Loop induced H±W±Z vertex in CP violating two Higgs doublet model

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arXiv:2408.06863

Workshop on Multi Higgs Models at Lisbon
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Introduction

- **Higgs discovery and remaining problems**
  e.g., baryon asymmetry of the Universe

- **Sakharov third conditions for baryon asymmetry**

  ① Baryon # violation
  ② C and CP violation
  ③ Departure from thermal equilibrium

  Sakharov (1967)

  Ex) Electroweak baryogenesis in two Higgs doublet model — Kuzmin, Rubakov and Shaposhnikov (1985)

  Fromme et al., (2006); Cline et al., (2011); Dorsch et al. (2017); Enomoto, Kanemura and YM (2021), (2022); and more works

- **CP violating observables**

  Ex) Electron EDM $|d_e| < 4.1\times10^{-30}\ e$ cm

  JILA, Science (2023)

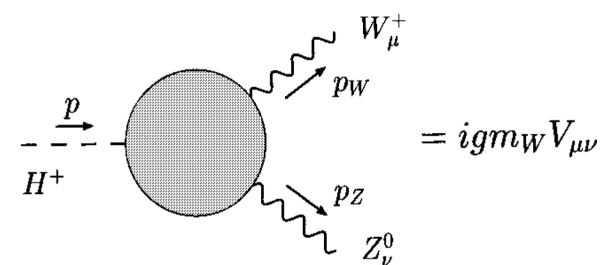


Fig. from S. Kanemura (2000)

In this talk

- **Loop induced $H^\pm W^\mp Z$ vertex in general CPV 2HDM**

  MSSM, — Mendez and Pomarol, Nucl.Phys.B 349 (1991) 369;
  CP conserving 2HDM — Kanemura, Phys.Rev.D 61 (2000) 095001; and more works

- **New observable for custodial and CP symmetry violation**

  Cf.) ρ parameter — Veltman (1977); Peskin and Takeuchi (1990), (1992); Haber and O'Neil (2011); and more works

General two Higgs doublet model

- **Most general potential**

Higgs basis

$$\boldsymbol{H}_1 = \begin{pmatrix} G^{\pm} \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix} \quad \boldsymbol{H}_2 = \begin{pmatrix} H^{\pm} \\ \frac{1}{\sqrt{2}}(h_2 + ih_3) \end{pmatrix}$$

Davidson and Haber (2005)

$$\begin{aligned} V = &-Y_1^2 \boldsymbol{H}_1^\dagger \boldsymbol{H}_1 - Y_2^2 \boldsymbol{H}_2^\dagger \boldsymbol{H}_2 - \left(Y_3^2 \boldsymbol{H}_1^\dagger \boldsymbol{H}_2 + \mathrm{h.c.}\right) \\ &+ \frac{1}{2} Z_1 \left(\boldsymbol{H}_1^\dagger \boldsymbol{H}_1\right)^2 + \frac{1}{2} Z_2 \left(\boldsymbol{H}_2^\dagger \boldsymbol{H}_2\right)^2 + Z_3 \left(\boldsymbol{H}_1^\dagger \boldsymbol{H}_1\right)\left(\boldsymbol{H}_2^\dagger \boldsymbol{H}_2\right) + Z_4 \left(\boldsymbol{H}_1^\dagger \boldsymbol{H}_2\right)\left(\boldsymbol{H}_2^\dagger \boldsymbol{H}_1\right) \\ &+ \left\{\left(\frac{1}{2} Z_5 \boldsymbol{H}_1^\dagger \boldsymbol{H}_2 + Z_6 \boldsymbol{H}_1^\dagger \boldsymbol{H}_1 + Z_7 \boldsymbol{H}_2^\dagger \boldsymbol{H}_2\right) \boldsymbol{H}_1^\dagger \boldsymbol{H}_2 + \mathrm{h.c.}\right\} \end{aligned} \qquad (Y_3^2, Z_5, Z_6, Z_7 \in \mathbb{C})$$

- **Most general Yukawa sector**

$$\mathcal{L}_Y = -\sum_{k=1,2} \left(\overline{Q_L} Y_{k,u}^\dagger \widetilde{\boldsymbol{H}}_k u_R + \overline{Q_L} Y_{k,d} \boldsymbol{H}_k d_R + \overline{L_L} Y_{k,l} \boldsymbol{H}_k e_R + \mathrm{h.c.}\right)$$

$$Y_{1,u} = \mathrm{diag}(y_u, y_c, y_t) \qquad Y_{1,d} = \mathrm{diag}(y_d, y_s, y_b) \qquad Y_{1,l} = \mathrm{diag}(y_e, y_\mu, y_\tau)$$

- **$\boldsymbol{Y}_2$ is general complex matrix**

Ex) Up type sector

$$Y_{2,u} = \begin{pmatrix} \rho_{uu} & \rho_{cu} & \rho_{tu} \\ \rho_{uc} & \rho_{cc} & \rho_{tc} \\ \rho_{ut} & \rho_{ct} & \rho_{tt} \end{pmatrix}$$

General two Higgs doublet model

- **Stationary conditions and mass spectra**

$$\frac{\partial V}{\partial h_i} = 0 \;\Leftrightarrow\; Y_1^2 = \frac{1}{2}\lambda_1 v^2,\; Y_3^2 = \frac{1}{2}\lambda_6 v^2$$

Absorbed by phase redefinition for H_2

$$\frac{\partial^2 V}{\partial h_i \partial h_j} = \mathcal{M}_{ij}^n = \begin{pmatrix} Z_1 v^2 & \mathrm{Re}[Z_6]v^2 & -\mathrm{Im}[Z_6]v^2 \\ \mathrm{Re}[Z_6]v^2 & -Y_2^2 + \frac{1}{2}(Z_3 + Z_4 + Z_5)v^2 & -\frac{1}{2}\mathrm{Im}[Z_5] \\ -\mathrm{Im}[Z_6]v^2 & -\frac{1}{2}\mathrm{Im}[Z_5] & -Y_2^2 + \frac{1}{2}(Z_3 + Z_4 - Z_5)v^2 \end{pmatrix}$$

$$m_{H^\pm}^2 = -Y_2^2 + \frac{1}{2}Z_3 v^2$$

- **Neutral scalar mixing by Z_6**

ATLAS, Nature (2022);
CMS, Nature (2022);

125 GeV Higgs

Orthogonal matrix R

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix}, \qquad R^T \mathcal{M}^n R = \mathrm{diag}(m_{H_1}, m_{H_2}, m_{H_3})$$

Custodial symmetry

Pomarol and Vega (1994), Gerard and Herquet (2007), Haber and O'Neil (2011);

- **Two conditions for custodial symmetric Higgs potential**

(Usual)

$Z_4 = Z_5, \ \ \mathrm{Im}[Z_6] = \mathrm{Im}[Z_7] = 0$

(Twisted)

$Z_4 = -Z_5, \ \ \mathrm{Re}[Z_6] = \mathrm{Re}[Z_7] = 0$

- **Relation with CP violation**

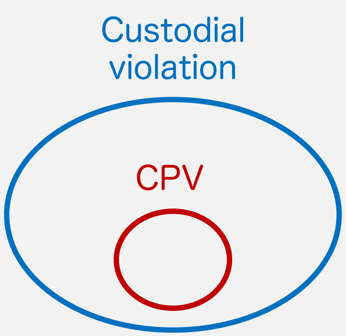
For CP violating potential, at least one of $\mathrm{Im}[Z_6^2], \mathrm{Im}[Z_7^2], \mathrm{Im}[Z_6^* Z_7]$

must be non-zero (Taking $\mathrm{Im}[Z_5] = 0$ basis)

Cf.) ($Z_6 = 0$ limit)

$Z_4 + Z_5 \propto m_{H_2}^2 - m_{H^\pm}^2$

$Z_4 - Z_5 \propto m_{H_3}^2 - m_{H^\pm}^2$



- $\boldsymbol{H^\pm \to W^\pm Z}$ **decay with** $\boldsymbol{Z_6 \simeq 0}$ **(alignment limit)**

$$\mathcal{M} \sim \frac{i\,\mathrm{Re}[Z_7]}{16\pi^2 v}\left(m_{H^\pm}^2 - m_{H_3}^2\right) \times (\text{loop functions})$$ ← known part

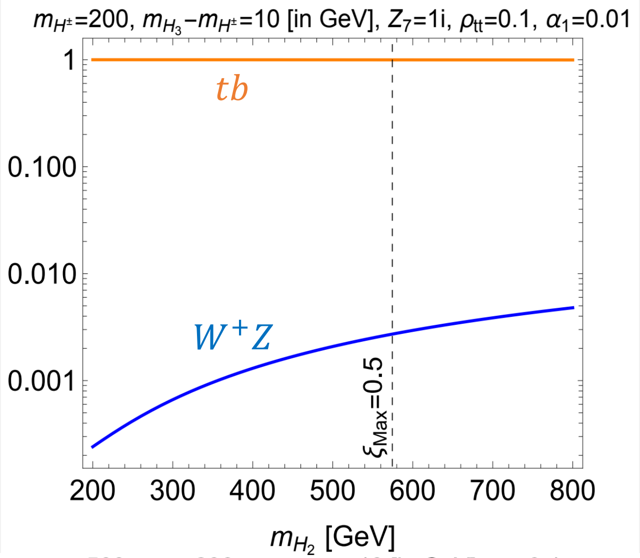
$$+\frac{\mathrm{Im}[Z_7]}{16\pi^2 v}\left(m_{H^\pm}^2 - m_{H_2}^2\right) \times (\text{loop functions})$$ ← new part (general 2HDM)

- **We have calculated full $\boldsymbol{H^\pm \to W^\pm Z}$ decay in the most general setup of 2HDM (non-alignment, CPV, general Yukawa)**

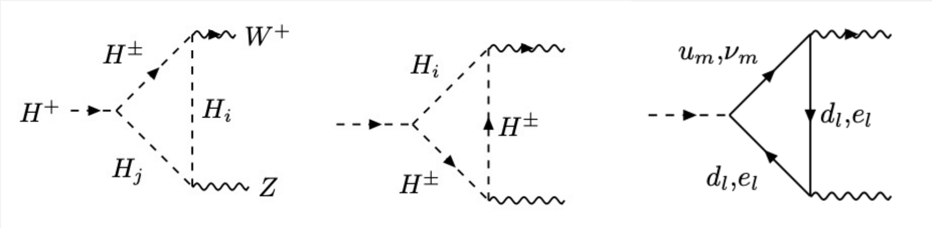
S. Kanemura and **Y.M.**, arXiv:2408.06863

Branching ratio and CP asymmetry

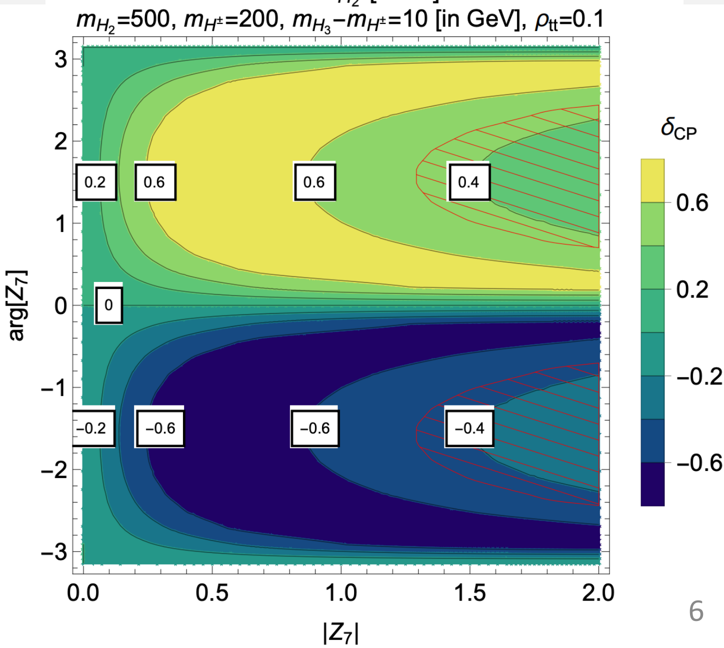
- **Branching ratio for $H^+ \to XY$ ($\rho_{ij} = 0$ except for ρ_{tt})**
  - Custodial symmetry violation $\propto m_{H_2} - m_{H^\pm}$ and Z_7^I
  - For $m_{H^\pm} < m_{H_2}$, main modes are $H^\pm \to tb, WZ, WH_1$.
  - If $m_{H^\pm} < m_W + m_{H_1}$, $\mathrm{Br}(H^\pm \to W^\pm Z)$ can be large.



