1st IUEP (Institute of Universe & Elementary Particles) mini-workshop

Exotic decays of the charged Higgs boson via vectorlike quark loops

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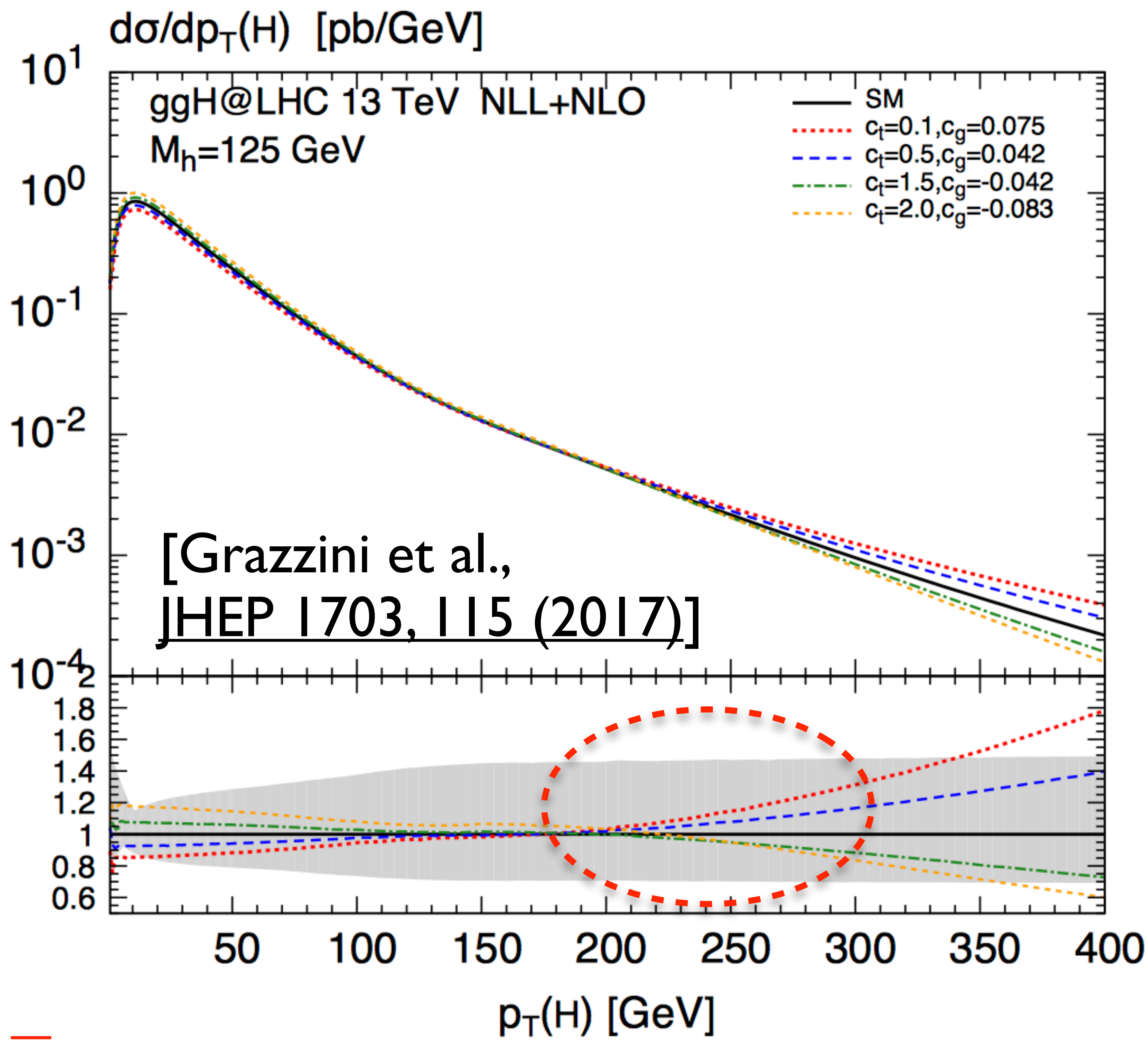
Chonnam National University, 2018.10.06

1. Current experimental status of the Higgs bosons
2. Tricky mass window for the charged Higgs boson
3. New search channels
4. 2HDM with VL fermions
5. Constraints form other indirect signals
6. BR
7. Conclusions

