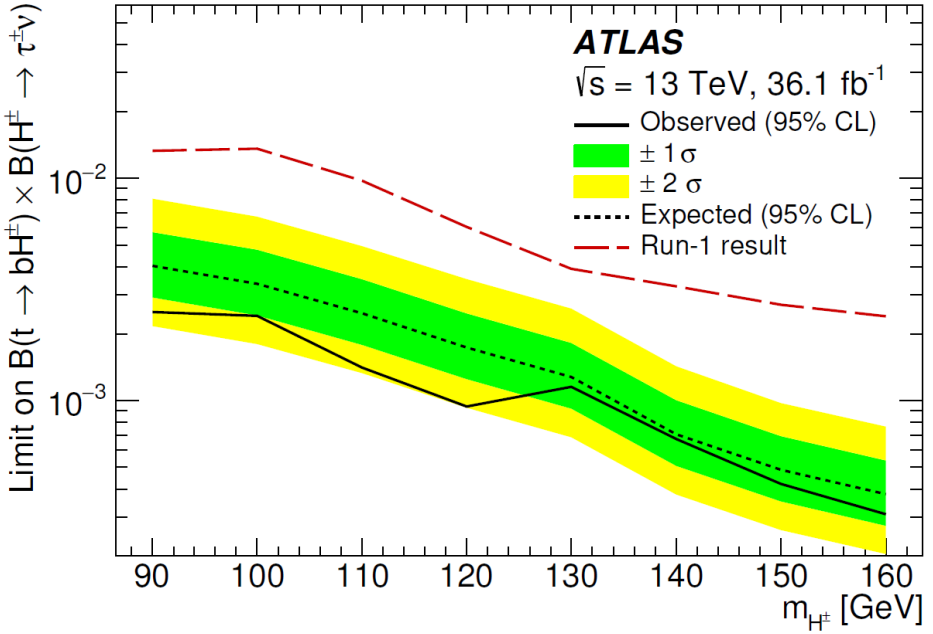
Constrains on VLL mass

$M_E > 300\mathrm{GeV}$

Constraints from the Direct Searches

Charged Higgs search from $H^+ \to \tau\nu$

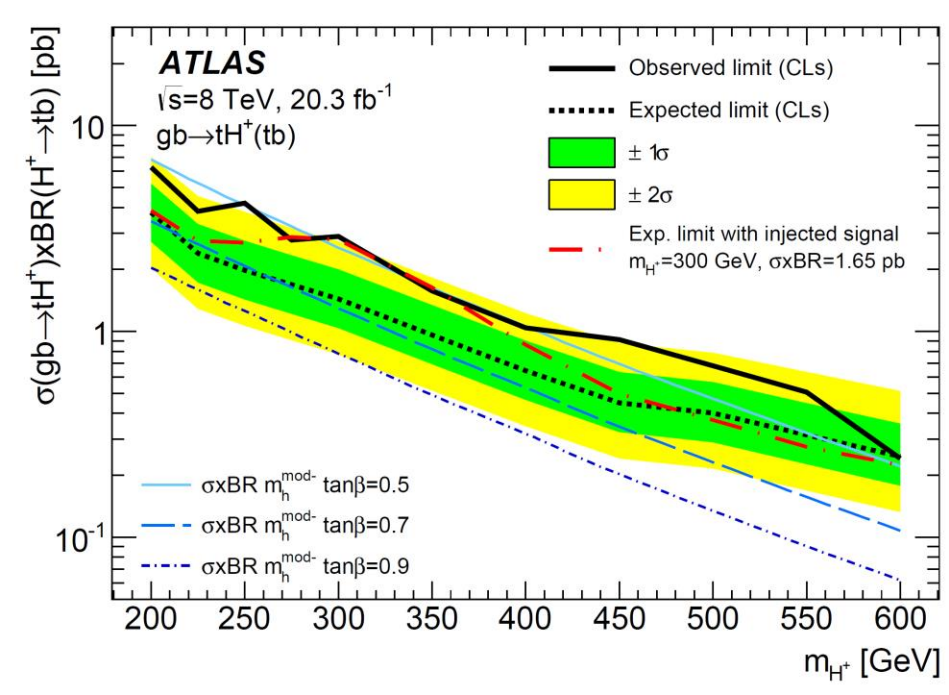




ATLAS, 1807.07915

Constraints from the Direct Searches

