Exploring the global symmetry structure of the Higgs potential via same-sign pair production of charged Higgs bosons

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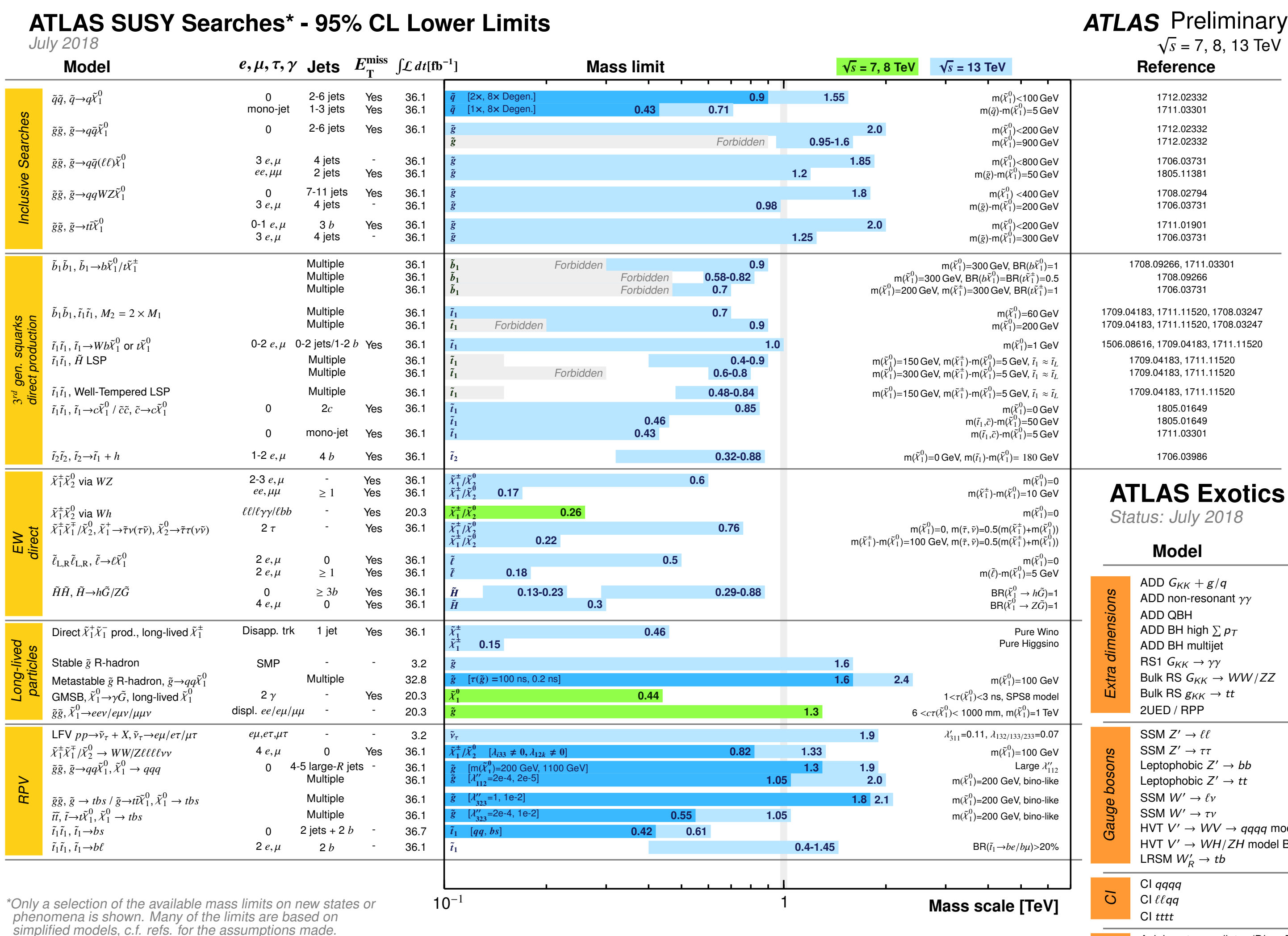
[arXiv:1906.09101]

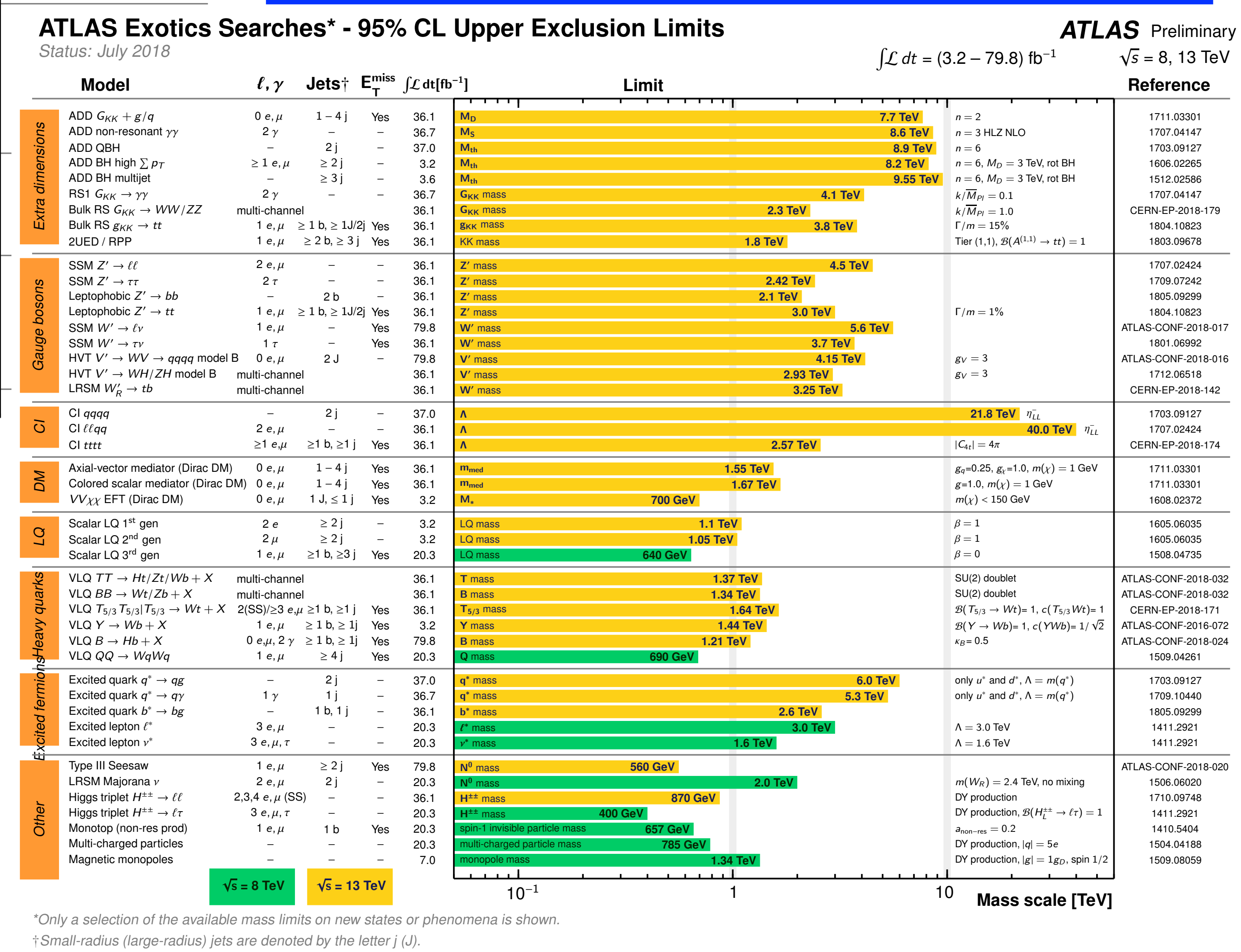
work with Masashi Aiko and Shinya Kanemura (Osaka U.)