- **Asymmetry b/w $H^+ \to W^+Z$ and $H^- \to W^-Z$ is sensitive to $\mathrm{Im}[\rho^f Z_7]$.**



$$\delta_{CP} \equiv \frac{\Gamma(H^+ \to W^+Z) - \Gamma(H^- \to W^-Z)}{\Gamma(H^+ \to W^+Z) + \Gamma(H^- \to W^-Z)}$$



Conclusion

- **Additional CP violation is necessary for baryon asymmetry of the Universe**
  - Insufficient CP violation in the SM
  - Enough CP violation can be introduced in 2HDM

- **CP violation and custodial symmetry violation**
  - CP violating 2HDM breaks custodial symmetry in the potential
  - New contributions in loop induced $H^{\pm}W^{\mp}Z$ vertex

- **$\boldsymbol{H^{\pm} \to W^{\pm}Z}$ decay in CP violating general 2HDM**
  - We calculated $H^{\pm} \to W^{\pm}Z$ decay with the most general setup in 2HDM
  - We find CP phases cause asymmetry b/w H^{+} and H^{-} decays

Back up

S. Kanemura and **Y.M.**, arXiv:2408.06863

Impacts on collider phenomenology

- **Benchmark points**

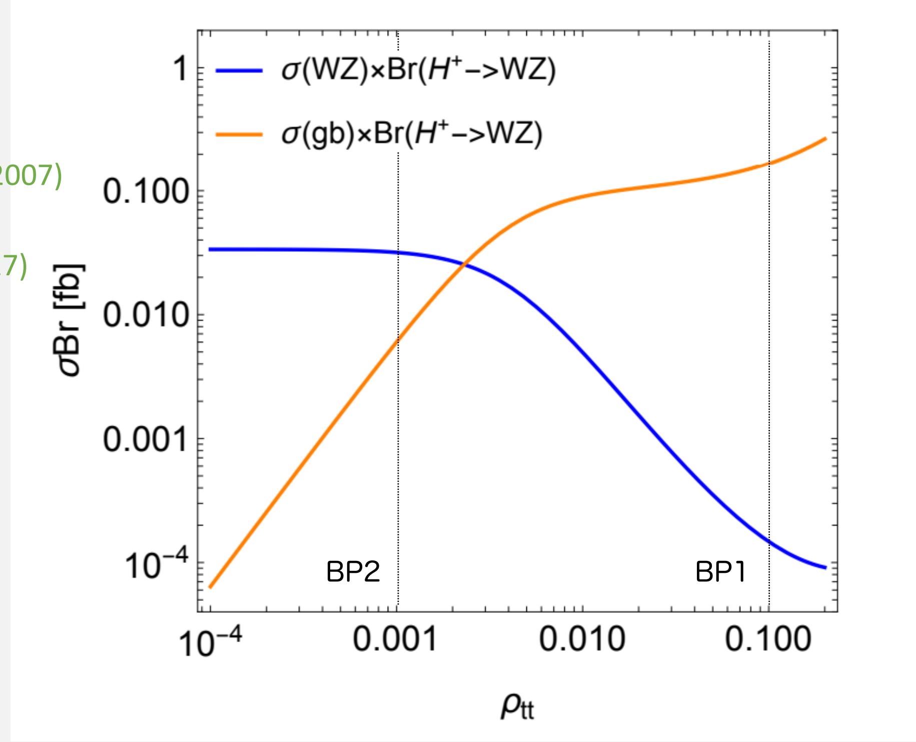
(in GeV)	$m_{H^\pm}$	m_{H_2}	m_{H_3}	Z_7	ρ_{tt}	$\alpha_1 = -\alpha_2$
BP1 (large ρ_{tt})	200	500	210	$1.3e^{2.0i}$	0.1	0.01
BP2 (small ρ_{tt})	200	500	210	$1.3e^{2.0i}$	0.001	0.01

- **Production of $H^\pm$ in hadron collider**

$pp(WZ) \to H^\pm + X$ Asakawa, Kanemura, and Kanzaki (2007)

$gb \to \bar{t}H^\pm$ LHC Higgs Cross Section Working Group (2017)

	BP1	BP2
$\lvert F\rvert^2$	2.8×10^{-5}	1.7×10^{-5}
$\mathrm{Br}(H^+ \to W^+ Z)$	2.6×10^{-3}	9.4×10^{-1}
σ_{WZ} [fb]	5.6×10^{-2}	3.4×10^{-2}
$\sigma_{WZ} \times \mathrm{Br}$ [fb]	1.5×10^{-4}	3.2×10^{-2}
σ_{gb} [fb]	6.4×10	6.4×10^{-3}
$\sigma_{gb} \times \mathrm{Br}$ [fb]	1.7×10^{-1}	6.0×10^{-3}



At HL-LHC ($3000\ \mathrm{fb}^{-1}$), O(100) events are expected.

S. Kanemura and **Y.M.**, arXiv:2408.06863

Impacts on collider phenomenology

- **Benchmark points**

large ρ_{tt}

small ρ_{tt}

(in GeV)	$m_{H^\pm}$	m_{H_2}	m_{H_3}	Z_7	ρ_{tt}	$\alpha_1 = -\alpha_2$
BP1	200	500	210	$1.3e^{2.0i}$	0.1	0.01
BP2	200	500	210	$1.3e^{2.0i}$	0.001	0.01

- **Production of $H^\pm$ in e+e- collider**
  - Pair production process $e^+e^- \to H^+H^-$ S. Komamiya, Phys. Rev. D (1988)
  - $\sigma(e^+e^- \to H^+H^-) \simeq 30$ fb (ILC 500 GeV)

- **At BP2, almost all H^+ decay into W^+Z**
  - When $3\ \mathrm{ab}^{-1}$ integrated luminosity is assumed, $O(10^5)$ events can be expected

- **Testing $H^\pm W^\mp Z$ vertex in the general 2HDM motivates future colliders**

$H^{\pm}W^{\mp}Z$ vertex

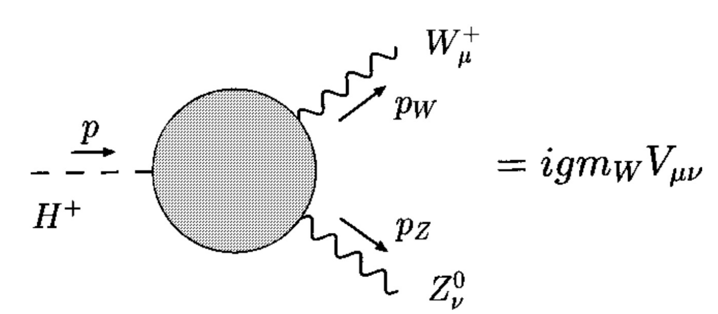


Fig. from S. Kanemura, Phys.Rev.D 61 (2000) 095001

$$V_{\mu\nu} = F g_{\mu\nu} + \frac{G}{m_W^2} p_{Z,\mu} p_{W,\nu} + \frac{H}{m_W^2} \epsilon_{\mu\nu\rho\sigma} p_Z^\rho p_W^\sigma$$

Parity violation

$$\Gamma = \frac{m_{H^\pm} \lambda^{1/2}(1, w, z)}{16\pi} \left(|\mathcal{M}_{LL}|^2 + |\mathcal{M}_{TT}|^2 \right) \qquad w = \frac{m_W^2}{m_{H^\pm}^2},\ z = \frac{m_Z^2}{m_{H^\pm}^2}$$

$$|\mathcal{M}_{LL}|^2 = \frac{g^2}{4z} \left| (1 - w - z) F + \frac{\lambda(1,2,z)}{2w} G \right|^2$$

$$|\mathcal{M}_{TT}|^2 = \frac{g^2}{4z} \left(2w|F|^2 + \frac{\lambda(1,2,z)}{2w} |H|^2 \right)$$

$$\Rightarrow \frac{|\mathcal{M}_{TT}|^2}{|\mathcal{M}_{LL}|^2} \propto \frac{m_W^2 m_Z^2}{m_{H^\pm}^4}$$

- Effectively,

$$\mathcal{L}_{eff} = f H^+ W_\mu^- Z^\mu + g H^+ F_Z^{\mu\nu} F_{\mu\nu}^W + h\, i\epsilon_{\mu\nu\rho\sigma} H^+ F_Z^{\mu\nu} F_W^{\rho\sigma} + \text{h.c.}$$

$f \propto \frac{M_i^2}{v}$: Non-decoupling effects provide leading contribution

Equivalence theorem

Lee, Quigg and Thacker (1977)

- Partition function for the Green functions

$$Z[J_L] = -i \log \int (dV_\mu \, d\phi \ldots) \ \exp\left[iS_{eff} + \int d^4x \, J_L V_L\right] \prod \delta(\partial^\mu V_\mu + iM\phi)$$

$$\widetilde{V_L}(k) = \epsilon_L^\mu \widetilde{V_\mu}(k) \qquad \epsilon_L^\mu = \frac{1}{M}(|\boldsymbol{k}|, 0, 0, k_0)$$

V: (massive) gauge boson
ϕ : NG boson

- Gauge fixing condition

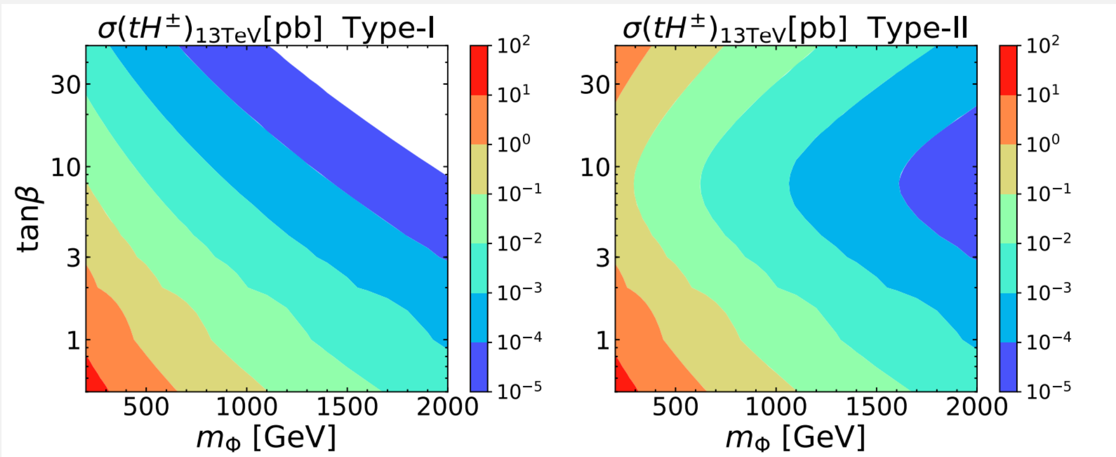
$$\partial^\mu V_\mu + iM\phi = 0 \quad \Rightarrow \quad \frac{k^\mu}{M} \widetilde{V_\mu} = \tilde{\phi}$$