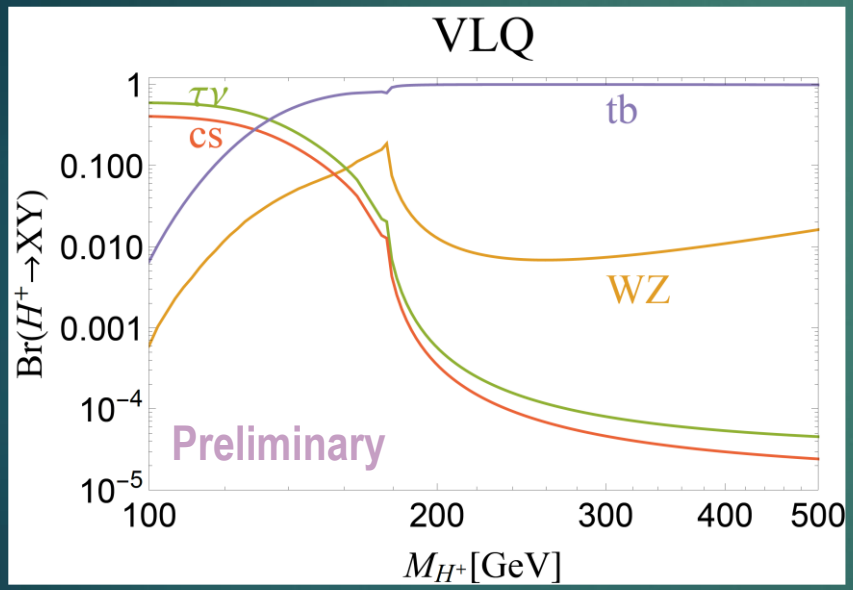
Charged Higgs search from $H^+ \to t\bar{b}$

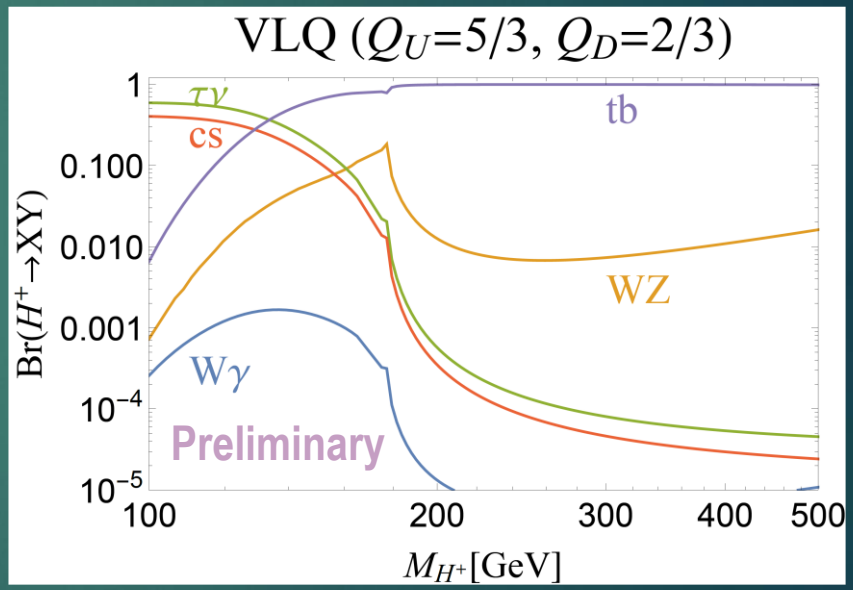


ATLAS, 1512.03704

Numeric - Branching Ratios

$M_{U_1} = 1310$ GeV, $M_{U_2} = 2500$ GeV, $Y_U = 2$, $Y_D = 6$
$M_{D_1} = 1030$ GeV, $M_{D_2} = 1500$ GeV, $t_\beta = 10$