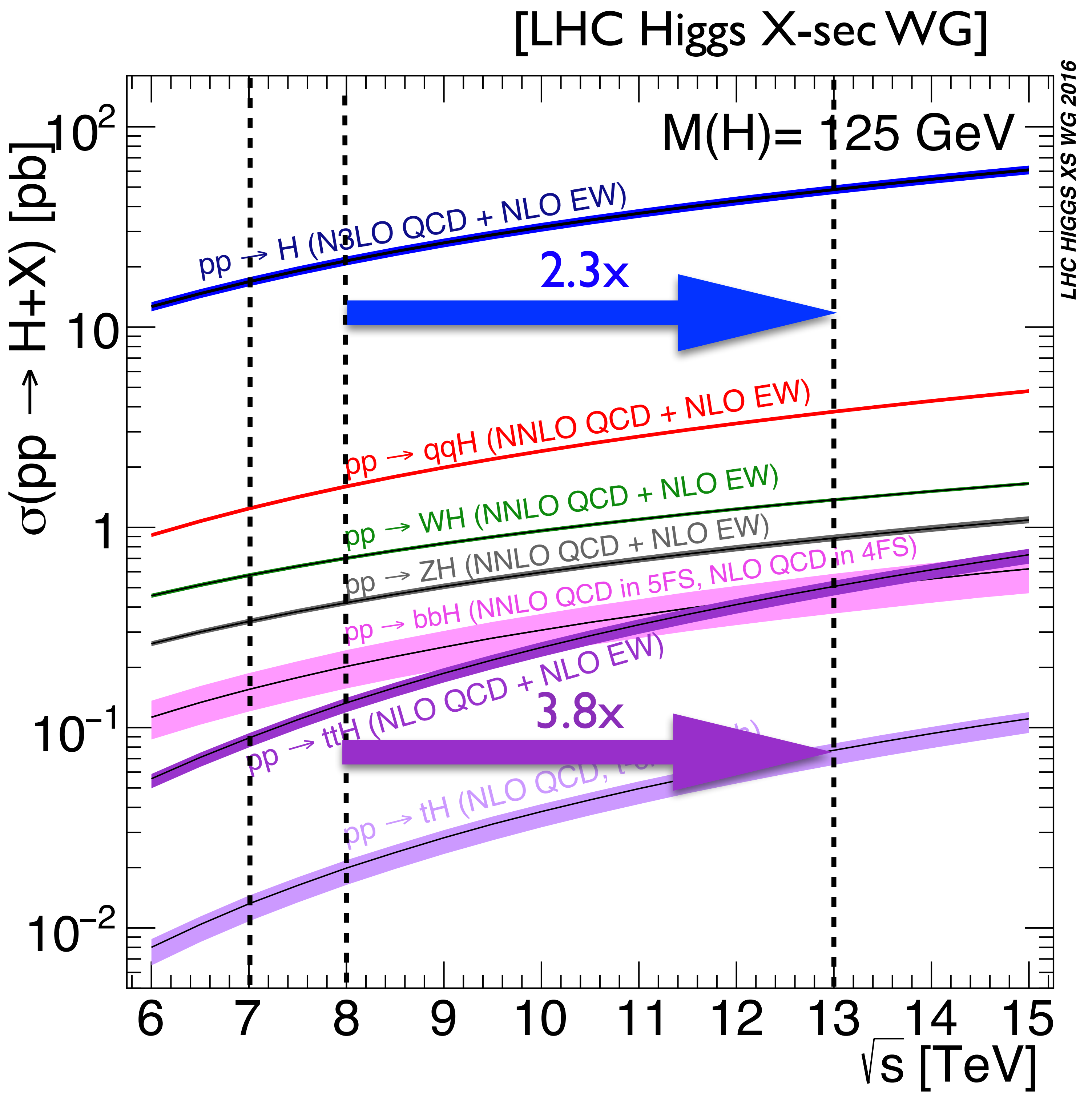
Current status of the Higgs boson measurements at the LHC

In the EFT approach

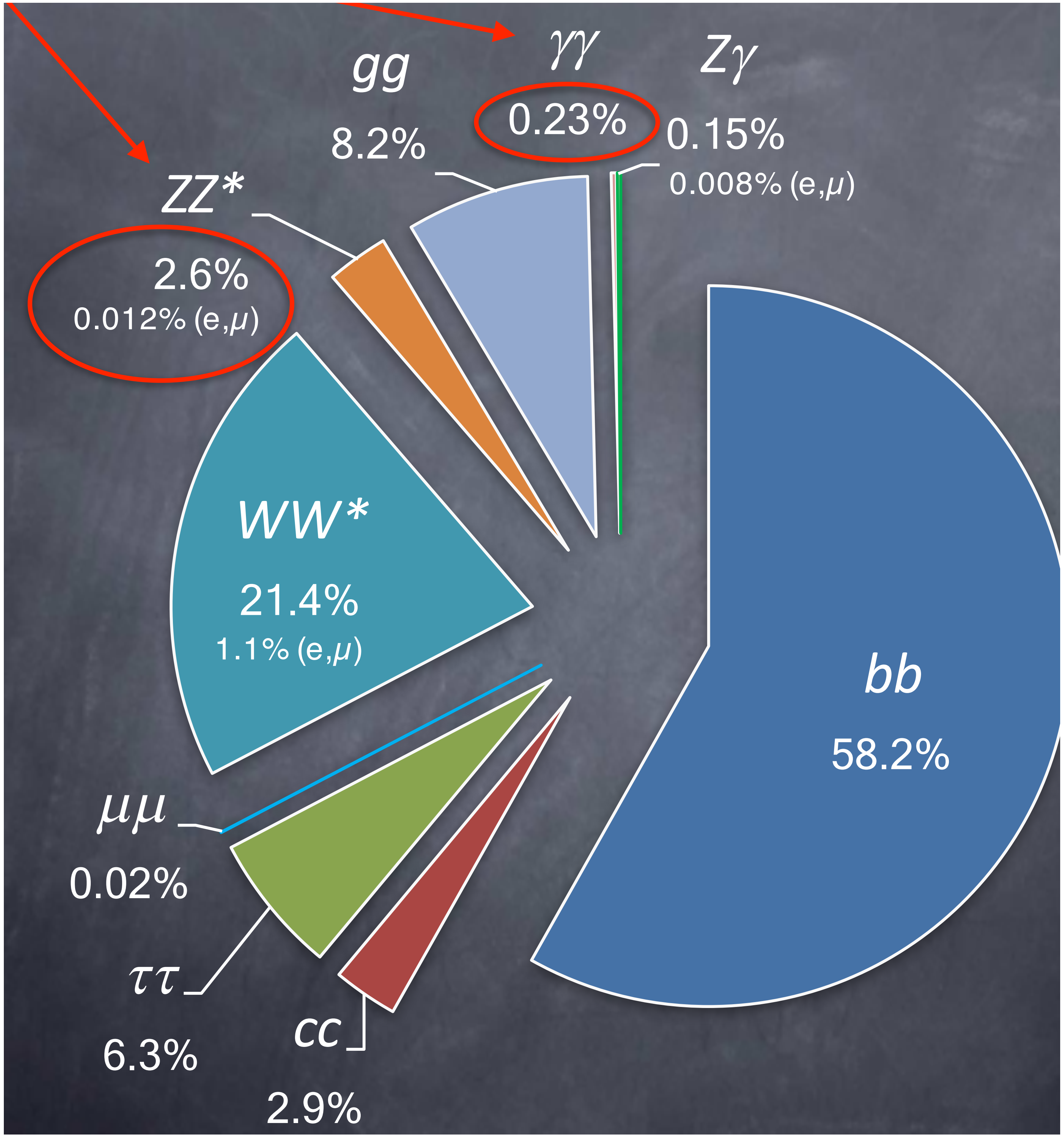
- From Run-1 to Run-2
- NP will show up in high pT region
- Significant increase in production rate due to higher center-of-mass energy from LHC Run-1 to Run-2!