No BSM so far…



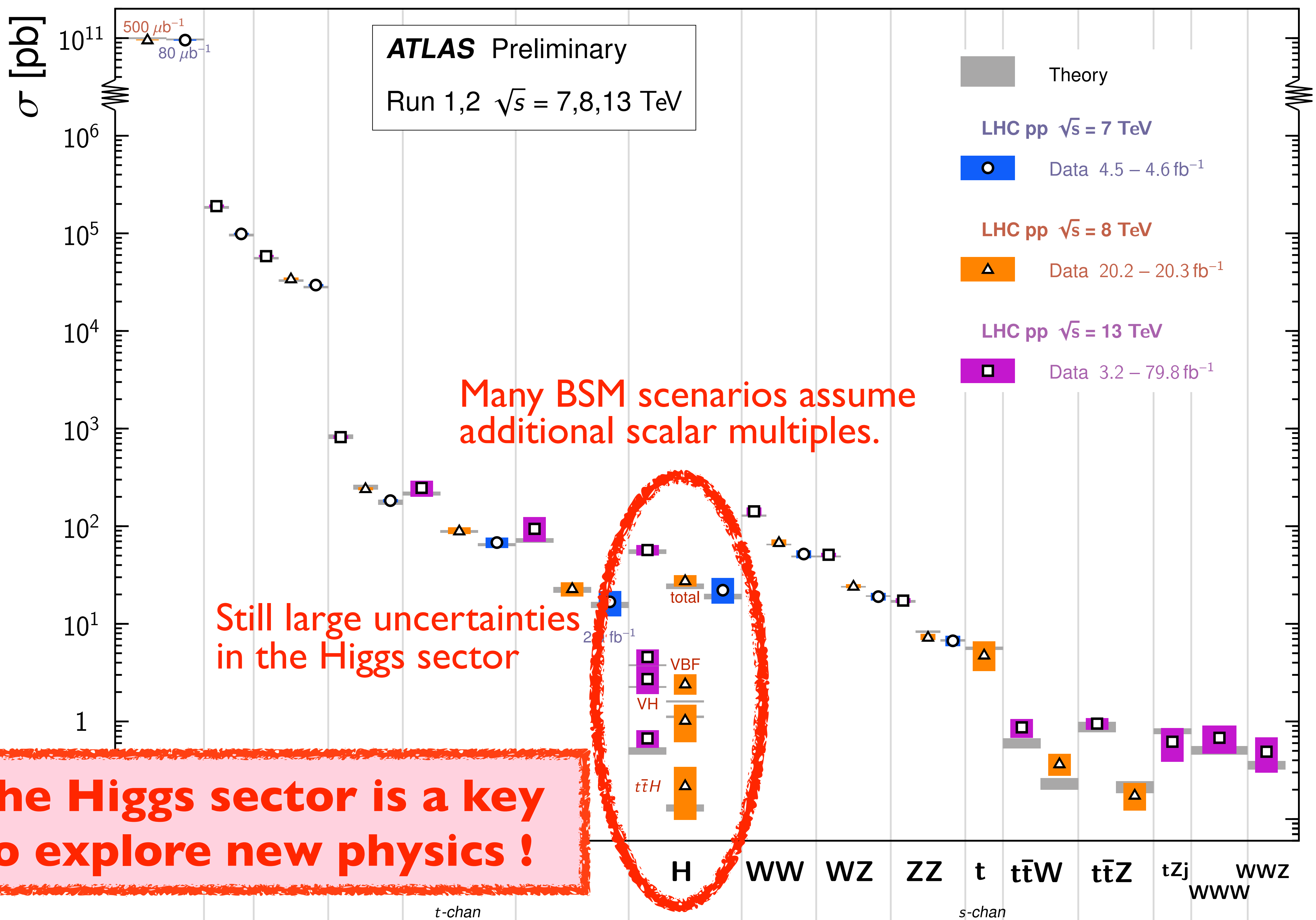
Mass limits for SUSY particles

Mass limits for non-SUSY particles



LHC data ≈ Standard Model (SM)

Standard Model Total Production Cross Section Measurements *Status: March 2019*



Many BSM scenarios assume additional scalar multiples.

Still large uncertainties in the Higgs sector

The Higgs sector is a key to explore new physics !

Non-minimal Higgs sector

- HSM: Higgs singlet model (a real singlet scalar)

$$V(\Phi,S)=m_\Phi^2|\Phi|^2+\lambda|\Phi|^4+\mu_{\Phi S}|\Phi|^2S+\lambda_{\Phi S}|\Phi|^2S^2+t_S S+m_S^2S^2+\mu_S S^3+\lambda_S S^4$$

[free parameters] $m_H,\ M^2(\equiv 2m_S^2),\ \mu_S,\ \lambda_S,\ \alpha$

- THDM: Two Higgs doublet model

$$V(\Phi_1,\Phi_2)=m_1^2|\Phi_1|^2+m_2^2|\Phi_2|^2-m_3^2(\Phi_1^\dagger\Phi_2+\text{h.c.})$$
$$+\frac{1}{2}\lambda_1|\Phi_1|^4+\frac{1}{2}\lambda_2|\Phi_2|^4+\lambda_3|\Phi_1|^2|\Phi_2|^2+\lambda_4|\Phi_1^\dagger\Phi_2|^2+\frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2+\text{h.c.}]$$

[free parameters] $m_H,\ m_A,\ m_{H^\pm},\ M^2(\equiv m_3^2/s_\beta c_\beta),\ \tan\beta,\ s_{\beta-\alpha}(\geq 0),\ \text{Sign}(c_{\beta-\alpha})$

- additional Higgs bosons ($H,A,H^\pm,\ldots$)
- deviations of the h(125) couplings from the SM

Kanemura, Kikuchi, KM, Sakurai, Yagyu
H-COUP [1803.01456, 1906.10070]

Especially, charged Higgs bosons can provide striking signals of an extended Higgs sector.