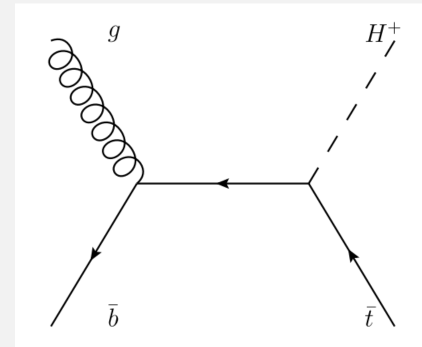
$$\widetilde{V_L}(k) = \frac{k^\mu}{M} \widetilde{V_\mu} + O(M/k_0) = \tilde{\phi} + O(M/k_0)$$

- For $M/k_0 \ll 1$, external line for longitudinal gauge boson can be replaced by NG boson

Production for $H^{\pm}$

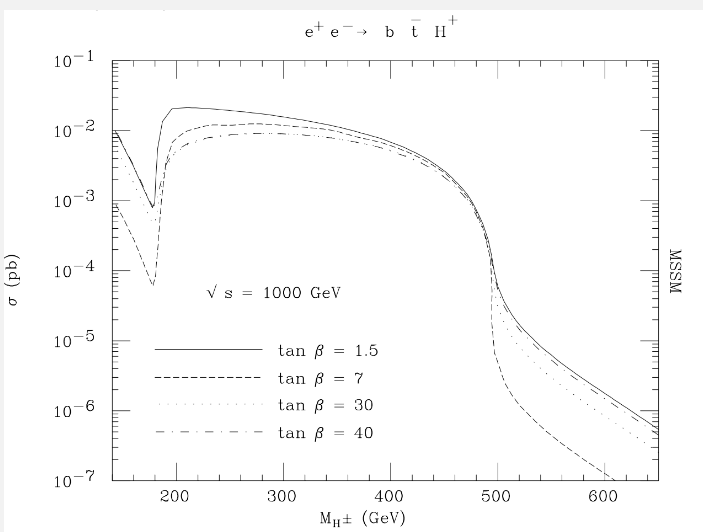
Aiko, Kanemura, Kikuchi, Mawatari and Sakurai, Nucl.Phys.B 966 (2021)



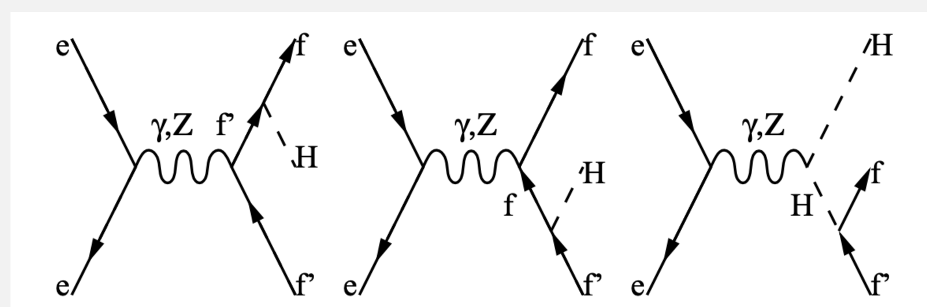


ATLAS, Phys. lett. B 759 (2016) 555

Kanemura, Moretti and Odagiri, JHEP02 (2001) 011

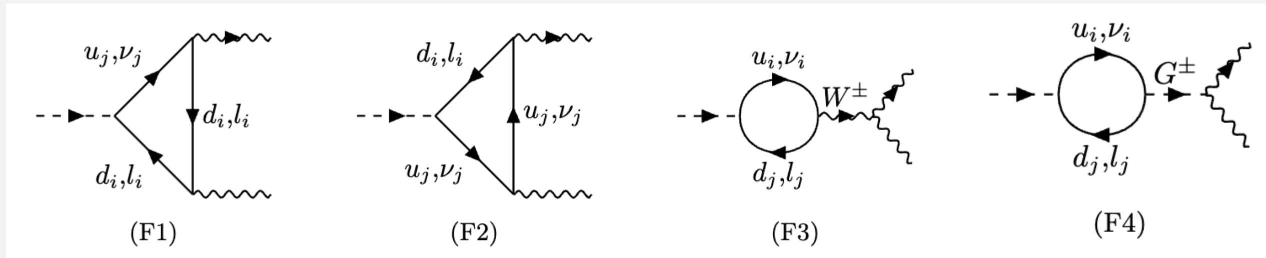


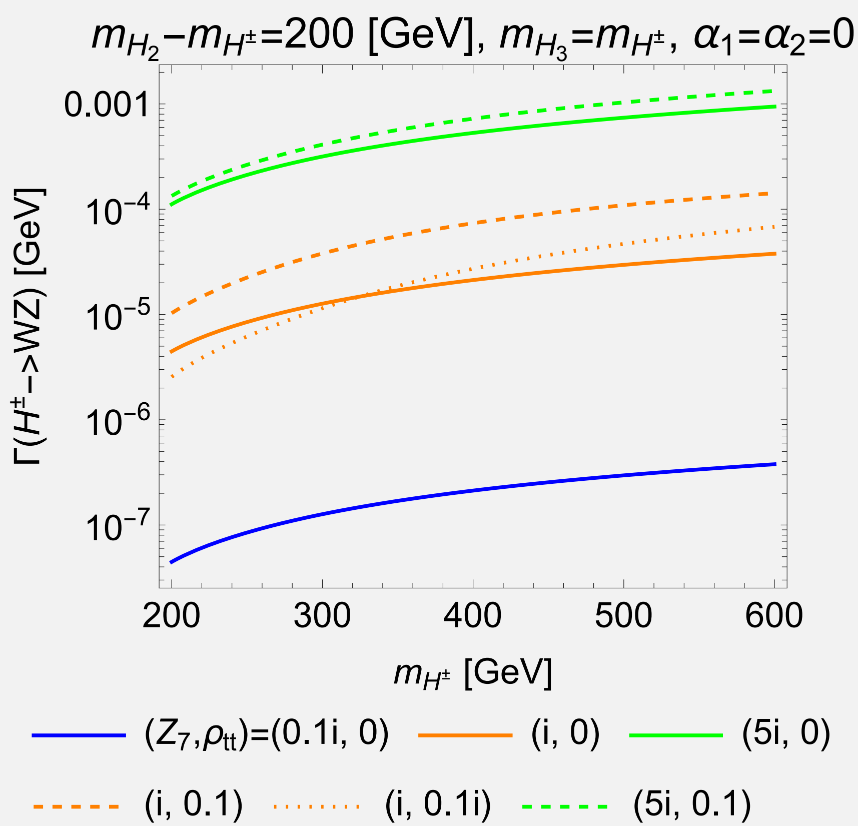
$$W^+W^-Z \to \begin{cases} 2j + 3l + E_T \; (\simeq 1/25 \times \varepsilon_b) \\ 4j + 1l + E_T \; (\simeq 7/25 \times \varepsilon_b) \end{cases}$$