Production


[LHC Higgs X-sec WG]
M(H)= 125 GeV
LHC HIGGS XS WG 2016
pp → H (N3LO QCD + NLO EW)
2.3x
pp → qqH (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD + NLO EW)
pp → bbH (NNLO QCD in 5FS, NLO QCD in 4FS)
pp → ttH (NLO QCD + NLO EW)
3.8x
σ(pp → H+X) [pb]
√s [TeV]
6
7
8
9
10
11
12
13
14
15
10^2
10
1
10^{-1}
10^{-2}

Decays



γγ
Zγ
gg
0.23%
8.2%
0.15%
0.008% (e,μ)
ZZ*
2.6%
0.012% (e,μ)
WW*
21.4%
1.1% (e,μ)
bb
58.2%
μμ
0.02%
ττ
6.3%
cc
2.9%

Inputs to combination

Decay \ Production	gluon fusion	vector boson fusion (VBF)	associated prod. with W/Z	associated prod. with tt
H → γ γ (tt̄, WW and ZZ pairs)	CMS ✓ ATLAS ✓ (80 fb^{-1})	CMS ✓ ATLAS ✓ (80 fb^{-1})	CMS ✓ ATLAS ✓ (80 fb^{-1})	CMS ✓ ATLAS ✓ (80 fb^{-1})
H → Z* Z	CMS ✓ ATLAS ✓ (80 fb^{-1})	CMS ✓ ATLAS ✓ (80 fb^{-1})	CMS ✓ ATLAS ✓ (80 fb^{-1})	CMS ✓ ATLAS ✓ (80 fb^{-1})
H → W* W	CMS ✓ ATLAS ✓	CMS ✓ ATLAS ✓	CMS ✓	CMS ✓ ATLAS ✓
H → τ τ̄	CMS ✓ ATLAS ✓	CMS ✓ ATLAS ✓		CMS ✓ ATLAS ✓
H → b b̄	CMS ✓		CMS ✓ ATLAS ✓	CMS ✓ ATLAS ✓
H → μ^- μ^+	CMS ✓ ATLAS ✓ (80 fb^{-1})	CMS ✓ ATLAS ✓ (80 fb^{-1})		
H → invisible invisible	CMS ✓	CMS ✓	CMS ✓	

CMS

ATLAS

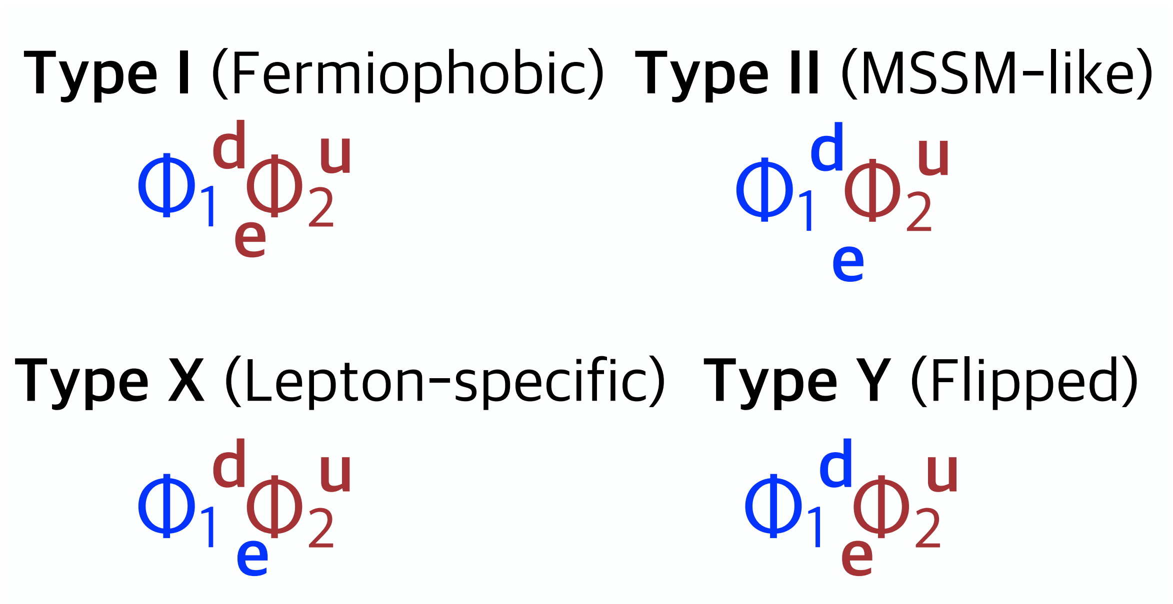
Another way to probe NP in the Higgs sector: New scalar bosons