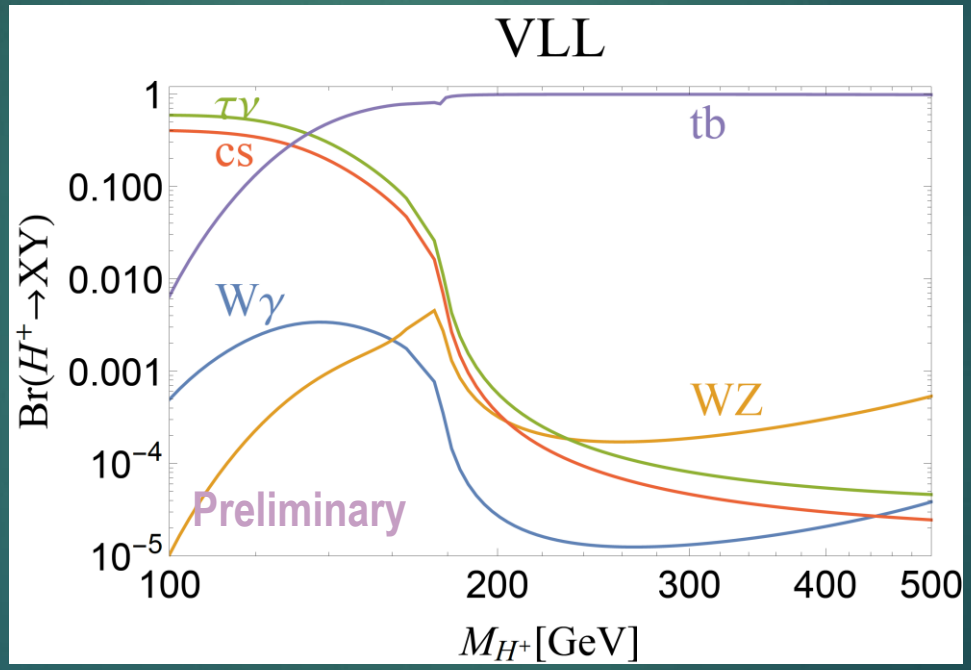




Numeric - Branching Ratios

$M_{\nu_1} = 300\ \text{GeV},\ M_{\nu_2} = 700\ \text{GeV},\quad Y_\nu = 1, Y_E = 5$