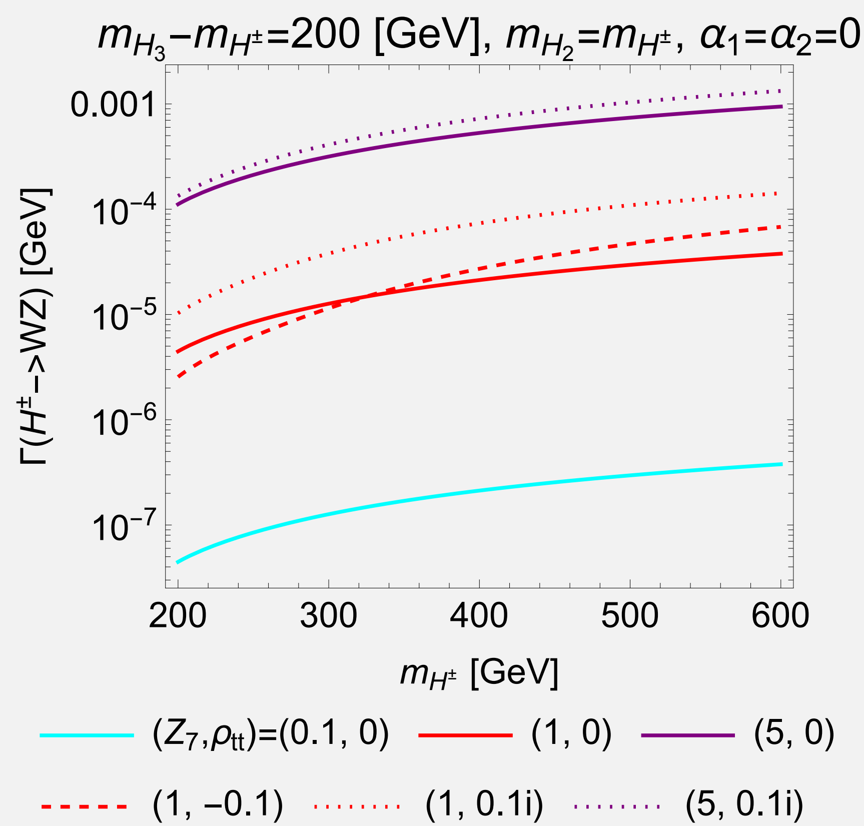


Fermion contributions

- Fermion contribution

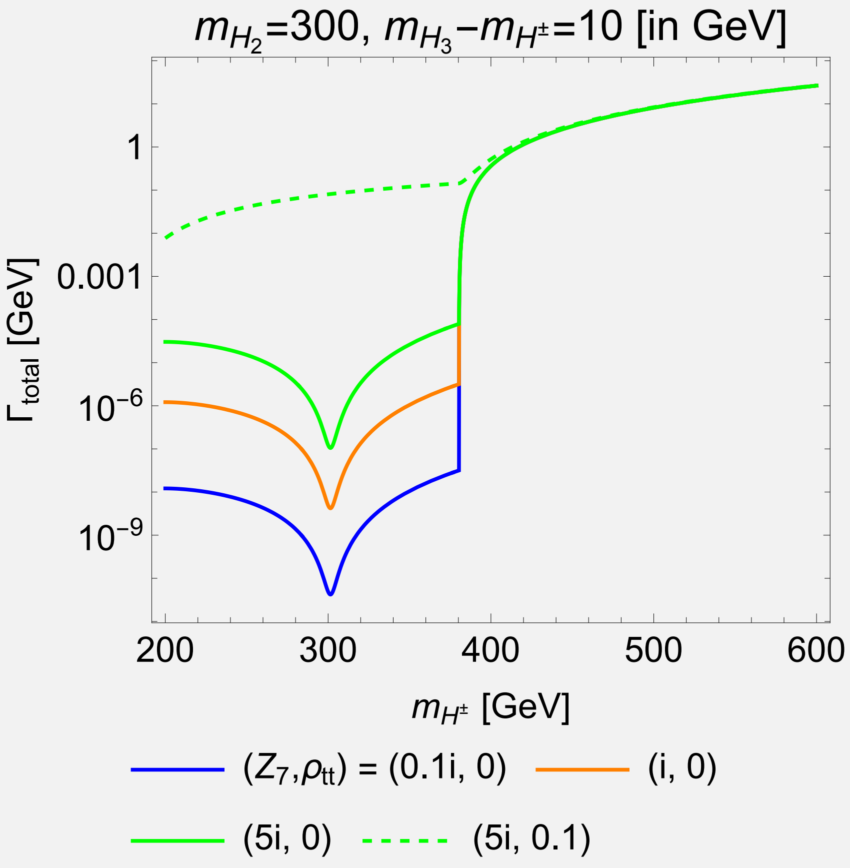


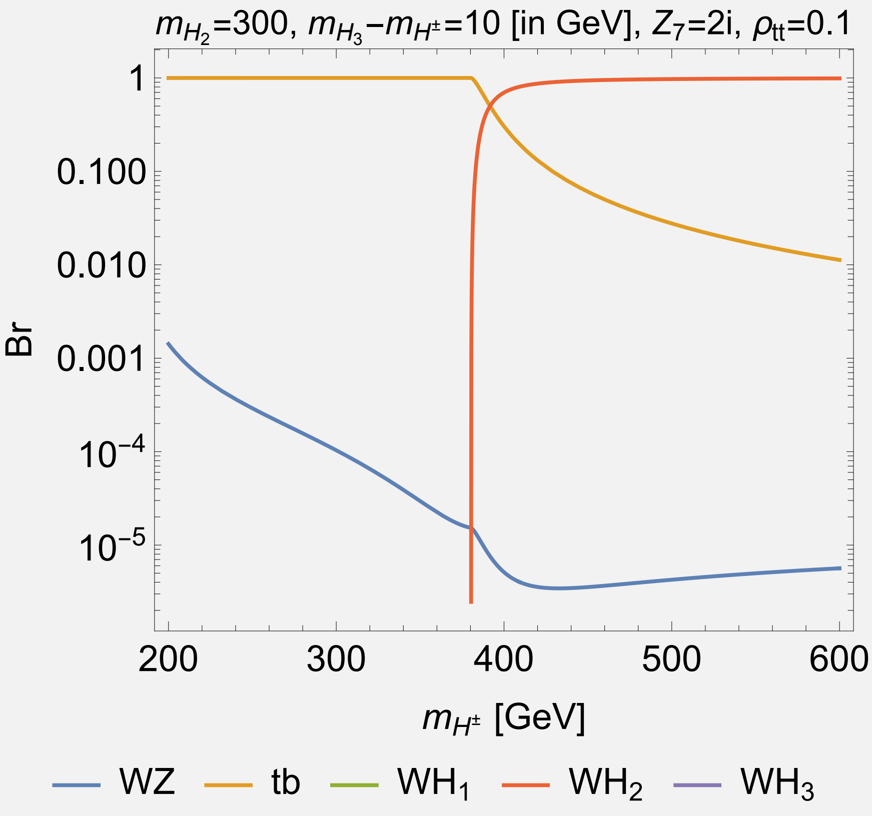




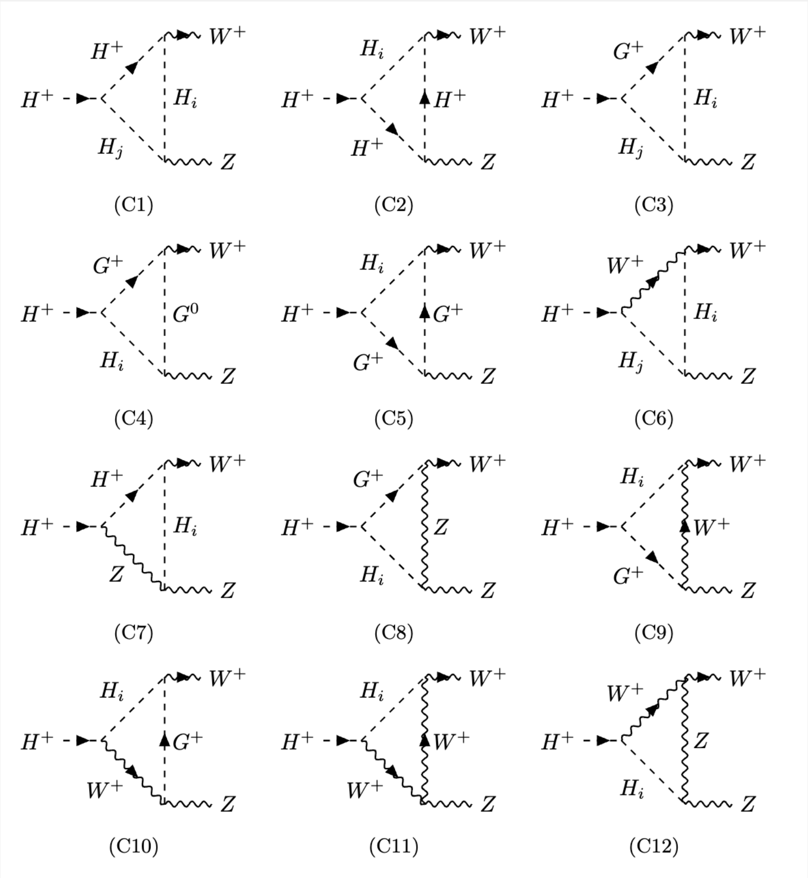
$m_{H_2} < m_{H^\pm}$ scenario

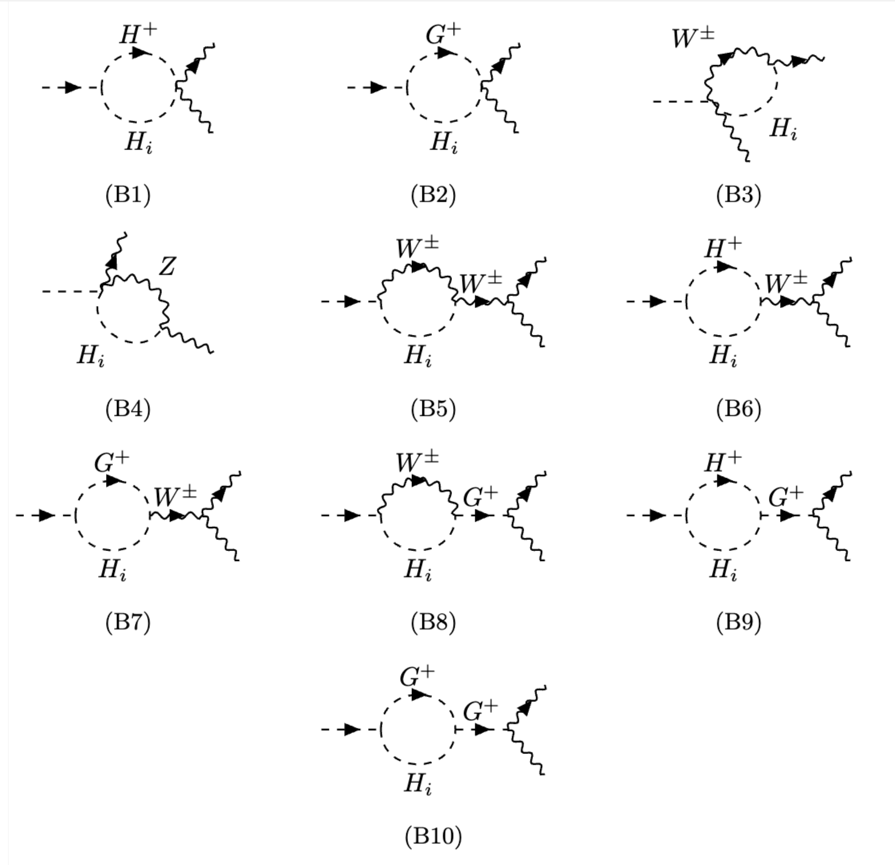
- After $H^\pm \to W^\pm H_2$ open, $H^\pm \to W^\pm Z$ is suppressed

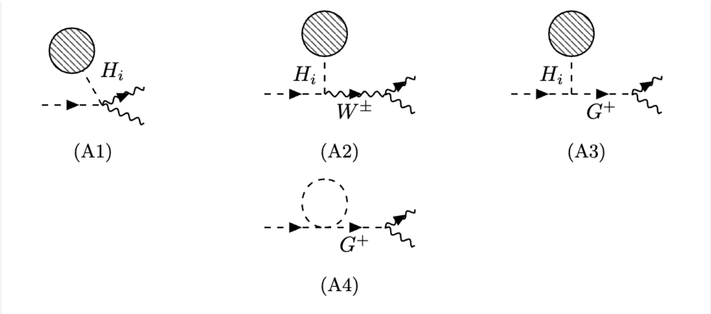




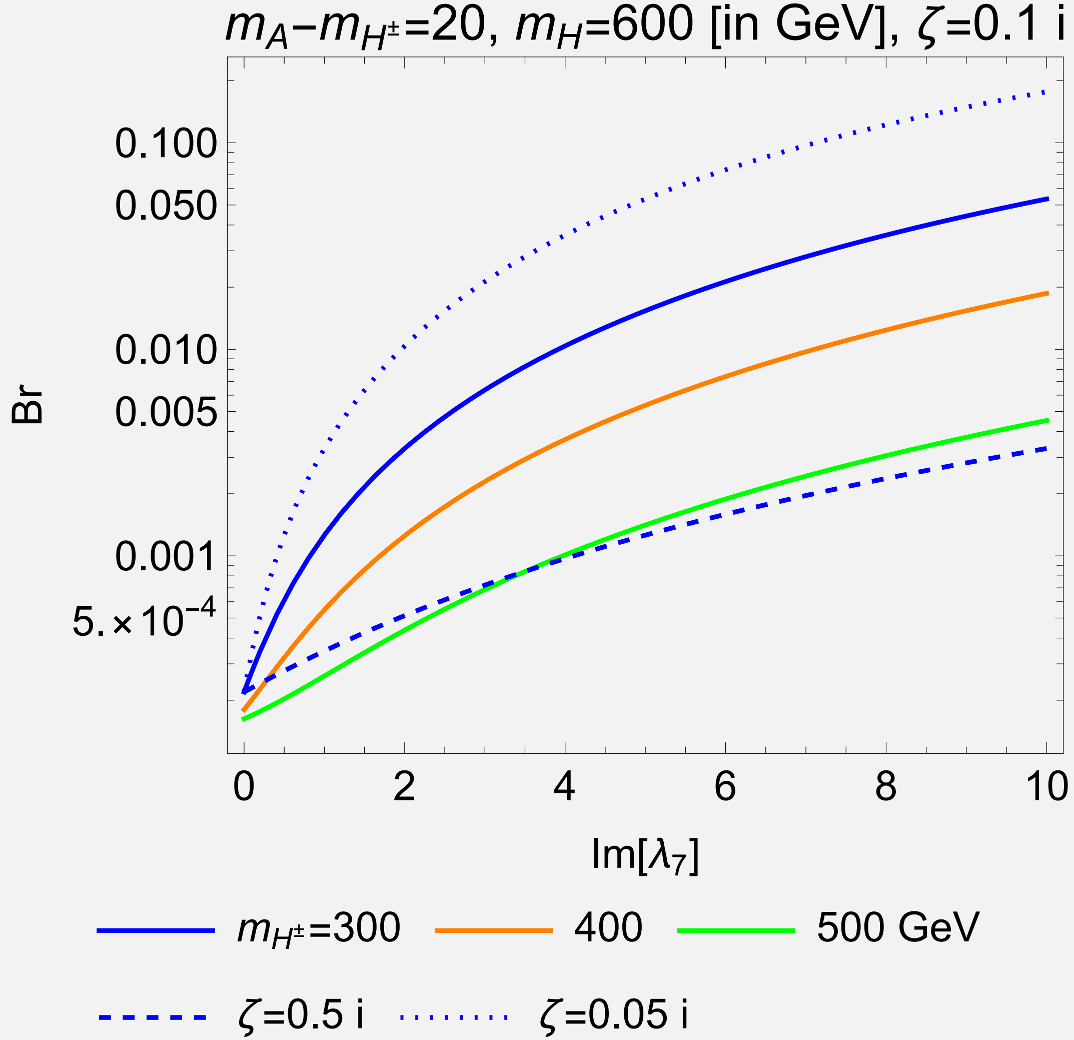
Diagrams


H+ W+ Hi Hj Z
(C1)
Hi W+ H+ H+ H+ Z
(C2)
G+ W+ H+ Hi Hj Z
(C3)
G+ W+ H+ G0 Hi Z
(C4)
Hi W+ H+ G+ G+ Z
(C5)
W+ W+ H+ Hi Hj Z
(C6)
H+ W+ H+ Hi Z Z
(C7)
G+ W+ H+ Z Hi Z
(C8)
Hi W+ H+ W+ G+ Z
(C9)
Hi W+ H+ G+ W+ Z
(C10)
Hi W+ H+ W+ W+ Z
(C11)
W+ W+ H+ Z Hi Z
(C12)