Another way to probe NP in the Higgs sector:

Charged Higgs boson

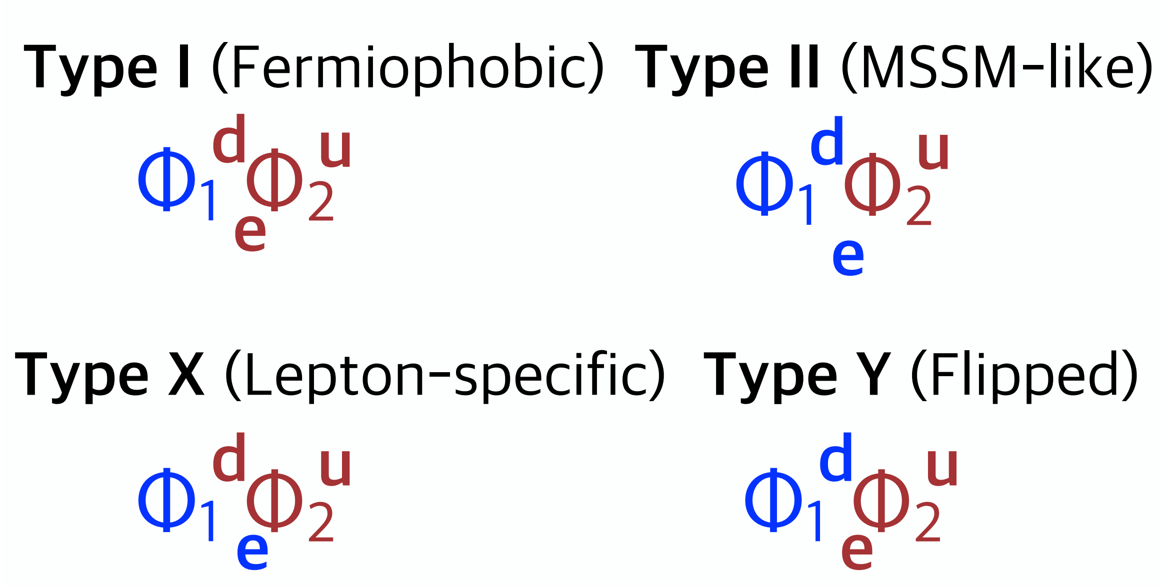
2 kinds of NP

- Doublet models
  - 5 scalars



2 kinds of NP

- Doublet models
  - 5 scalars



- Triplet models
  Georgi-Machacek Model
  - add one real and one complex SU(2) triplet
  - H+ phenomenology different from the doublet models
  - H+WZ couplings at tree level
  - Double-charged Higgs bosons H++

2HDM

Two Higgs doublets

$$\Phi_1 \text{ and } \Phi_2 .$$

$$\Phi_a = \begin{pmatrix} \phi_a^+ \\ \dfrac{v_a + \rho_a + i\eta_a}{\sqrt{2}} \end{pmatrix}, \quad a = 1, 2.$$

$$\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \qquad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

$$v^2 \equiv v_1^2 + v_2^2 = (246\ \mathrm{GeV})^2, \qquad \frac{v_2}{v_1} = \tan\beta.$$

Mixing angle!

Five physical Higgs bosons

$$h^0, H^0, A^0, H^\pm$$

Two Higgs doublets

$$\Phi_1 \text{ and } \Phi_2$$

In order to suppress FCNC at tree level,
we impose Z2 symmetry

$$\Phi_1 \to \Phi_1 \text{ and } \Phi_2 \to -\Phi_2$$

Higgs potential

Softly broken Z2

$$V = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \text{H.c.})$$
$$+\frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+\frac{1}{2}\lambda_5\left[(\Phi_1^\dagger\Phi_2)^2 + \text{H.c.}\right]$$

Q. What can all of the data tell about the potential?

Important roles of Yukawa interaction

4 types according to the charge assignment under Z2 symmetry

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

4 types according to the charge assignment under Z2 symmetry

Fixed

	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q_L, L_L
Type I	+	−	−	−	−	+
Type II	+	−	−	+	+	+
Type X	+	−	−	−	+	+
Type Y	+	−	−	+	−	+

4 types according to the charge assignment under Z2 symmetry

4 ways

	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q_L, L_L
Type I	+	−	−	−	−	+
Type II	+	−	−	+	+	+
Type X	+	−	−	−	+	+
Type Y	+	−	−	+	−	+

Only one combination acquires nonzero VEV v

$$H_1 \;=\; c_\beta \Phi_1 + s_\beta \Phi_2$$

Its orthogonal combination zero v

$$H_2 = -s_\beta \Phi_1 + c_\beta \Phi_2$$

Alignment limit

$$H^{\rm SM} = s_{\beta-\alpha} h^0 + c_{\beta-\alpha} H^0$$

For $h^0 = h_{125}$

$$s_{\beta-\alpha} = 1$$

$$\sin(\beta-\alpha) \;:\; g_{hW^+W^-}, \quad g_{hZZ}, \quad g_{ZAH}, \quad g_{W^\pm H^\mp H},$$

$$\cos(\beta-\alpha) \;:\; g_{HW^+W^-}, \quad g_{HZZ}, \quad g_{ZAh}, \quad g_{W^\pm H^\mp h}, \quad g_{Hhh}.$$

ZERO!