Contents of the talk

Kanemura, Kikuchi, Yagyu [1502.07716, NPB]

Feynman Rules in THDMs (Gauge)

Vertices	$g_{\phi V_1 V_2}$
$hW_\mu^+ W_\nu^-$	$\frac{g^2}{2} v s_{\beta-\alpha}$
$HW_\mu^+ W_\nu^-$	$\frac{g^2}{2} v c_{\beta-\alpha}$
$hZ_\mu Z_\nu$	$\frac{g_Z^2}{4} v s_{\beta-\alpha}$
$HZ_\mu Z_\nu$	$\frac{g_Z^2}{4} v c_{\beta-\alpha}$
$G^\pm Z_\mu W_\nu^\mp$	$-\frac{g g_Z}{2} v s_W^2$
$G^\pm A_\mu W_\nu^\mp$	$\frac{eg}{2} v$

mixing between h(125) and H

$$s_{\beta-\alpha} \equiv \sin(\beta-\alpha)$$

* alignment limit $s_{\beta-\alpha} = 1$

h(125) = SM-like

Vertices	$g_{\phi_1 \phi_2 V}$
$hG^\pm W_\mu^\mp$	$\mp i\frac{g}{2} s_{\beta-\alpha}$
$HG^\pm W_\mu^\mp$	$\mp i\frac{g}{2} c_{\beta-\alpha}$
$G^0 G^\pm W_\mu^\mp$	$-\frac{g}{2}$
$hH^\pm W_\mu^\mp$	$\mp i\frac{g}{2} c_{\beta-\alpha}$
$HH^\pm W_\mu^\mp$	$\pm i\frac{g}{2} s_{\beta-\alpha}$
$AH^\pm W_\mu^\mp$	$-\frac{g}{2}$
$G^+ G^- Z_\mu$	$i\frac{g_Z}{2} c_{2W}$
$H^+ H^- Z_\mu$	$i\frac{g_Z}{2} c_{2W}$
$hG^0 Z_\mu$	$-\frac{g_Z}{2} s_{\beta-\alpha}$
hAZ_μ	$-\frac{g_Z}{2} c_{\beta-\alpha}$
$HG^0 Z_\mu$	$-\frac{g_Z}{2} c_{\beta-\alpha}$
HAZ_μ	$\frac{g_Z}{2} s_{\beta-\alpha}$
$G^+ G^- A_\mu$	ie
$H^+ H^- A_\mu$	ie

Vertices	$g_{\phi_1 \phi_2 V_1 V_2}$	Vertices	$g_{\phi_1 \phi_2 V_1 V_2}$
$hhW_\mu^+ W_\nu^-$	$\frac{g^2}{4}$	$G^\pm G^0 W_\mu^\mp Z_\nu$	$\pm i\frac{g g_Z}{2} s_W^2$
$HHW_\mu^+ W_\nu^-$	$\frac{g^2}{4}$	$H^\pm A W_\mu^\mp Z_\nu$	$\pm i\frac{g g_Z}{2} s_W^2$
$AAW_\mu^+ W_\nu^-$	$\frac{g^2}{4}$	$G^\pm H W_\mu^\mp Z_\nu$	$-\frac{g g_Z}{2} s_W^2 c_{\beta-\alpha}$
$G^0 G^0 W_\mu^+ W_\nu^-$	$\frac{g^2}{4}$	$H^\pm h W_\mu^\mp Z_\nu$	$-\frac{g g_Z}{2} s_W^2 c_{\beta-\alpha}$
$G^+ G^- W_\mu^+ W_\nu^-$	$\frac{g^2}{2}$	$G^\pm h W_\mu^\mp Z_\nu$	$-\frac{g g_Z}{2} s_W^2 s_{\beta-\alpha}$
$H^+ H^- W_\mu^+ W_\nu^-$	$\frac{g^2}{2}$	$H^\pm H W_\mu^\mp Z_\nu$	$\frac{g g_Z}{2} s_W^2 s_{\beta-\alpha}$
$hhZ_\mu Z_\nu$	$\frac{g_Z^2}{8}$	$H^\pm A W_\mu^\mp A_\nu$	$\mp\frac{eg}{2}$
$HHZ_\mu Z_\nu$	$\frac{g_Z^2}{8}$	$G^\pm G^0 W_\mu^\mp A_\nu$	$\mp\frac{eg}{2}$
$AAZ_\mu Z_\nu$	$\frac{g_Z^2}{8}$	$H^\pm h W_\mu^\mp A_\nu$	$\frac{eg}{2} c_{\beta-\alpha}$
$G^0 G^0 Z_\mu Z_\nu$	$\frac{g_Z^2}{8}$	$G^\pm H W_\mu^\mp A_\nu$	$\frac{eg}{2} c_{\beta-\alpha}$
$G^+ G^- Z_\mu Z_\nu$	$\frac{g_Z^2}{4} c_{2W}^2$	$G^+ G^- A_\mu Z_\nu$	$e g_Z c_{2W}$
$H^+ H^- Z_\mu Z_\nu$	$\frac{g_Z^2}{4} c_{2W}^2$	$H^+ H^- A_\mu Z_\nu$	$e g_Z c_{2W}$
$G^+ G^- A_\mu A_\nu$	e^2	$G^\pm h W_\mu^\mp A_\nu$	$\frac{eg}{2} s_{\beta-\alpha}$
$H^+ H^- A_\mu A_\nu$	e^2	$H^\pm H W_\mu^\mp A_\nu$	$-\frac{eg}{2} s_{\beta-\alpha}$

Feynman Rules in THDMs (Yukawa)

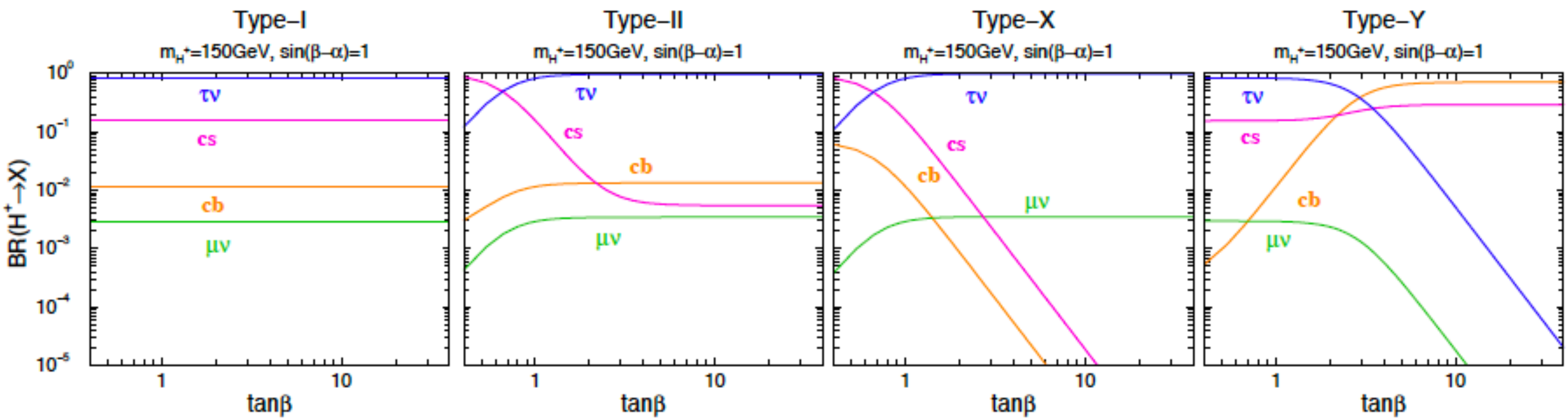
$$-\mathcal{L}_Y = Y_u \overline{Q}_L i\sigma_2 \Phi_u^* u_R + Y_d \overline{Q}_L \Phi_d d_R + Y_e \overline{L}_L \Phi_e e_R + \text{h.c.}$$

$$\frac{\sqrt{2}}{v}\left[V_{ud}\overline{u}\left(m_d\xi_d P_R - m_u\xi_u P_L\right) d\, H^+ + m_e\xi_e\overline{\nu}P_R e H^+ + \text{h.c.}\right]$$