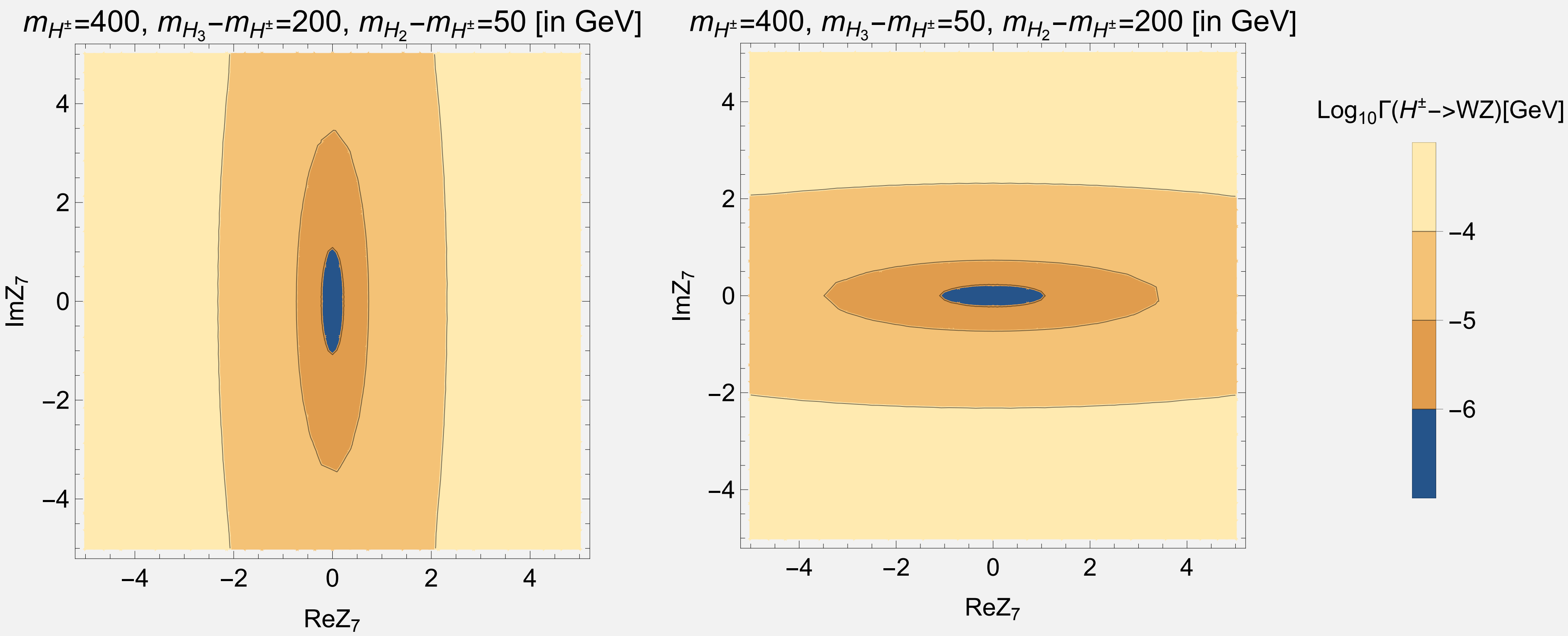

H+ Hi
(B1)
G+ Hi
(B2)
W± Hi
(B3)
Z Hi
(B4)
W± W± Hi
(B5)
H+ W± Hi
(B6)
G+ W± Hi
(B7)
W± G+ Hi
(B8)
H+ G+ Hi
(B9)
G+ G+ Hi
(B10)


Hi
(A1)
Hi W±
(A2)
Hi G+
(A3)
G+
(A4)