Review of 2HDM gauge-gauge-scalar vertices

HVV couplings		
Coupling	Tree–level?	Loop?
$H_i ZZ, H_i WW$	YES	–
$H_i \gamma\gamma, H_i \gamma Z$	NO ($Q = 0$)	1–loop
$H_i gg$	NO (col=0)	1–loop
$A_i ZZ, A_i WW$	NO (Cc)	1–loop
$A_i \gamma\gamma, A_i \gamma Z$	NO (Cc,$Q = 0$)	1–loop
$A_i gg$	NO (Cc, col= 0)	1–loop
$H^+ W^- Z$	NO for doublets	1–loop
$H^+ W^- \gamma$	NO ($\mathrm{U(1)_Q}$–c)	1–loop

Review of 2HDM gauge-scalar-scalar vertices

HHV couplings		
Coupling	Tree–level?	Loop?
H_iH_iZ, A_iA_iZ	NO: Bose statistics	
$H_iH_i\gamma$, $A_iA_i\gamma$	NO (Bose statistics)	
$H_iH_j\gamma$, $A_iA_j\gamma$	NO $(Q=0)$	3–loop
H_iH_jZ, A_iA_jZ	NO (CPc)	3–loop
$H_iA_i\gamma^*$	NO $(Q = 0)$	1–loop
H_iA_jZ	YES	–
$H^+H^-Z(\gamma)$	YES	–
$H^+W^-H_i(A_i)$	YES	–

$h : c_{\beta-\alpha}$ $H : s_{\beta-\alpha}$

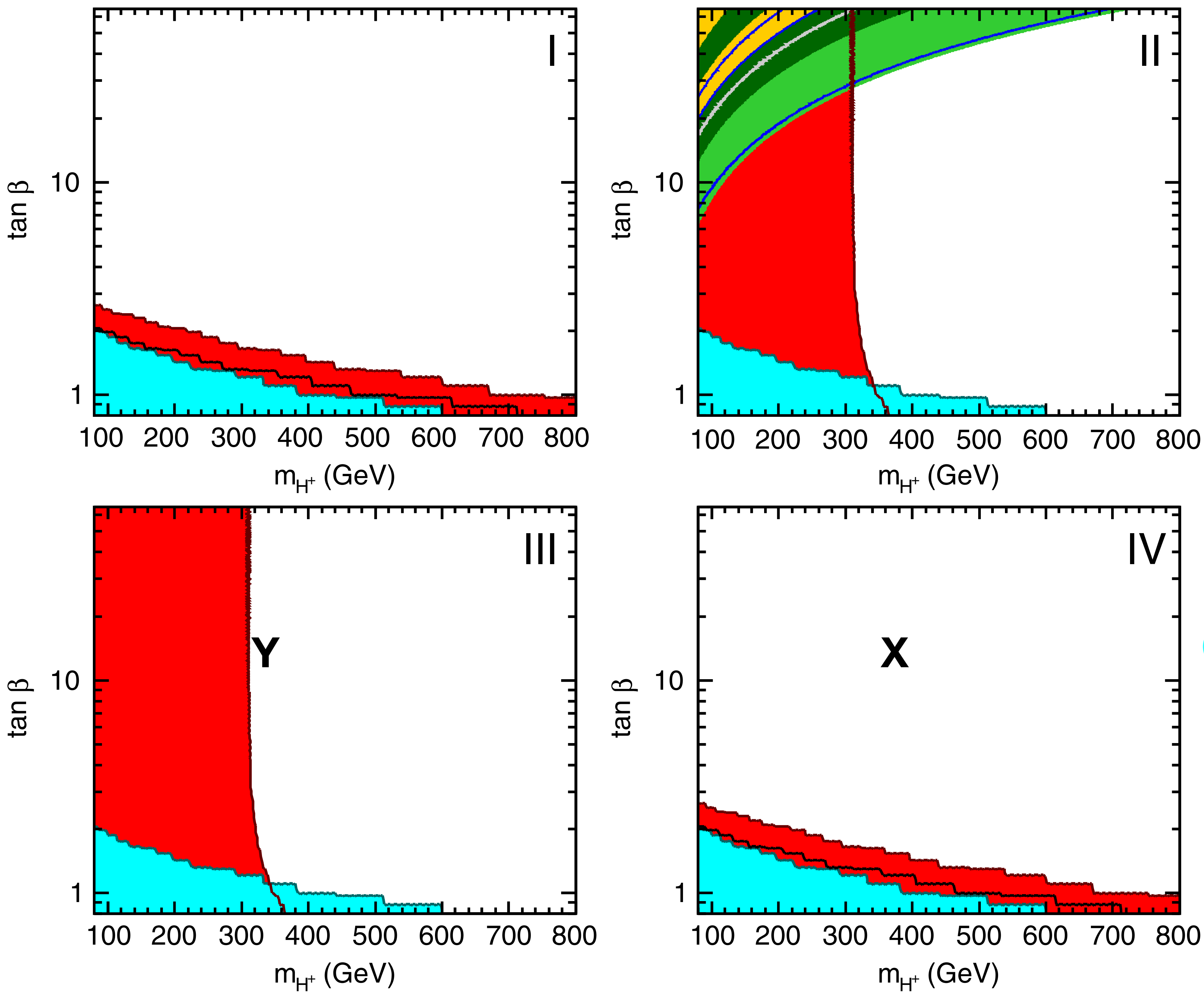
$s_{\beta-\alpha}(1)$

Yukawa couplings

$$\mathcal{L}_{\text{yukawa}}^{\text{THDM}} = -\sum_{f=u,d,\ell}\left(\frac{m_f}{v}\xi_h^f \bar{f} f h + \frac{m_f}{v}\xi_H^f \bar{f} f H - i\frac{m_f}{v}\xi_A^f \bar{f}\gamma_5 f A\right) - \left\{\frac{\sqrt{2}V_{ud}}{v}\bar{u}(m_u \xi_A^u P_L + m_d \xi_A^d P_R) d H^+ + \frac{\sqrt{2} m_\ell \xi_A^\ell}{v}\bar{\nu}_L \ell_R H^+ + \text{H.c.}\right\},$$