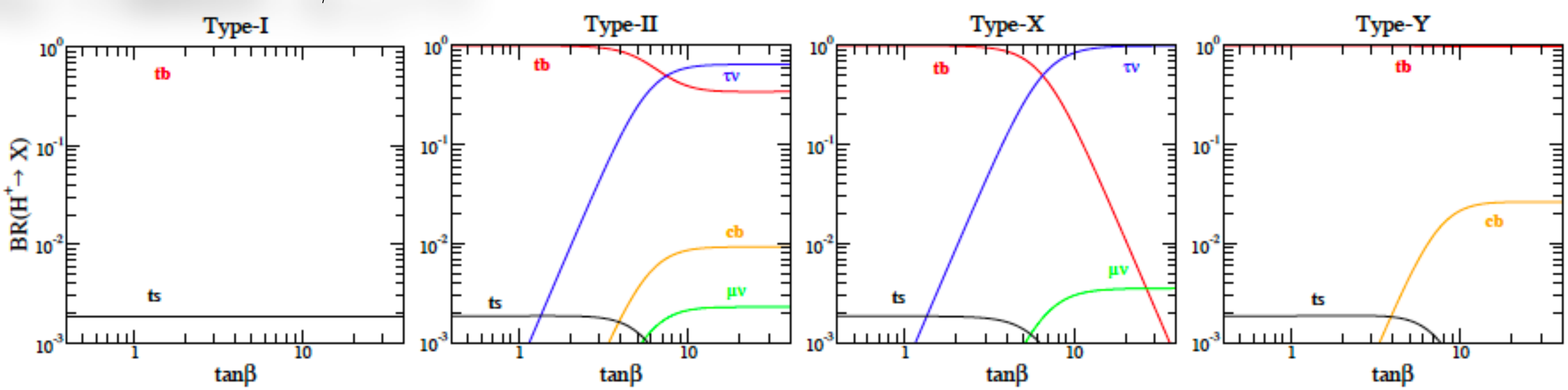
	Z_2 charge							Mixing factor		
	Φ_1	Φ_2	Q_L	L_L	u_R	d_R	e_R	ξ_u	ξ_d	ξ_e
Type-I	+	−	+	+	−	−	−	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type-II	+	−	+	+	−	+	+	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type-X	+	−	+	+	−	−	+	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type-Y	+	−	+	+	−	+	−	$\cot\beta$	$-\tan\beta$	$\cot\beta$

Aoki, Kanemura, Tsumura, Yagyu [0902.4665, PRD]
Kanemura, Tsumura, Yagyu, Yokoya [1406.3294, PRD]

Branching ratios ($m_{H^+} < m_t$ or $m_{H^+} > m_t$)

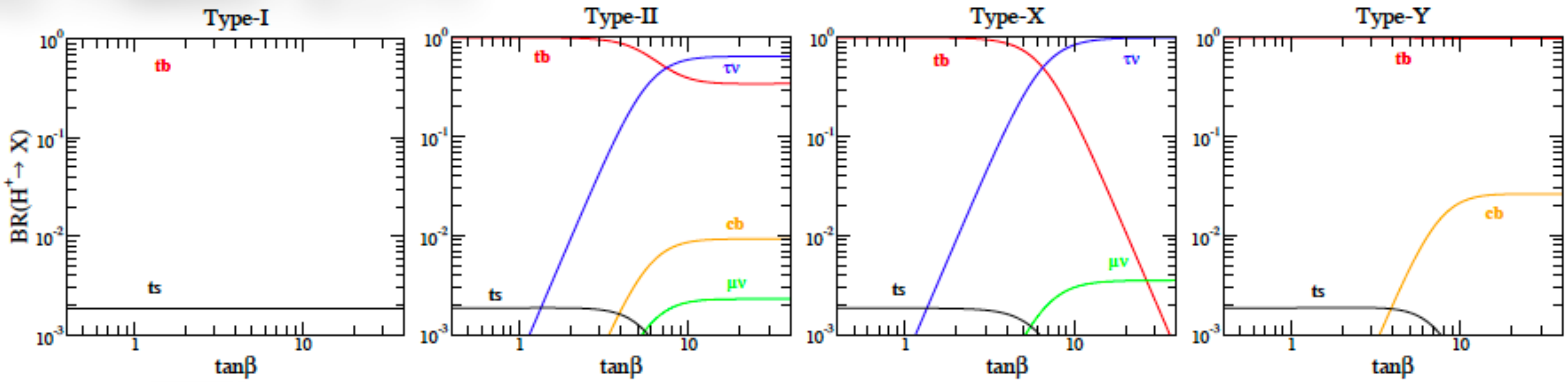


$m_{H^+} = 200\text{GeV},\ s_{\beta-\alpha} = 1$

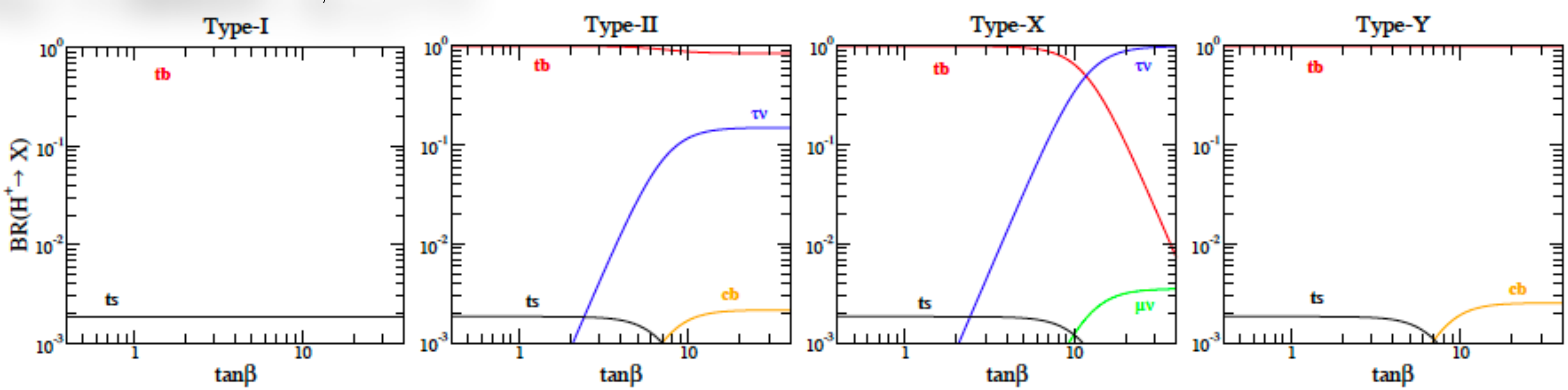


Branching ratios ($\sin(\beta-\alpha)=1$)