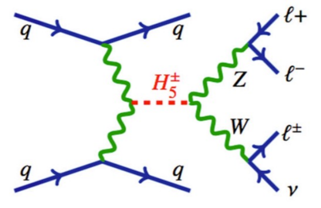
Z_7 dependence



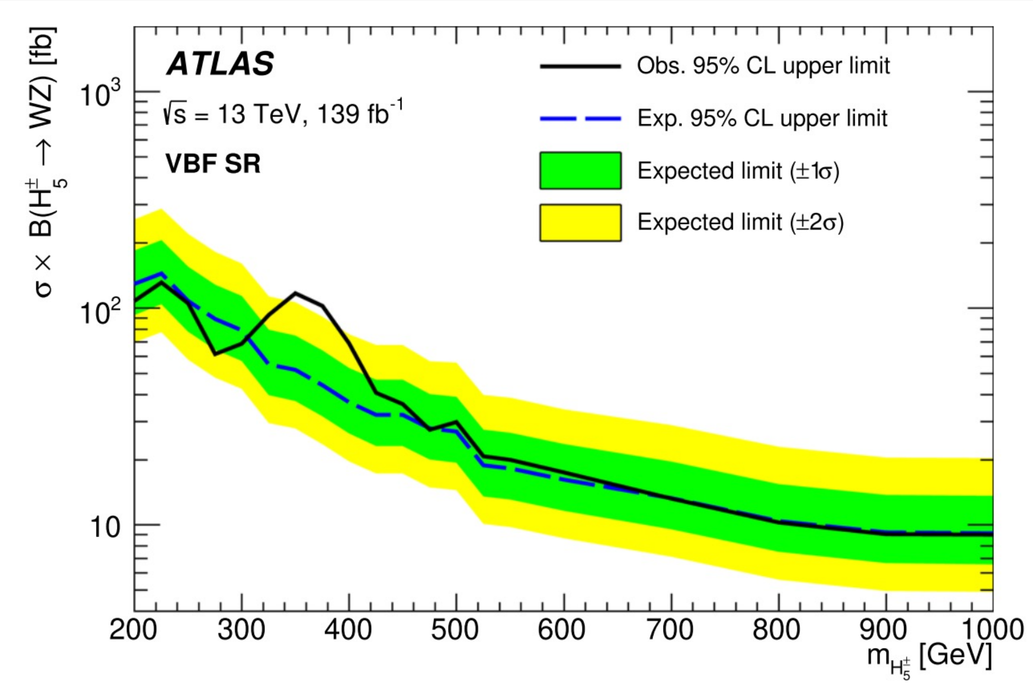
Contour in Z_7 plane



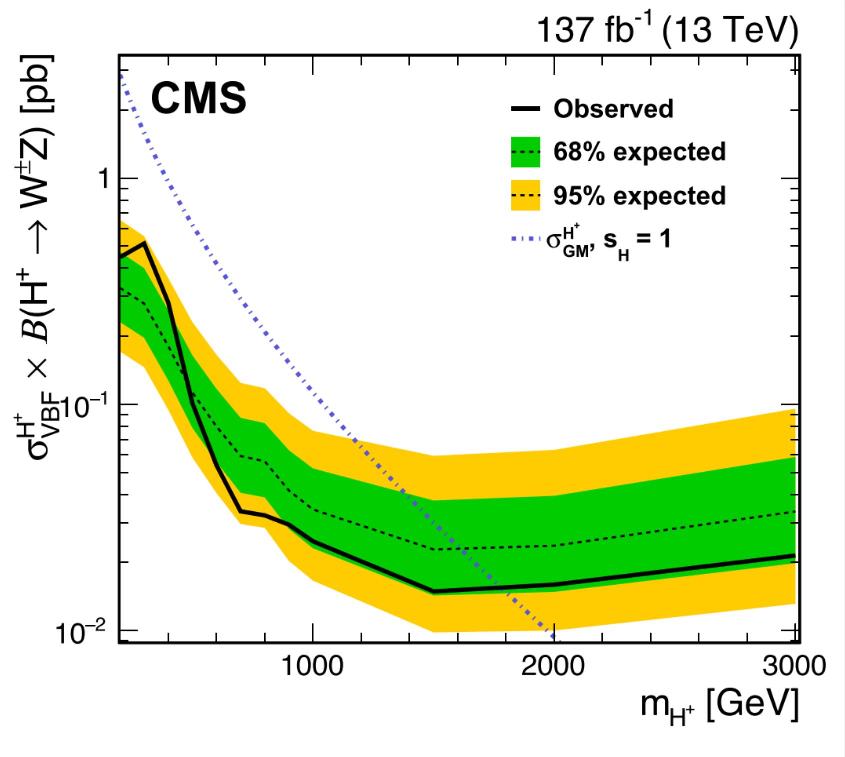
Current data



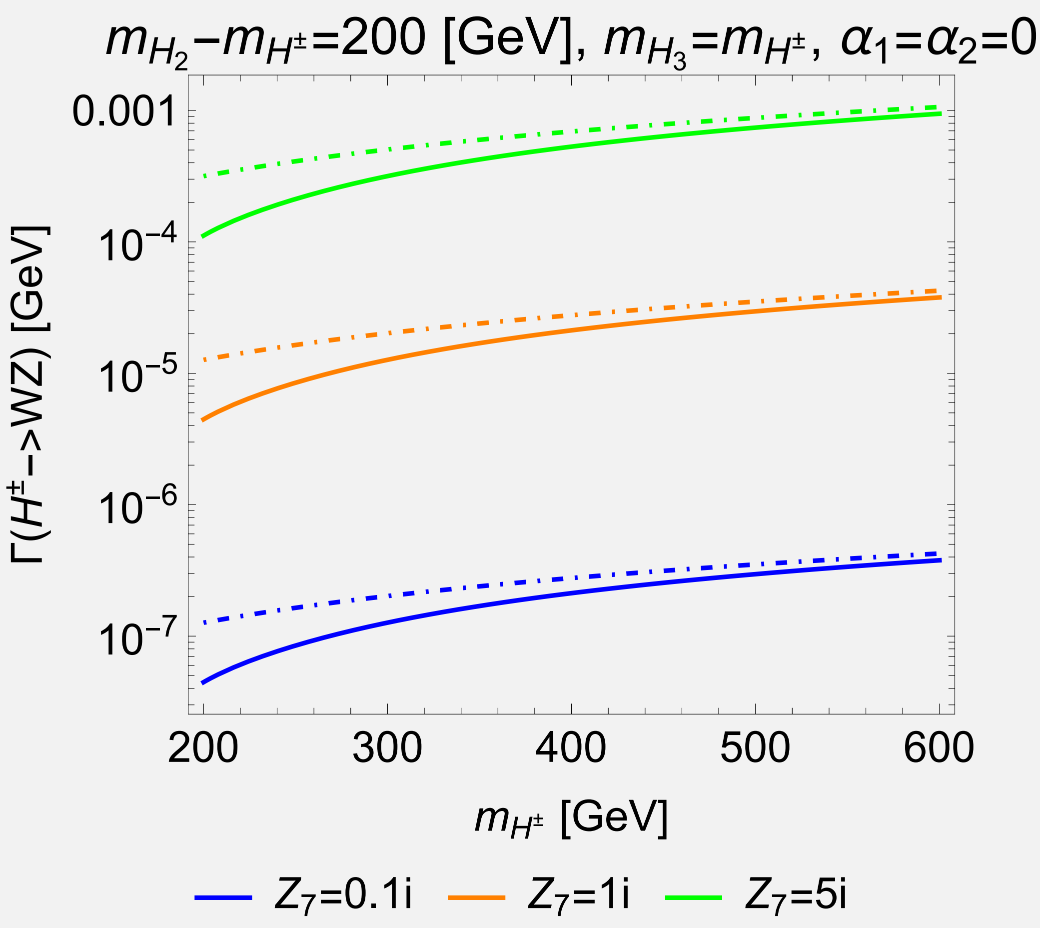
ATLAS, Eur. Phys. J. C (2023) 83:633



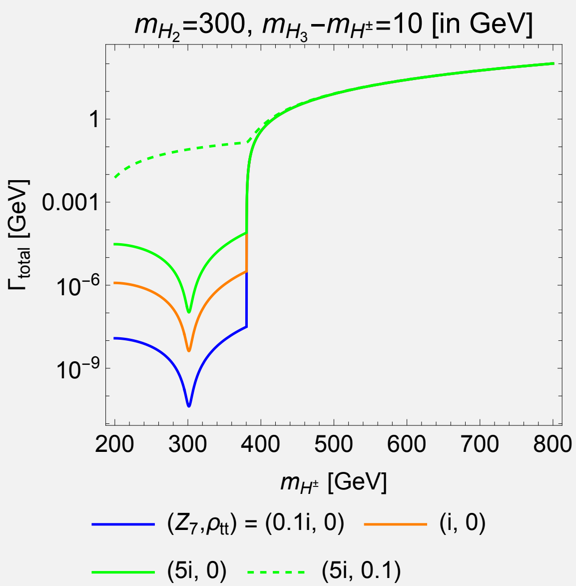
CMS, Eur. Phys. J. C 81 (2021) 8, 723

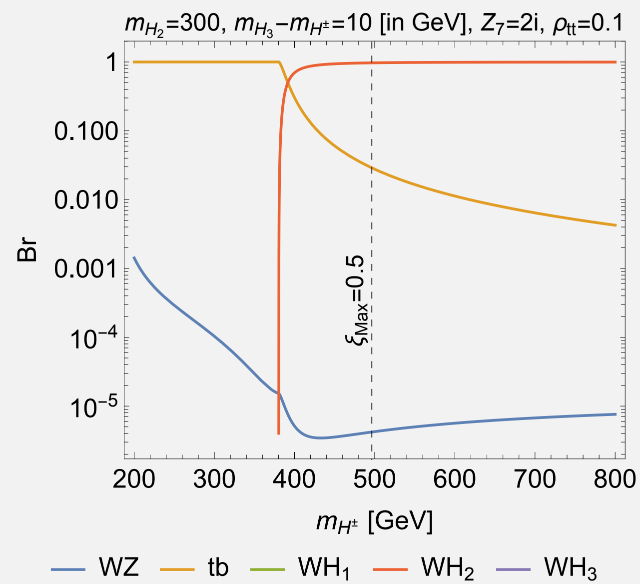


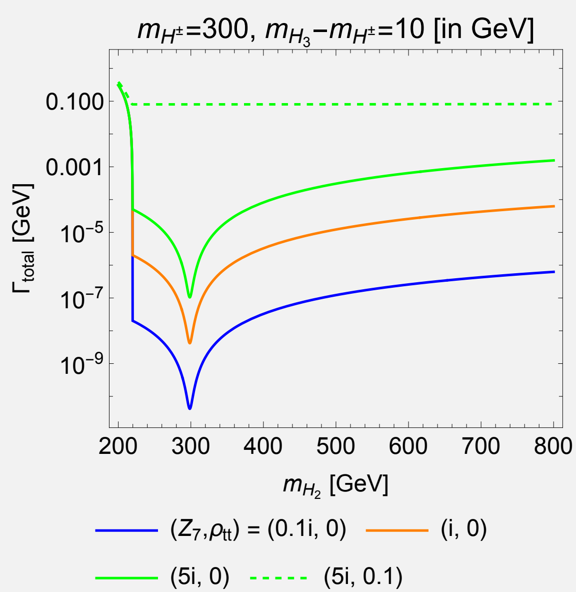
Comparing to equivalence theorem

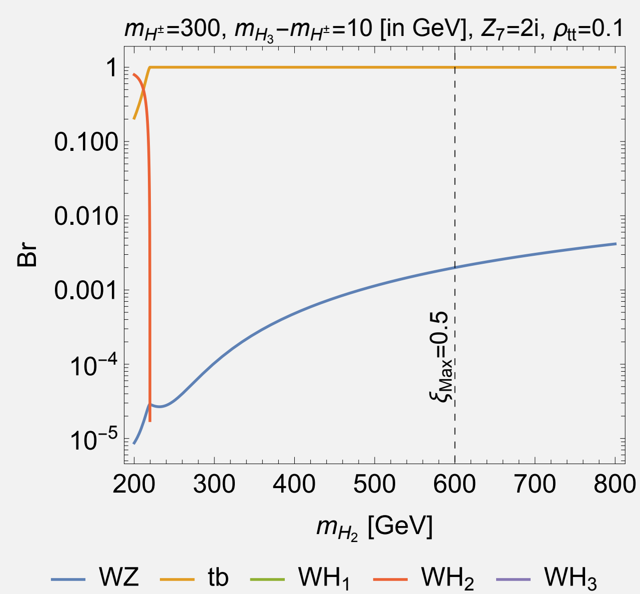


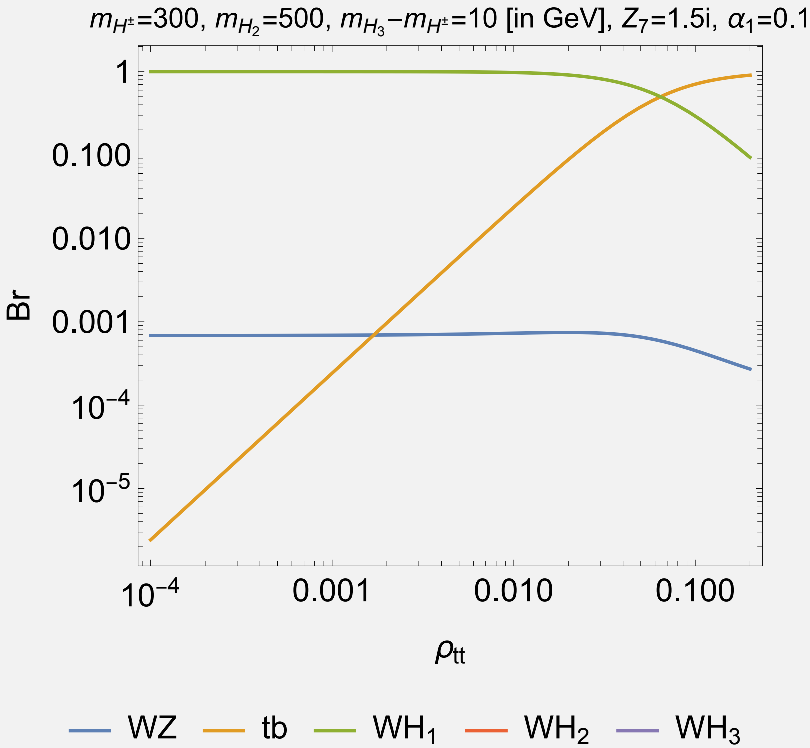
Supplement figures

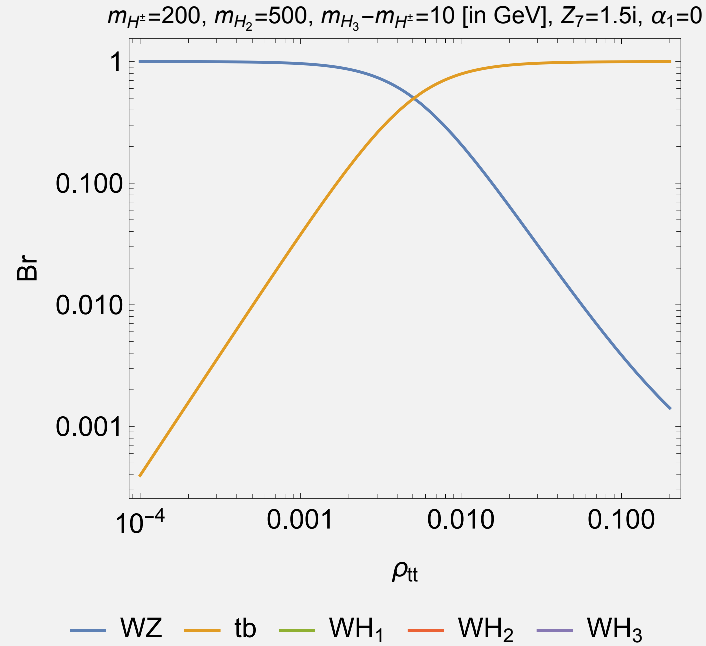


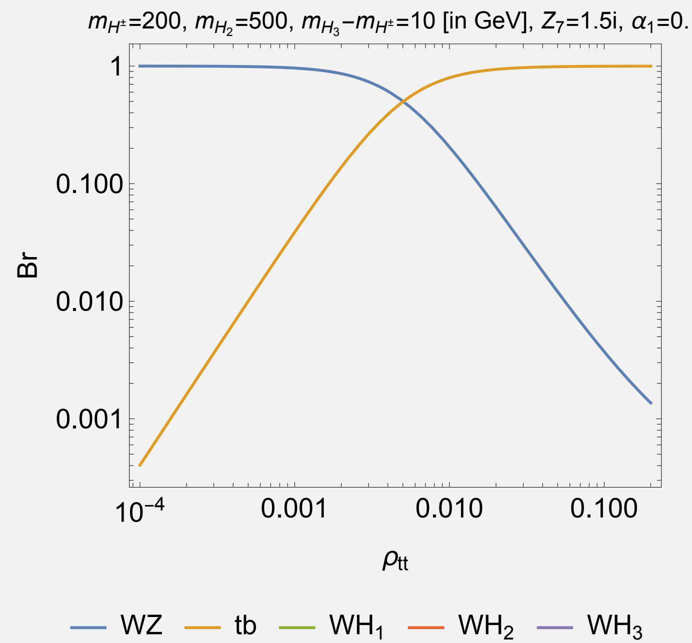







$m_{H^{\pm}}$=300, m_{H_2}=500, $m_{H_3}-m_{H^{\pm}}$=10 [in GeV], Z_7=1.5i, α_1=0.1
Br
1
0.100
0.010
0.001
10^{-4}
10^{-5}
10^{-4}
0.001
0.010
0.100
ρ_{tt}
WZ
tb
WH_1
WH_2
WH_3


$m_{H^{\pm}}$=200, m_{H_2}=500, $m_{H_3}-m_{H^{\pm}}$=10 [in GeV], Z_7=1.5i, α_1=0
Br
1
0.100
0.010
0.001
10^{-4}
0.001
0.010
0.100
ρ_{tt}
WZ
tb
WH_1
WH_2
WH_3


$m_{H^{\pm}}$=200, m_{H_2}=500, $m_{H_3}-m_{H^{\pm}}$=10 [in GeV], Z_7=1.5i, α_1=0.1
Br
1
0.100
0.010
0.001
10^{-4}
0.001
0.010
0.100
ρ_{tt}
WZ
tb
WH_1
WH_2
WH_3

Custodial symmetry

- **Bi-linear form** $\mathbb{M}_1 = (\tilde{\boldsymbol{H}}_1, \boldsymbol{H}_1),\ \mathbb{M}_2 = (\tilde{\boldsymbol{H}}_2, \boldsymbol{H}_2)\,\mathrm{diag}(e^{-i\chi}, e^{i\chi})$

$$\mathrm{SU}(2)_L\!: \ \mathbb{M}_i \to U(x)\mathbb{M}_i, \quad \mathrm{U}(1)_Y\!: \ \mathbb{M}_i \to \mathbb{M}_i \exp(-ig'Y\alpha(x)\sigma_3)$$

Pomarol and Vega (1994)

Haber and Neil (2011)

- **Global transformation**

$$\mathbb{M}_1 \to L\mathbb{M}_1 R^\dagger$$
$$\mathbb{M}_2 \to L\mathbb{M}_2 R^\dagger$$