	ξ_A^u	ξ_A^d	ξ_A^ℓ
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	$\cot\beta$	$\tan\beta$	$-\cot\beta$

FCNC constraint

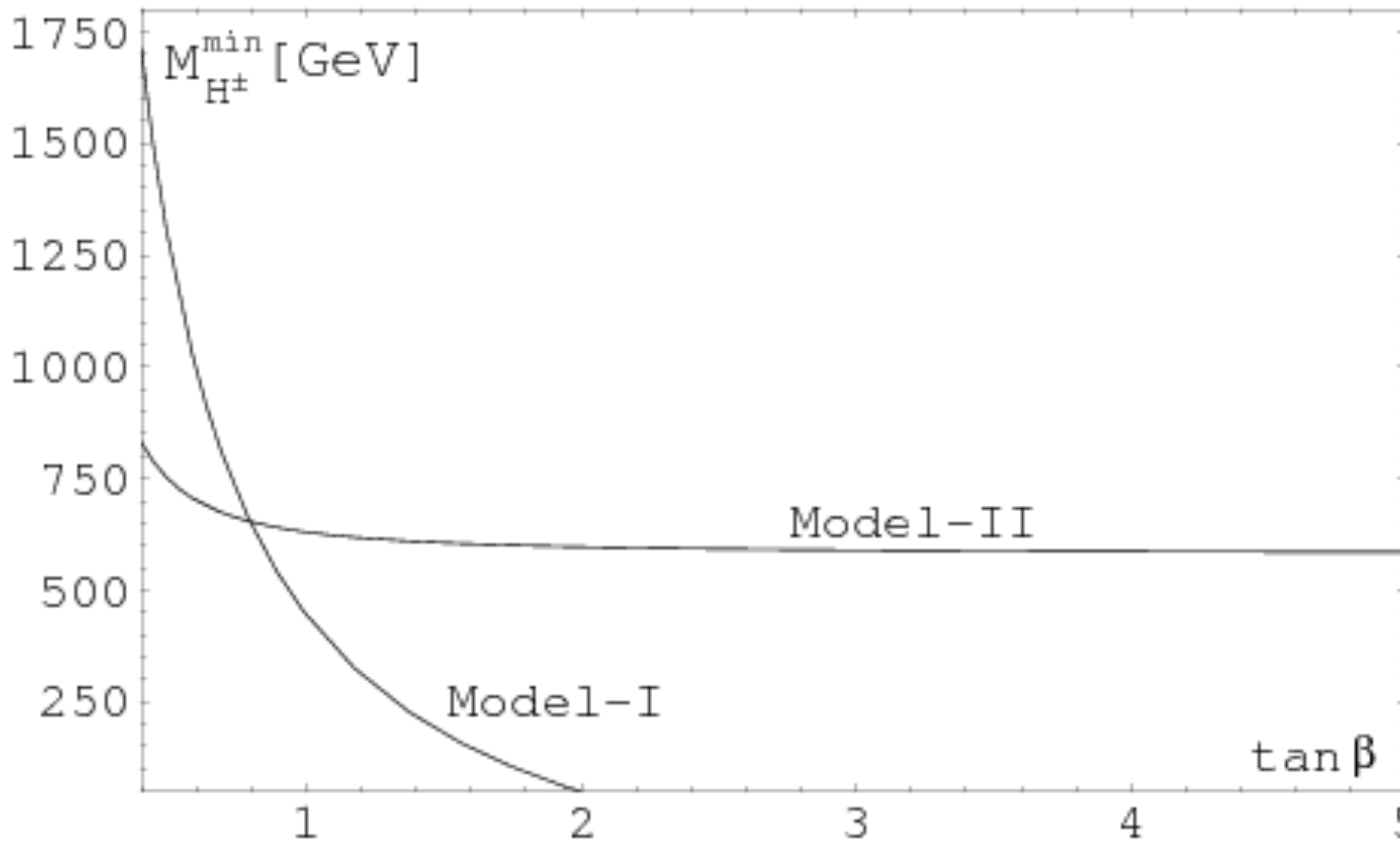