$m_{H^+} = 200\text{GeV},\ s_{\beta-\alpha}=1$



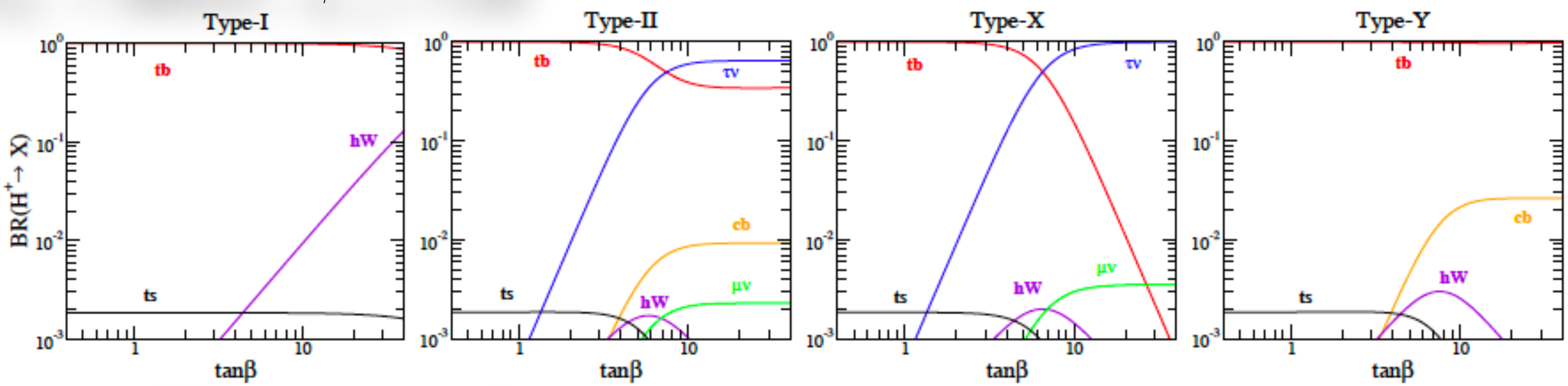
$m_{H^+} = 400\text{GeV},\ s_{\beta-\alpha}=1$



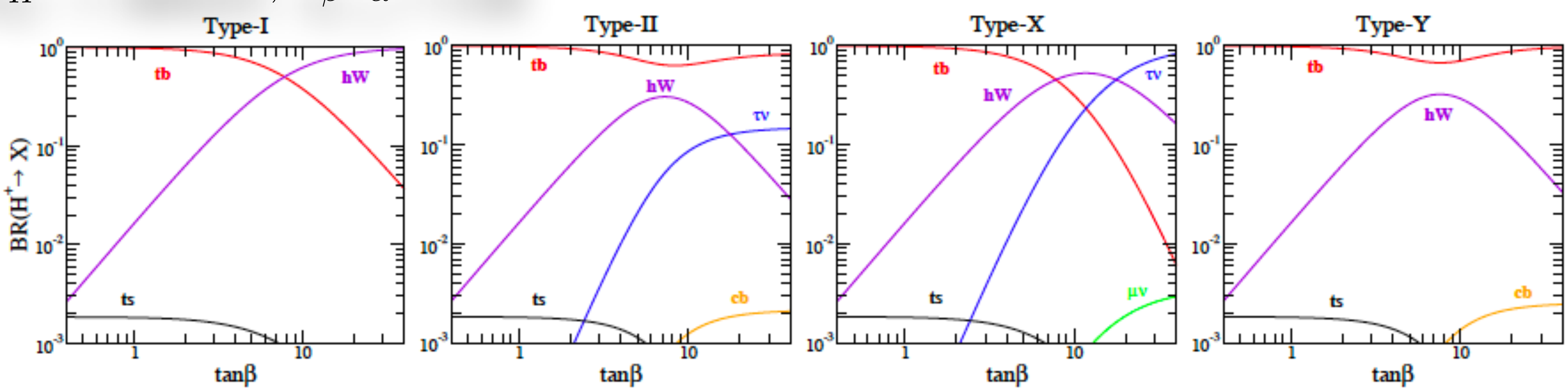
Kanemura, Tsumura, Yagyu, Yokoya [1406.3294, PRD]

Branching ratios ($\sin(\beta-\alpha)\neq 1$)

$m_{H^+} = 200\text{GeV},\ s_{\beta-\alpha} = 0.99$



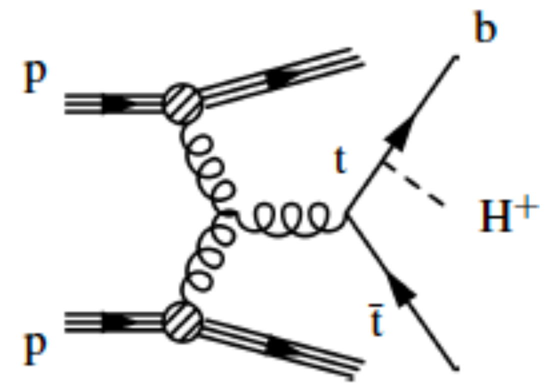
$m_{H^+} = 400\text{GeV},\ s_{\beta-\alpha} = 0.99$