$M_{E_1} = 300\ \text{GeV},\ M_{E_2} = 700\ \text{GeV},\quad t_\beta = 20$



Numeric - Branching Ratios

VLQ : $M_{U_1} = 1310\,\text{GeV},\ M_{D_1} = 1030\,\text{GeV}$

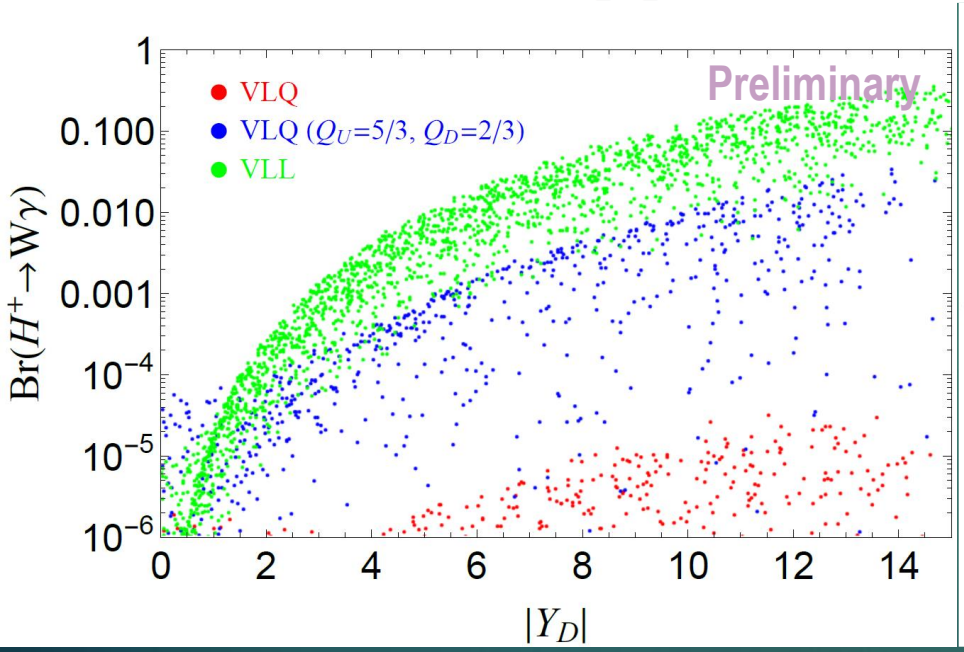
$M_{U_2} \subset [1310, 4000]\,\text{GeV},\quad M_{U_2} \subset [1030, 4000]\,\text{GeV}$

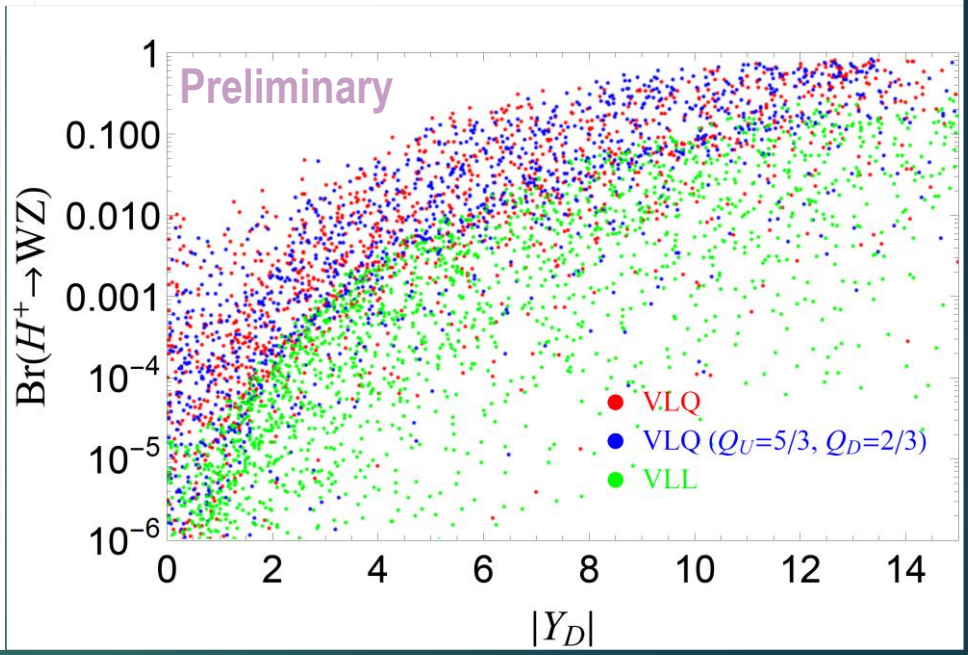
$t_\beta \subset [1, 50],\quad \theta_U, \theta_D \subset \left[-\frac{\pi}{2}, \frac{\pi}{2}\right].$