Cyan: ΔM_{bd}

Red: $b \to s\gamma$

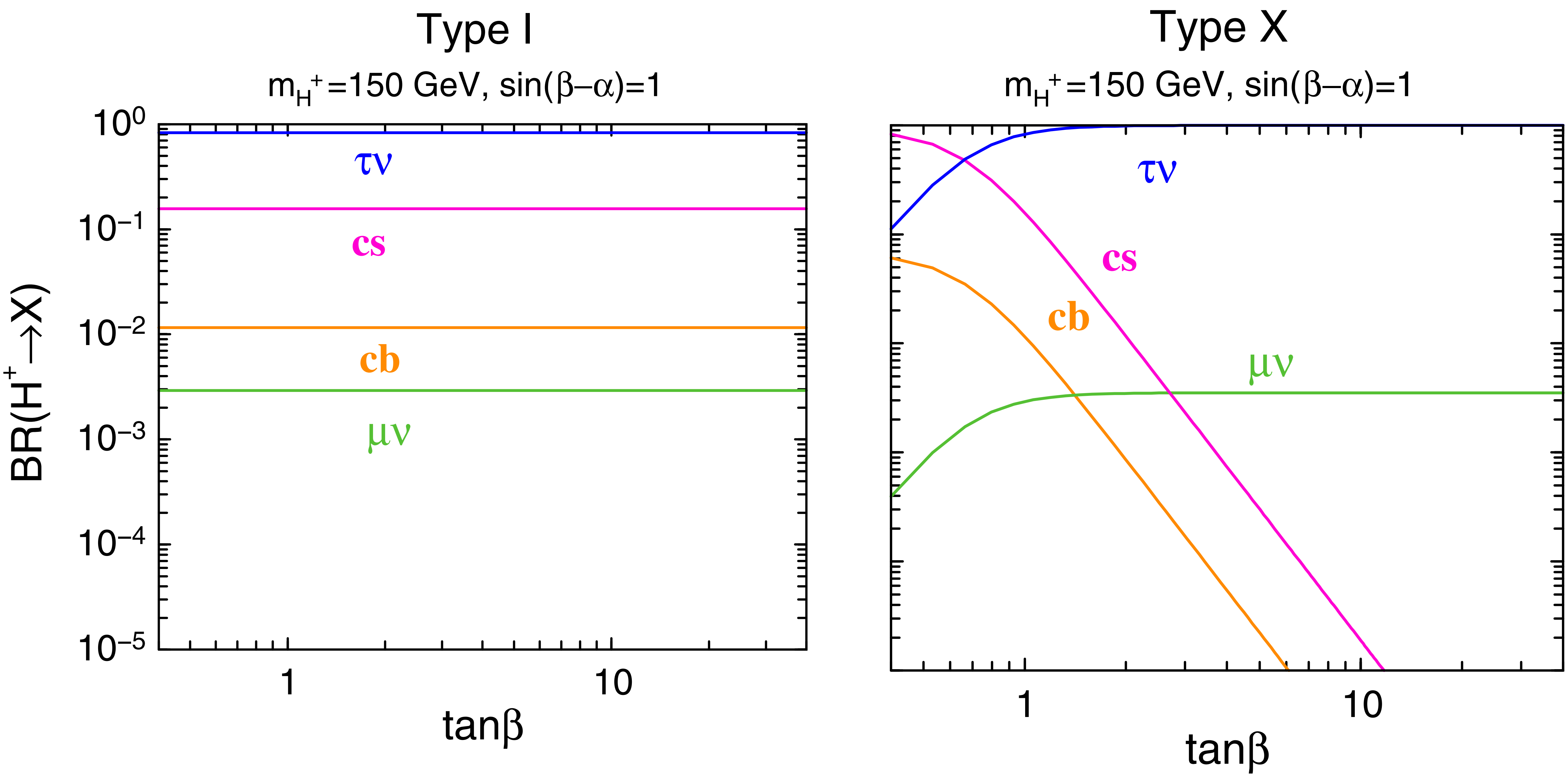
F. MAHMOUDI AND O. STÅL PHYSICAL REVIEW D **81,** 035016 (2010)