Charged Higgs boson productions

- for $m_{H^+} < m_t$
  - top pair

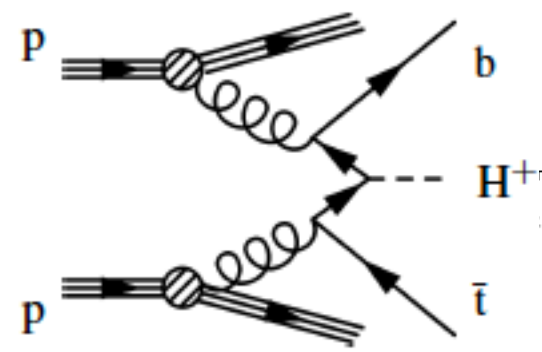
    $pp \to t\bar{t},\ t \to H^+ b$



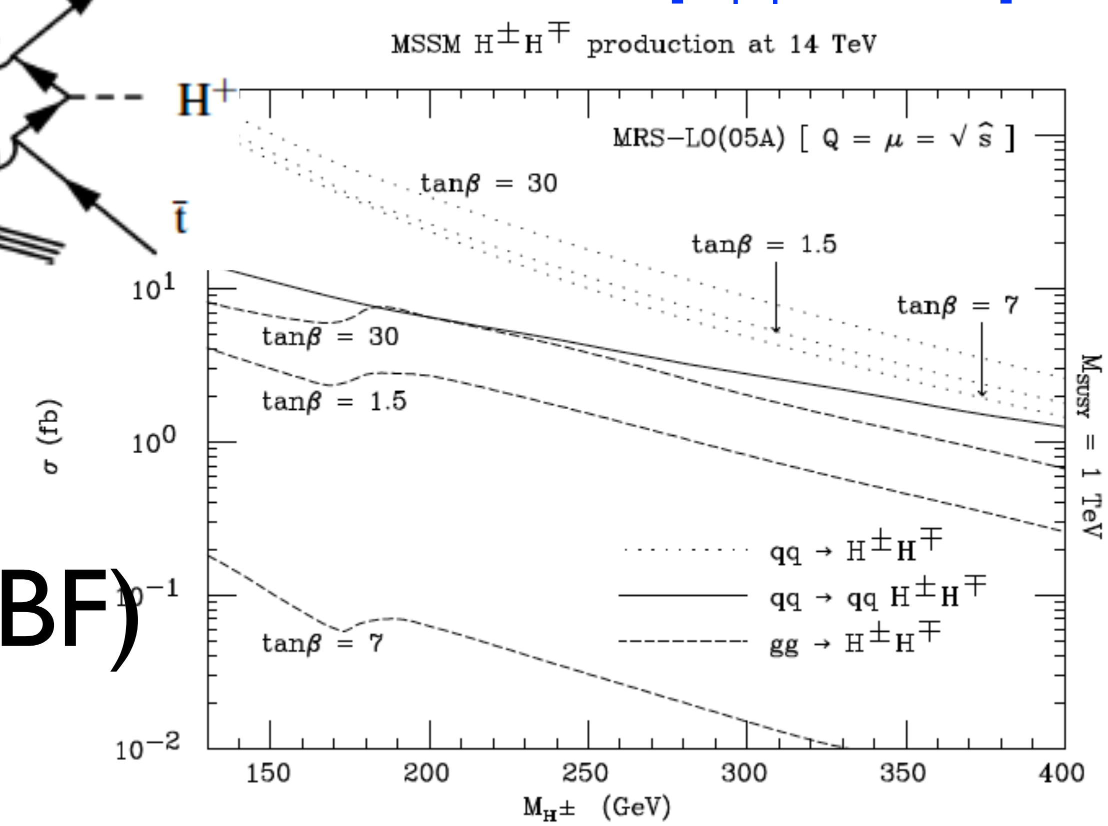
- for $m_{H^+} > m_t$
  - single production

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

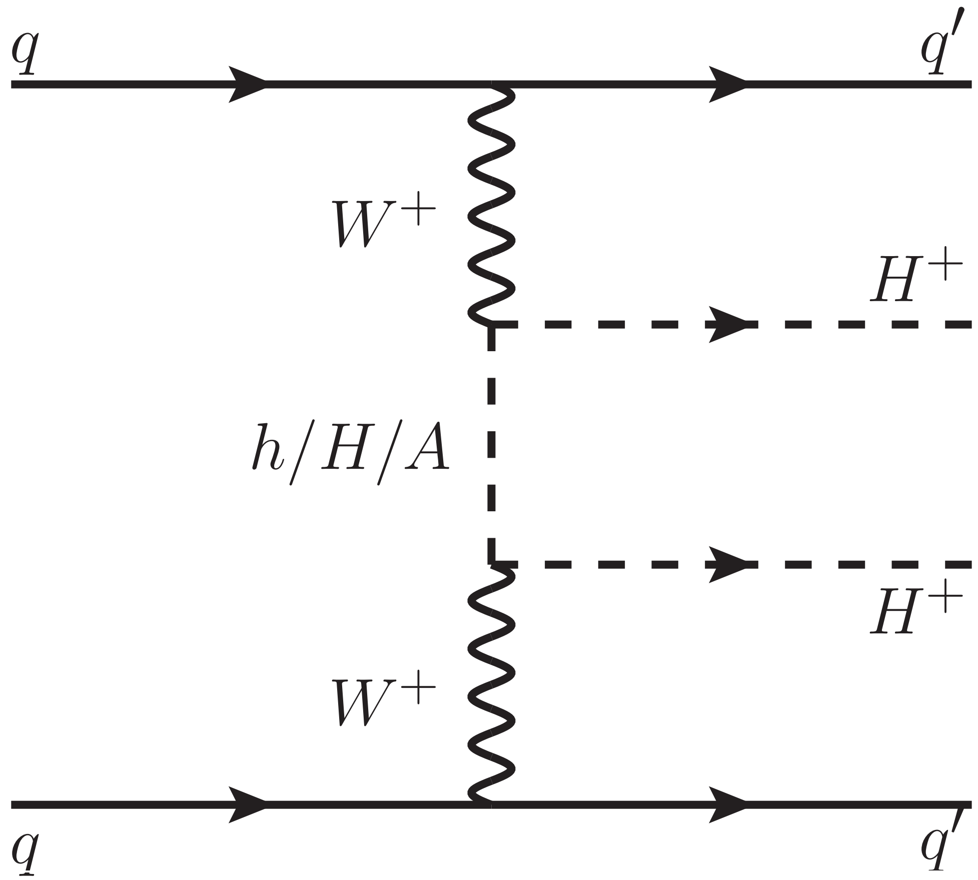
  - pair production (DY/VBF)



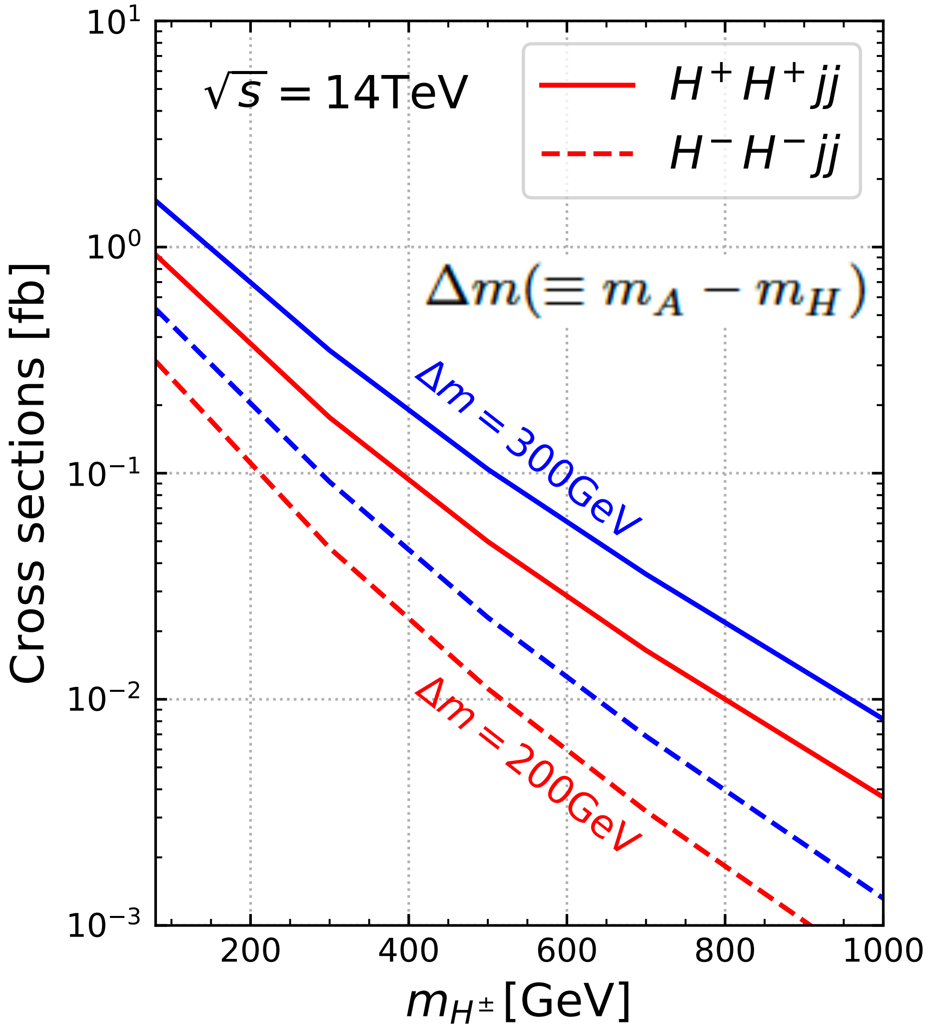
Alves, Plehn [hep-ph/0503135]
Moretti [hep-ph/0102116]



Same-sign pair production of charged Higgs bosons



Aiko, Kanemura, Mawatari [1906.09101]



$\Delta m \to 0 \;\Rightarrow\; \sigma \to 0$

symmetry?