- **After EWSB,** $\langle \mathbb{M}_1 \rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} v & 0 \\ 0 & v \end{pmatrix},\ \langle \mathbb{M}_2 \rangle = 0$

⇨ $\langle \mathbb{M}_1 \rangle$ and $\langle \mathbb{M}_2 \rangle$ are invariant
for transformation with $L = R$ **(Custodial symmetry)**

- **Gauge invariant quantities**

$\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ inv.

$$\mathrm{Tr}[\mathbb{M}_1^\dagger \mathbb{M}_1] = 2|\boldsymbol{H}_1|^2$$
$$\mathrm{Tr}[\mathbb{M}_2^\dagger \mathbb{M}_2] = 2|\boldsymbol{H}_2|^2$$
$$\mathrm{Tr}[\mathbb{M}_1^\dagger \mathbb{M}_2] = e^{-i\chi}\boldsymbol{H}_1^\dagger \boldsymbol{H}_2 + \mathrm{h.c.}$$
$$\mathrm{Tr}[\mathbb{M}_1^\dagger \mathbb{M}_2 \sigma_3] = e^{-i\chi}\boldsymbol{H}_1^\dagger \boldsymbol{H}_2 - \mathrm{h.c.}$$

$\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ inv. (first three)

Custodial symmetry

$$\mathbb{M}_1 = (\widetilde{\boldsymbol{H}}_1, \boldsymbol{H}_1),$$
$$\mathbb{M}_2 = (\widetilde{\boldsymbol{H}}_2, \boldsymbol{H}_2)\,\mathrm{diag}(e^{-i\chi}, e^{i\chi})$$

- **Focus on Higgs potential** $\mathbb{M}_a \to L\mathbb{M}_a R^\dagger$ ($L = R$ -> Custodial symmetry)

$$V = (\text{global } \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \text{ inv. terms})$$
$$+i\,\mathrm{Im}[Y_3^2 e^{-i\chi}]\mathrm{Tr}[\mathbb{M}_1^\dagger \mathbb{M}_2 \sigma_3] - \frac{1}{4}(Z_4 - \mathrm{Re}[Z_5 e^{-2i\chi}])\mathrm{Tr}[\mathbb{M}_1^\dagger \mathbb{M}_2 \sigma_3]^2$$
$$+\frac{i}{2}\,\mathrm{Im}[Z_5 e^{-2i\chi}]\mathrm{Tr}[\mathbb{M}_1^\dagger \mathbb{M}_2]\mathrm{Tr}[\mathbb{M}_1^\dagger \mathbb{M}_2 \sigma_3]$$
$$+\frac{i}{2}\left(\mathrm{Im}[Z_6 e^{-i\chi}]\mathrm{Tr}[\mathbb{M}_1^\dagger \mathbb{M}_1] + \mathrm{Im}[Z_7 e^{-i\chi}]\mathrm{Tr}[\mathbb{M}_2^\dagger \mathbb{M}_2]\right)\mathrm{Tr}[\mathbb{M}_1^\dagger \mathbb{M}_2 \sigma_3]$$

- **Two custodial symmetry** Gerard and Herquet (2007)

Pomarol and Vega (1994)
Haber and Neil (2011)

$\chi = 0, \pi$ $\quad Z_4 = Z_5,\ \mathrm{Im}[Z_6] = \mathrm{Im}[Z_7] = 0$ (Usual)

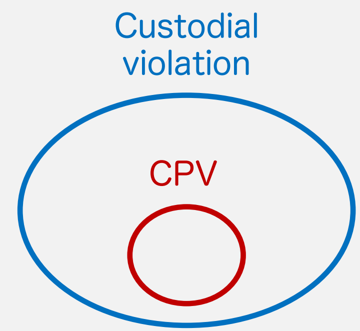
$\chi = \pi/2, 3\pi/2$ $\quad Z_4 = -Z_5,\ \mathrm{Re}[Z_6] = \mathrm{Re}[Z_7] = 0$ (Twisted)

Cf.) ($Z_6 = 0$ limit)
$Z_4 + Z_5 \propto m_{H_2}^2 - m_{H^\pm}^2$
$Z_4 - Z_5 \propto m_{H_3}^2 - m_{H^\pm}^2$

- **Relation with CP violation**

For CP violating potential, at least one of $\mathrm{Im}[Z_6^2], \mathrm{Im}[Z_7^2], \mathrm{Im}[Z_6^* Z_7]$

must be non-zero (Taking $\mathrm{Im}[Z_5] = 0$ basis)



$H^{\pm} \to W^{\pm}Z$ decay

- Loop induced $H^{\pm}W^{\mp}Z$ vertex

  cf.) ρ parameter $\rho_{\rm exp} \simeq 1$ Global fit value from PDG

  With $m_{H_2}^2 = m_{H^{\pm}}^2$ or $m_{H_3}^2 = m_{H^{\pm}}^2$, $\Delta\rho = 0$ (1 loop level) Pomarol and Vega (1994)

- $H^{\pm} \to W^{\pm}Z$ decay with $Z_6 \simeq 0$ (alignment limit)

  $m_{H^{\pm}}^2 = m_{H_3}^2$, ${\rm Im}[Z_7] = 0$ (Usual)

  $m_{H^{\pm}}^2 = m_{H_2}^2$, ${\rm Re}[Z_7] = 0$ (Twisted)

$$\mathcal{M} \sim \frac{i\,{\rm Re}[Z_7]}{16\pi^2 v}\left(m_{H^{\pm}}^2 - m_{H_3}^2\right) \times (\text{loop functions}) \quad \leftarrow \text{known part}$$

$$+\frac{{\rm Im}[Z_7]}{16\pi^2 v}\left(m_{H^{\pm}}^2 - m_{H_2}^2\right) \times (\text{loop functions}) \quad \leftarrow \text{new part (general 2HDM)}$$

- We have calculated full $H^{\pm} \to W^{\pm}Z$ decay in the most general setup of 2HDM (non-alignment, CPV, general Yukawa)

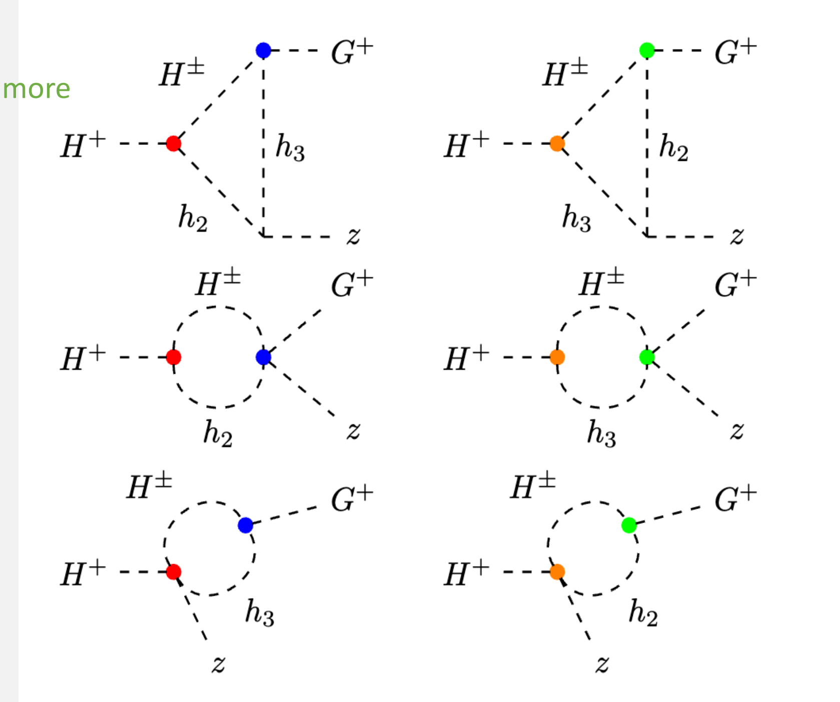
$H^{\pm} \to W^{\pm} Z$ decay

S. Kanemura and Y.M, work in progress

- **Equivalence theorem for $m_{H^{\pm}}/m_W \gg 1$**

  Cornwall, Levin and Tiktopoulos (1974); Lee, Quigg and Thacker (1977) and more

  - External (longitudinal) gauge boson becomes corresponding NG bosons
  - Here taking $Z_6 = 0$ (alignment limit)



(● ●) violate usual custodial symmetry

(● ●) violate twisted custodial symmetry

- **Decay amplitude**

$$\mathcal{M} = \frac{i\,\mathrm{Re}[Z_7]}{16\pi^2 v}\left(m_{H^{\pm}}^2 - m_{H_3}^2\right) \times (\text{loop functions}) \leftarrow \text{known part}$$

$$+ \frac{\mathrm{Im}[Z_7]}{16\pi^2 v}\left(m_{H^{\pm}}^2 - m_{H_2}^2\right) \times (\text{loop functions}) \leftarrow \text{new part (CP violating 2HDM)}$$

- **We have calculated full $H^{\pm} \to W^{\pm} Z$ decay in the most general setup of 2HDM (non-alignment, CPV, general Yukawa)**

$H^\pm \to W^\pm Z$ decay

- **Loop induced $H^\pm W^\mp Z$ vertex**

  cf.) ρ parameter $\rho_{\rm exp} \simeq 1$ Global fit value from PDG

  With $m_{H_2}^2 = m_{H^\pm}^2$ or $m_{H_3}^2 = m_{H^\pm}^2$, $\Delta\rho = 0$ (1 loop level) Pomarol and Vega (1994)

- **Analysis in CP conserving two Higgs doublet model**

  S. Kanemura, Phys.Rev.D 61 (2000) 095001

  - Z_i are not independent due to the softly broken Z2 symmetry
  - CP is conserved, so $\mathrm{Im}[Z_6] = \mathrm{Im}[Z_7] = 0$