VLL : $M_{\nu_1} = 300\,\text{GeV},\ M_{e_1} = 300\,\text{GeV},$

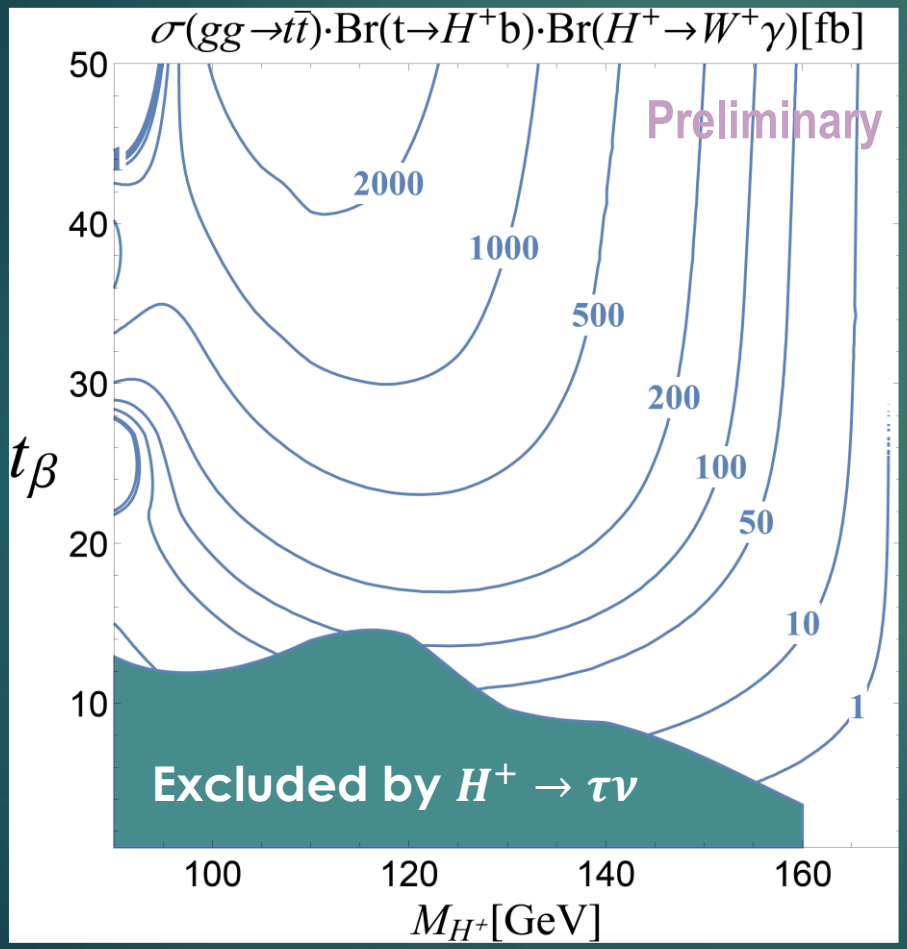
$M_{\nu_2} \subset [300, 1000]\,\text{GeV},\quad M_{e_2} \subset [300, 1000]\,\text{GeV}$

$t_\beta \subset [1, 50],\quad \theta_\nu, \theta_e \subset \left[-\frac{\pi}{2}, \frac{\pi}{2}\right].$





Numeric – Cross section for $W\gamma$ channel



$\sqrt{s} = 13\mathrm{TeV}$

$M_{U_1} = 1310\ \mathrm{GeV},\ M_{U_2} = 2500\ \mathrm{GeV},$
$M_{D_1} = 1030\ \mathrm{GeV},\ M_{D_2} = 1500\ \mathrm{GeV},$

$\theta_U = 0.01,\ \theta_D = 0.2$

VLQ with $Q_U = \frac{5}{3},\ Q_D = \frac{2}{3}$

Conclusion

- We have studied VLQ effect on the loop induced decays of charged Higgs $H^+ \to W(\gamma, Z)$
- $\mathrm{Br}(H^+ \to W\gamma)$ can be order of 10^{-3} in the presence of VLQ with exotic charges or VLL.
- $H^+ \to WZ$ decay rate has longitudinal enhancement so that $\mathrm{Br}(H^+ \to W\gamma)$ can be order of 10^{-2} in broad range of the allowed parameter space