Symmetry of the Higgs potential

$$V(\Phi_1,\Phi_2)=\sum_{i=1,2} m_i^2\,|\Phi_i|^2-(m_3^2\,\Phi_1^\dagger\Phi_2+\text{h.c.})$$
$$+\sum_{i=1,2}\frac{1}{2}\lambda_i\,|\Phi_i|^4+\lambda_3\,|\Phi_1|^2|\Phi_2|^2+\lambda_4\,|\Phi_1^\dagger\Phi_2|^2+\left\{\frac{1}{2}\lambda_5\,(\Phi_1^\dagger\Phi_2)^2+\left(\lambda_6|\Phi_1|^2+\lambda_7|\Phi_2|^2\right)\Phi_1^\dagger\Phi_2+\text{h.c.}\right\}$$

- suppressed FCNC → Z_2 symmetry → $\lambda_6=\lambda_7=0$
- h(125)～SM-like → alignment → $\lambda_1=\lambda_2=\lambda_3+\lambda_4+\lambda_5$

$$\begin{aligned}V_4=&\frac{1}{2}c_1(|\Phi_1|^2+|\Phi_2|^2)^2 &&\leftarrow O(8)\\ &+\frac{1}{2}c_2(|\Phi_1|^2-|\Phi_2|^2)^2 &&\leftarrow O(4)\times O(4)'\\ &+\frac{1}{2}c_3(\Phi_1^\dagger\Phi_2+\Phi_2^\dagger\Phi_1)^2 &&\leftarrow O(4)\\ &+\frac{1}{2}c_4(\Phi_1^\dagger\Phi_2-\Phi_2^\dagger\Phi_1)^2 &&\leftarrow O(4)\end{aligned}$$

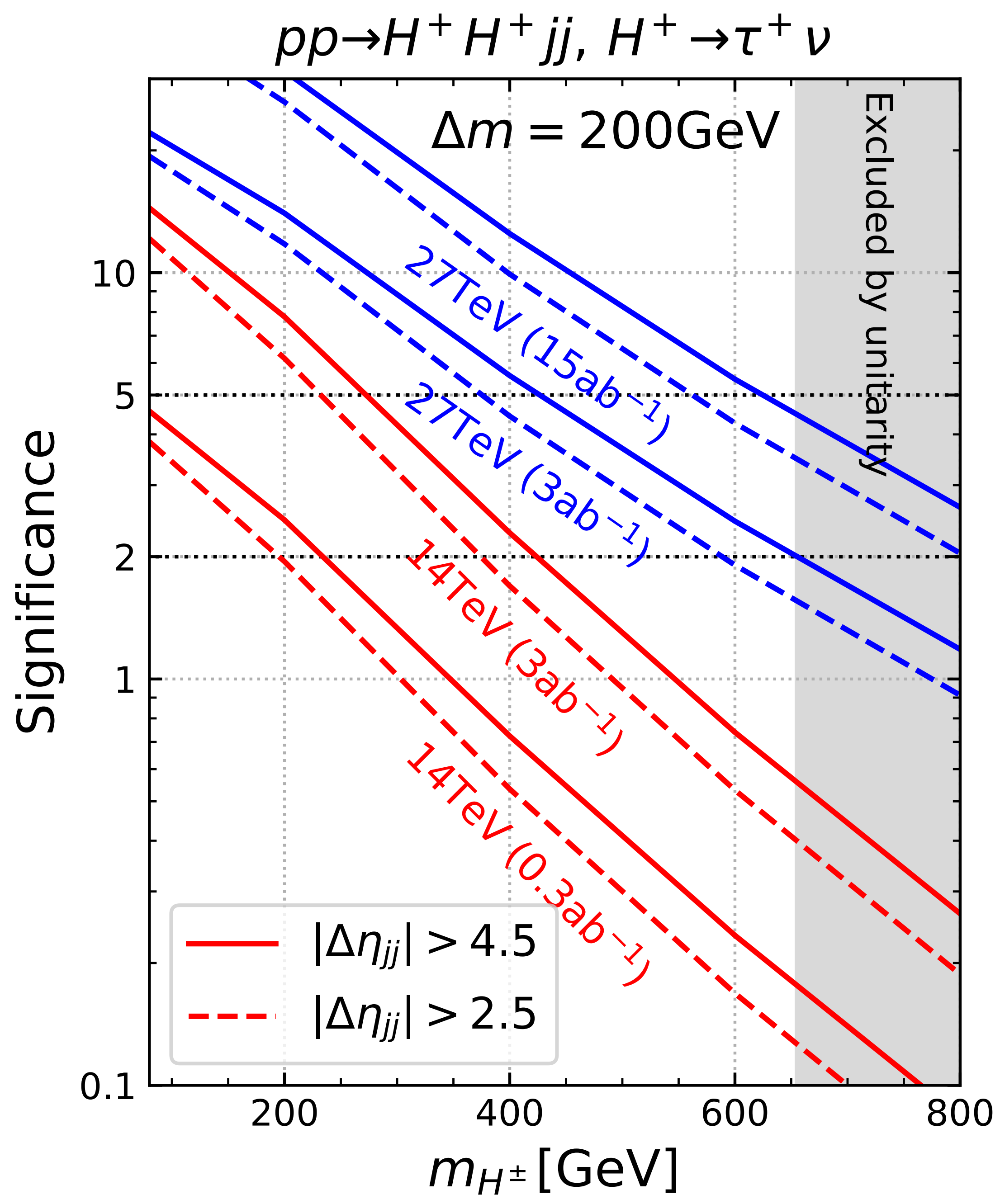
$$c_1=\lambda_3+(\lambda_4+\lambda_5)/2$$
$$c_2=c_3=(\lambda_4+\lambda_5)/2=(m_H^2-m_{H^\pm}^2)/v^2$$
$$c_4=-(\lambda_4-\lambda_5)/2=(m_{H^\pm}^2-m_A^2)/v^2$$

- ρ～1 → custodial symmetry $\mathrm{O(4)}\simeq\mathrm{SU(2)_L}\times\mathrm{SU(2)_R}\to\mathrm{SU(2)_V}$ →

$$(\text{Case I}: m_{H^\pm}^2=m_A^2)\quad c_1=m_h^2/v^2-\eta,\ c_2=c_3=\eta,\ c_4=0$$
$$(\text{Case II}: m_{H^\pm}^2=m_H^2)\quad c_1=m_h^2/v^2,\ c_2=c_3=0,\ c_4=\eta$$
$$\eta=(m_H^2-m_A^2)/v^2$$