  ⇨ Violation of usual custodial symmetry

$$Z_4 - Z_5 \propto m_{H_3}^2 - m_{H^\pm}^2 \quad (\text{If } Z_6 = 0)$$

- **CP violating case？**

  S. Kanemura and Y.M, work in progress

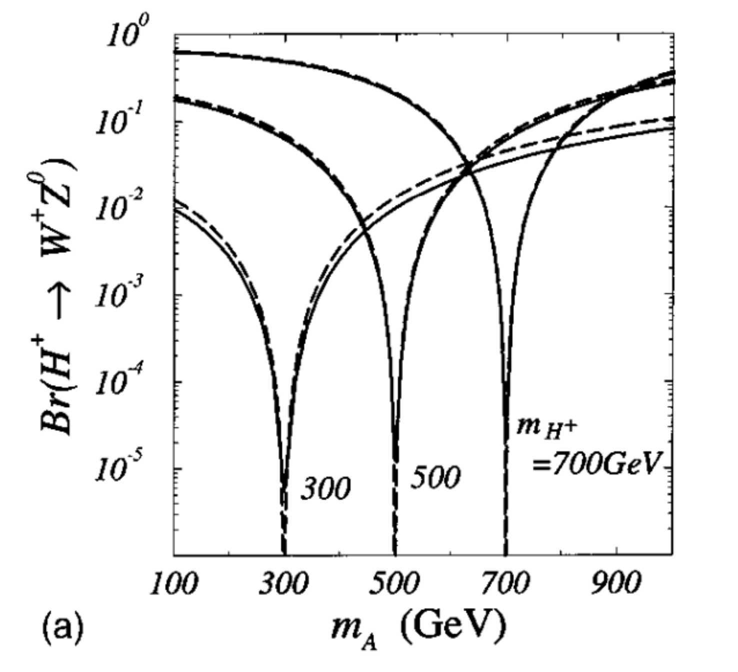
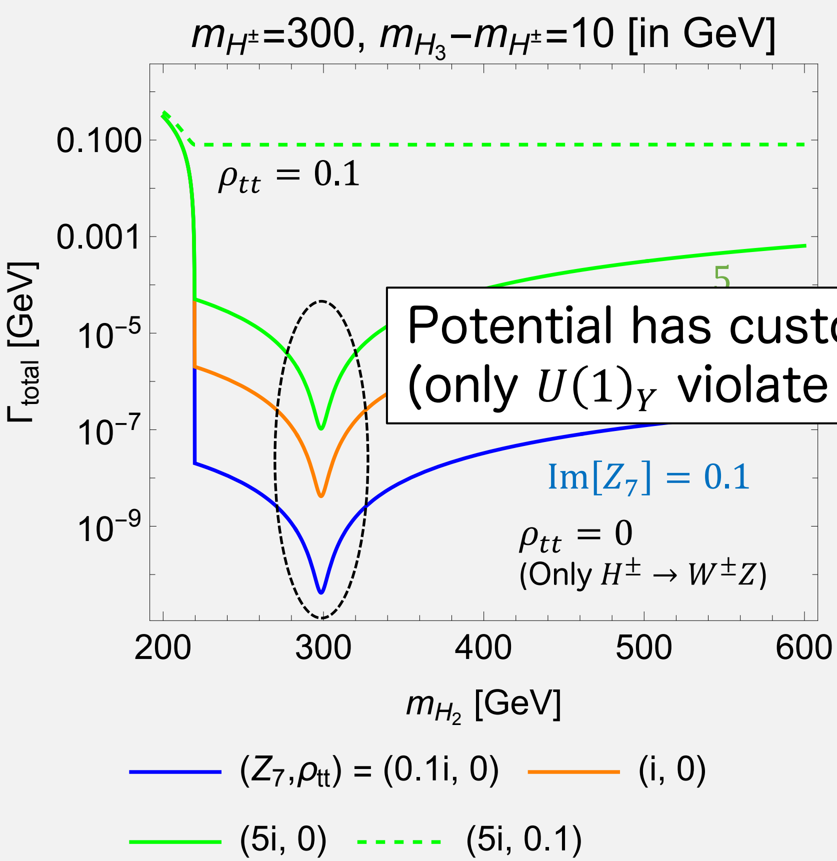


Fig. from S. Kanemura, Phys.Rev.D 61 (2000) 095001

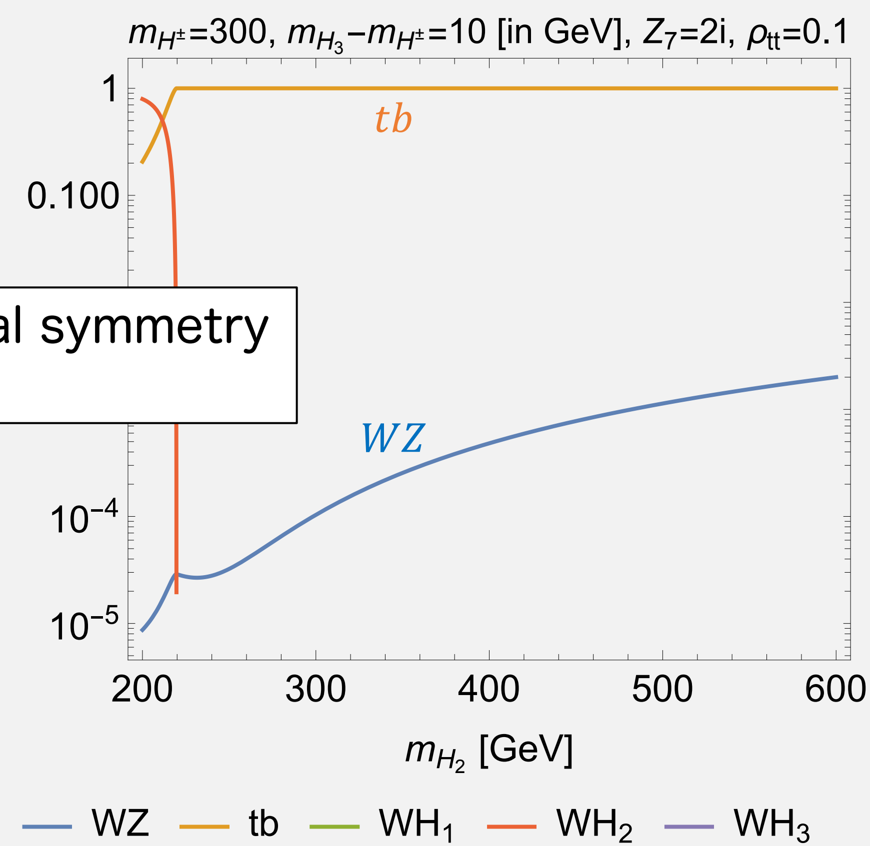
Numerical results

S. Kanemura and Y.M, work in progress

- **Non-zero $\mathrm{Im}[Z_7]$ and $Z_4 + Z_5 \propto m_{H_2}^2 - m_{H^\pm}^2$ case** (in Yukawa, only ρ_{tt} is switched on)
  - For $m_{H^\pm} < m_{H_2}$, main modes are $H^\pm \to tb, W^\pm Z$
  - For large $\mathrm{Im}[Z_7]$ and mass difference, branching ratio is $O(10^{-4})$ - $O(10^{-2})$



Potential has custodial symmetry
(only $U(1)_Y$ violate it)



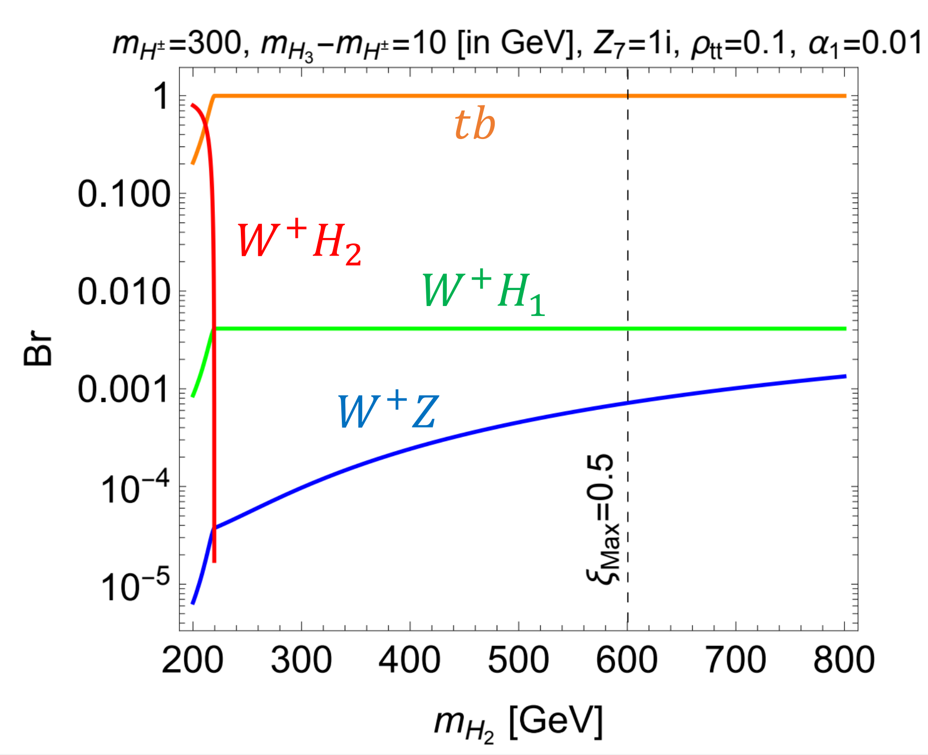
Branching ratio

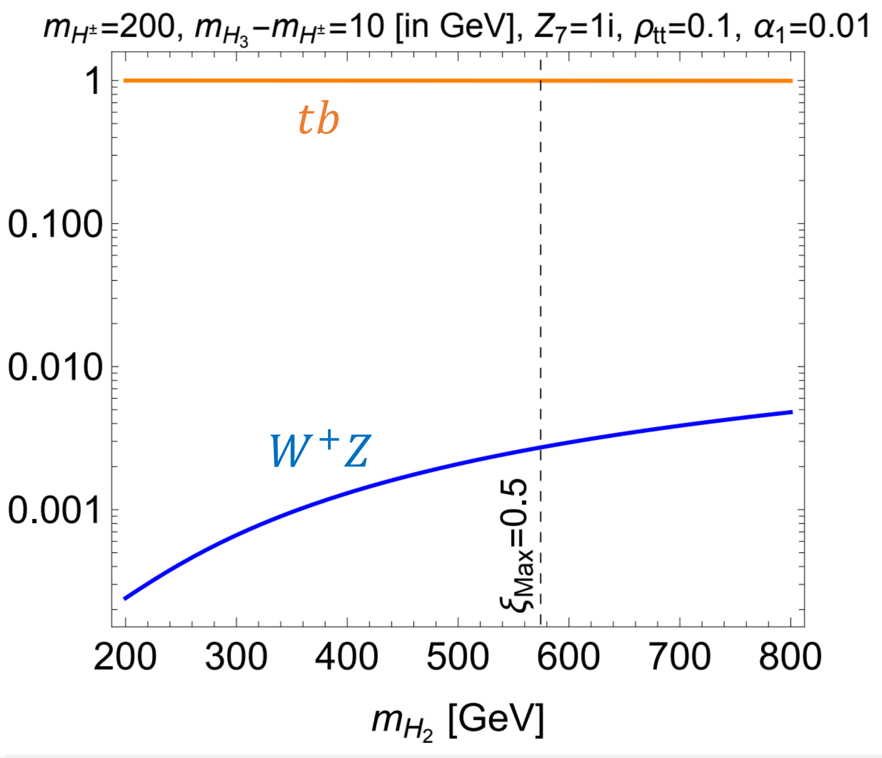
S. Kanemura and **Y.M.**, arXiv:2408.06863

- **Branching ratio for $H^+ \to XY$ ($\rho_{ij} = 0$ except for ρ_{tt})**
  - Custodial symmetry violation $\propto m_{H_2} - m_{H^\pm}$
  - For $m_{H^\pm} < m_{H_2}$, main modes are $H^\pm \to tb, WZ, WH_1$
  - If $m_{H^\pm} < m_W + m_{H_1}$, $\mathrm{Br}(H^\pm \to W^\pm Z)$ can be large

cf.) Mixing angle

$$H_1 = h_1 \cos\alpha_1 - h_2 \sin\alpha_1$$
$$H_2 = h_1 \sin\alpha_1 + h_2 \cos\alpha_1$$

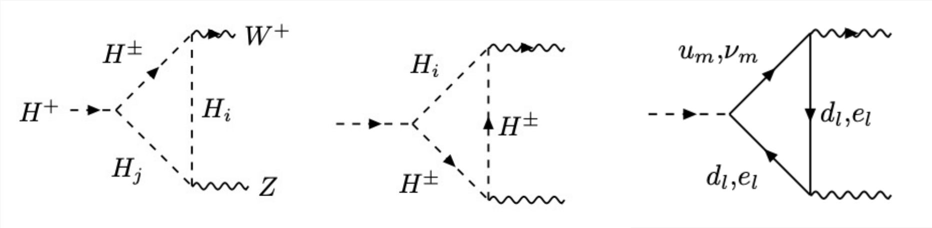




Testing CP violation

S. Kanemura and **Y.M.**, arXiv:2408.06863

- **Asymmetry b/w $H^+ \to W^+ Z$ and $H^- \to W^- Z$ is sensitive to $\mathrm{Im}[\rho^f Z_7]$.**



Left: $\Delta \equiv \Gamma(H^+ \to W^+ Z) - \Gamma(H^- \to W^- Z)$

Right: $\delta_{CP} \equiv \dfrac{\Delta}{\Gamma(H^+ \to W^+ Z) + \Gamma(H^- \to W^- Z)}$