V_4 respects O(8) if η=0, O(4) if η≠0 ⟷ $\sigma(H^\pm H^\pm jj)\propto\eta$

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



- same-sign tau-pair with 2 forward jets

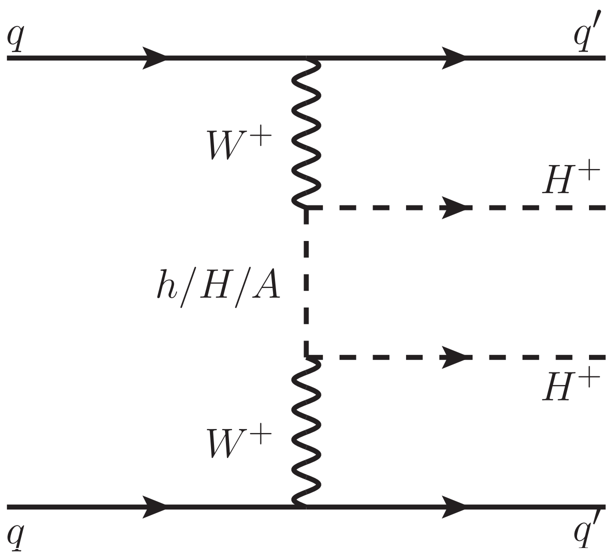
$$s = L\ \sigma^{\rm VBF}_{pp\to H+H+jj}(B_{H+\to\tau\nu})^2\epsilon^{\tau}_{\rm sel}(\epsilon_\tau)^2$$
$$b = L\ \sigma^{\rm VBF}_{pp\to W+W+jj}(B_{W+\to\tau\nu})^2\epsilon^{\tau}_{\rm sel}(\epsilon_\tau)^2$$

* Significance ($H^+ \to tb$) in backup.

[arXiv:1906.09101]

Exploring the global symmetry structure of the Higgs potential via same-sign pair production of charged Higgs bosons

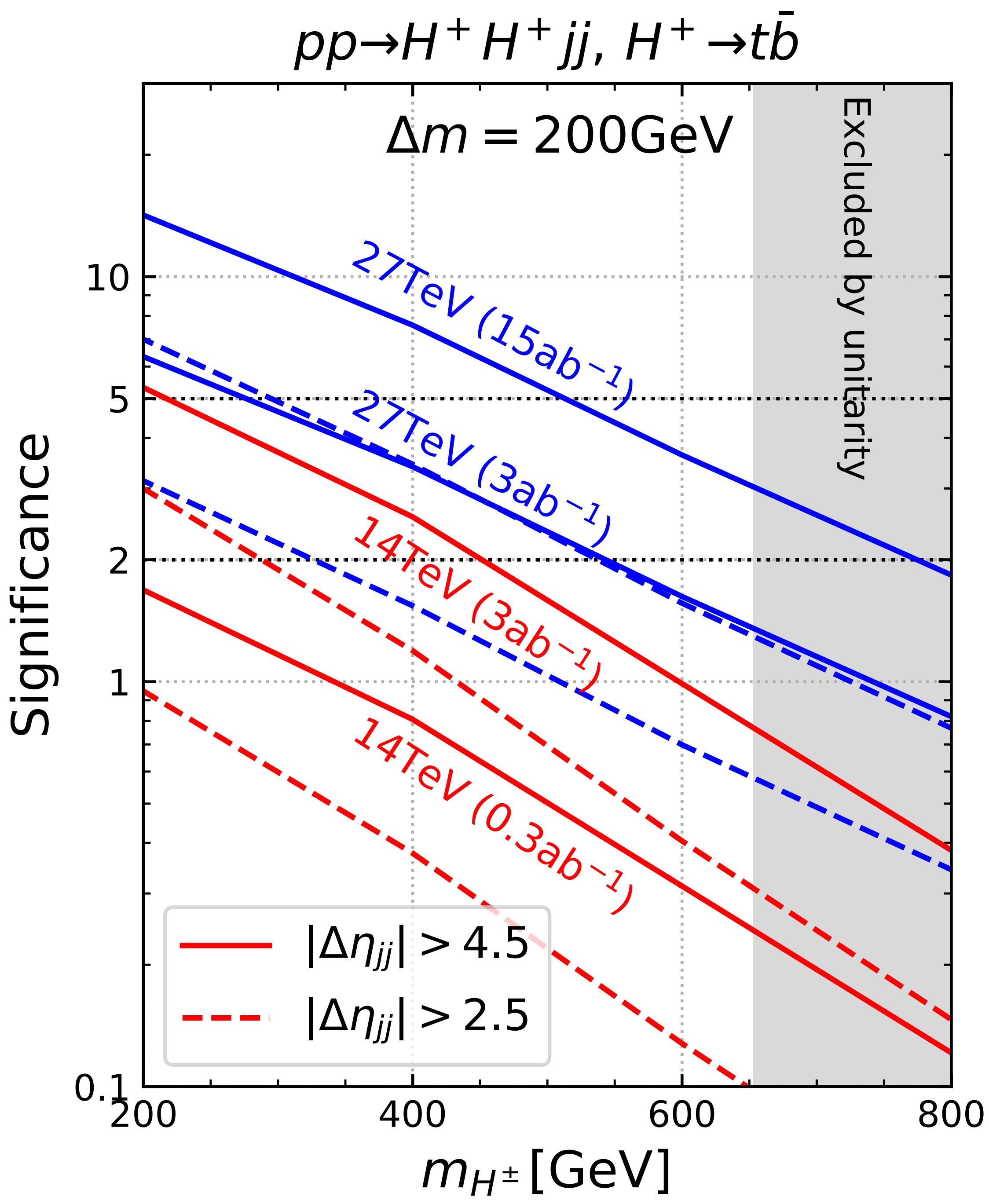
$$
\begin{aligned}
V_4 = &\frac{1}{2}c_1(|\Phi_1|^2 + |\Phi_2|^2)^2 && \leftarrow O(8) \\
&+ \frac{1}{2}c_2(|\Phi_1|^2 - |\Phi_2|^2)^2 && \leftarrow O(4)\times O(4)' \\
&+ \frac{1}{2}c_3(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1)^2 && \leftarrow O(4) \\
&+ \frac{1}{2}c_4(\Phi_1^\dagger\Phi_2 - \Phi_2^\dagger\Phi_1)^2 && \leftarrow O(4)
\end{aligned}
$$



- Charged Higgs bosons can provide striking signals of an extended Higgs sector.
- The same-sign pair production can be observed at the LHC and future higher-energy colliders.

buckup

Significance ($H^+ \to tb$)



- same-sign top-pair with 2 forward jets

$$s = L\ \sigma^{\rm VBF}_{pp\to H^+H^+jj} (B_{H^+\to t\bar{b}})^2 (B_{t\to b\ell^+\nu})^2 \epsilon^t_{\rm sel} (\epsilon_b)^2$$

$$b = L\ \sigma_{pp\to tt\bar{t}\bar{t}} (B_{t\to b\ell^+\nu})^2 (B_{\bar{t}\to\bar{b}jj})^2 \epsilon^t_{\rm sel} (\epsilon_b)^2$$

Cross sections