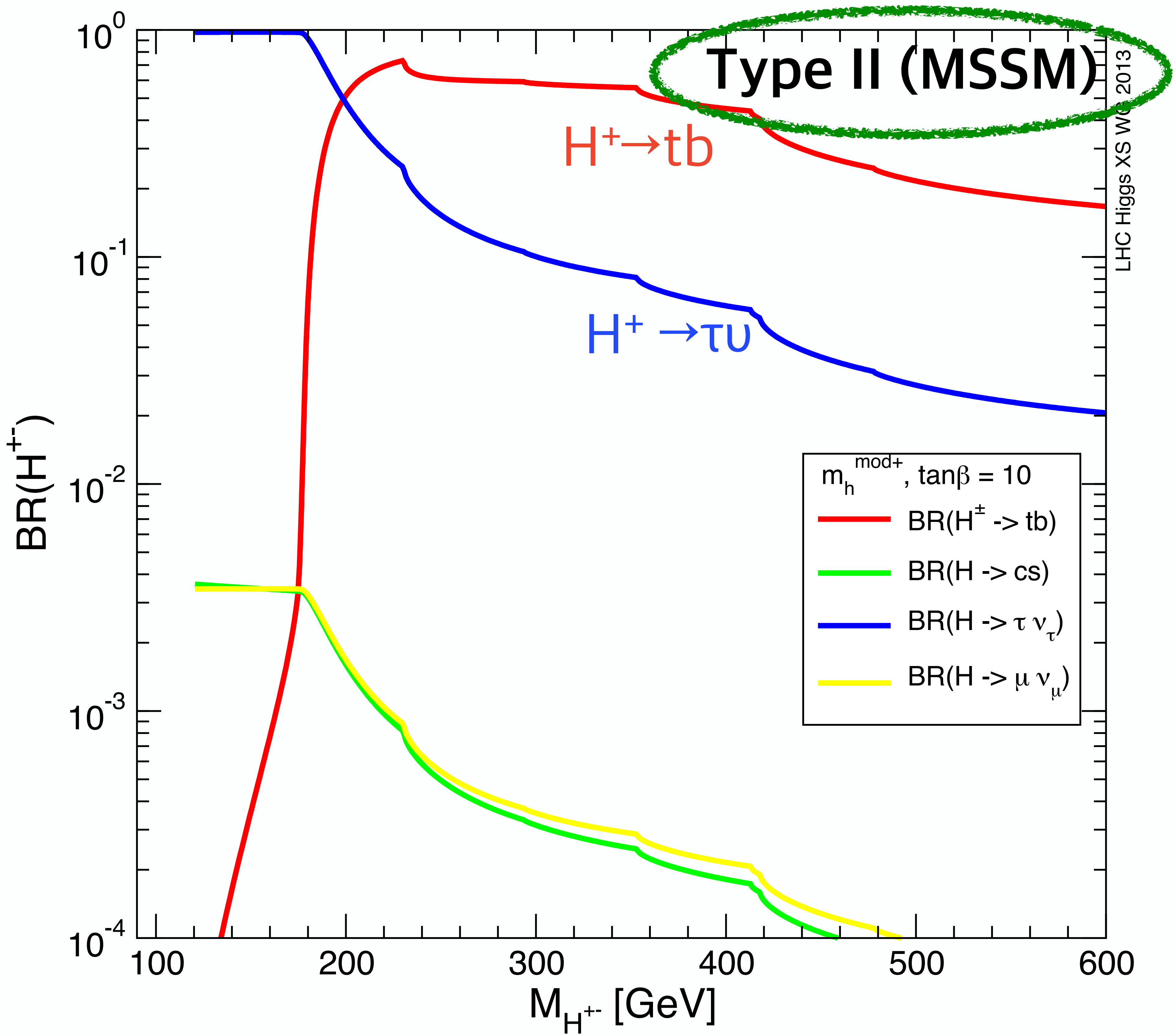
95% C.L. lower bounds on $M_{H^\pm}$



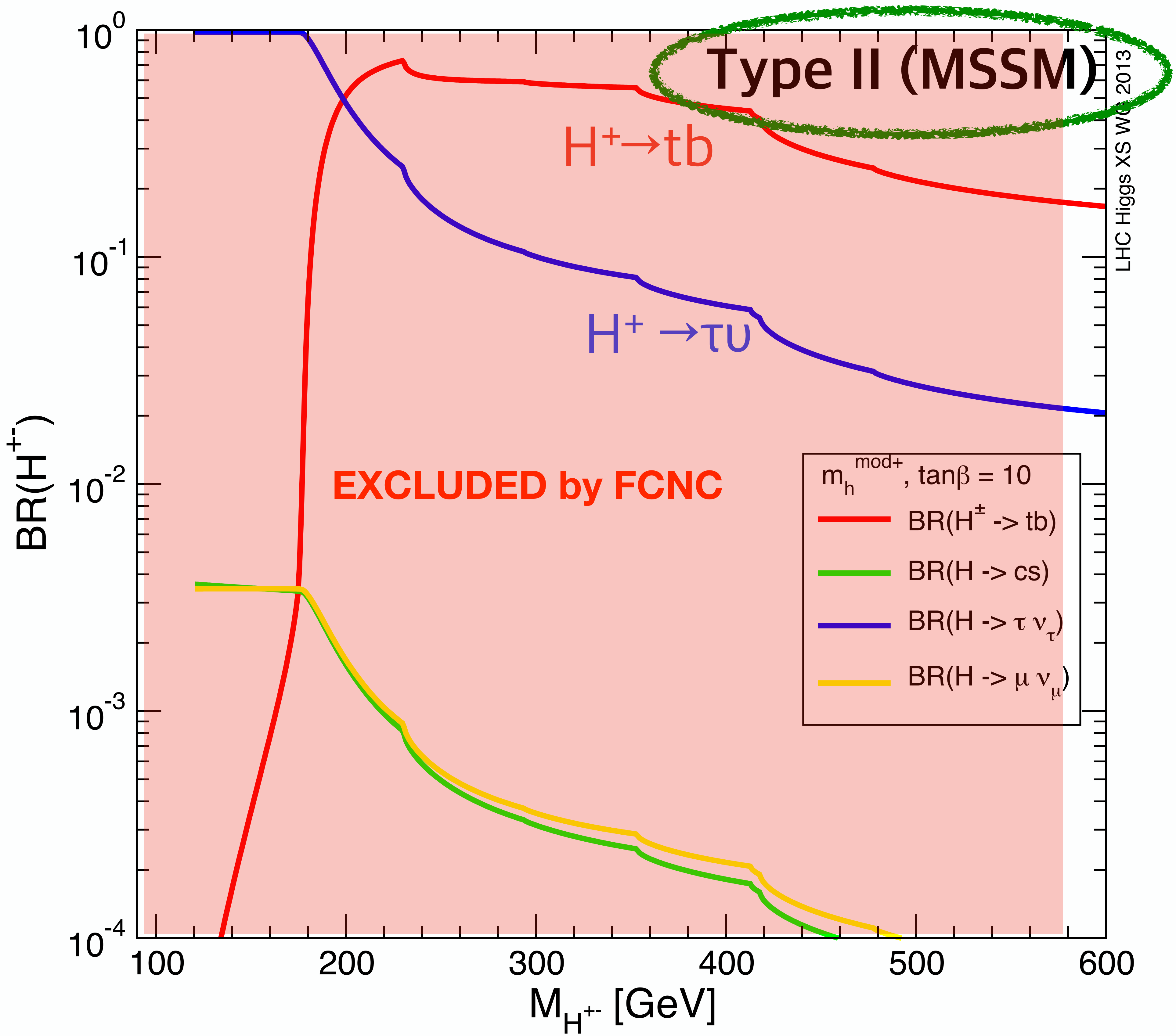
Misiak et al, Eur.Phys.J. C77 (2017) no.3, 201

Type I, X: H+ can be light

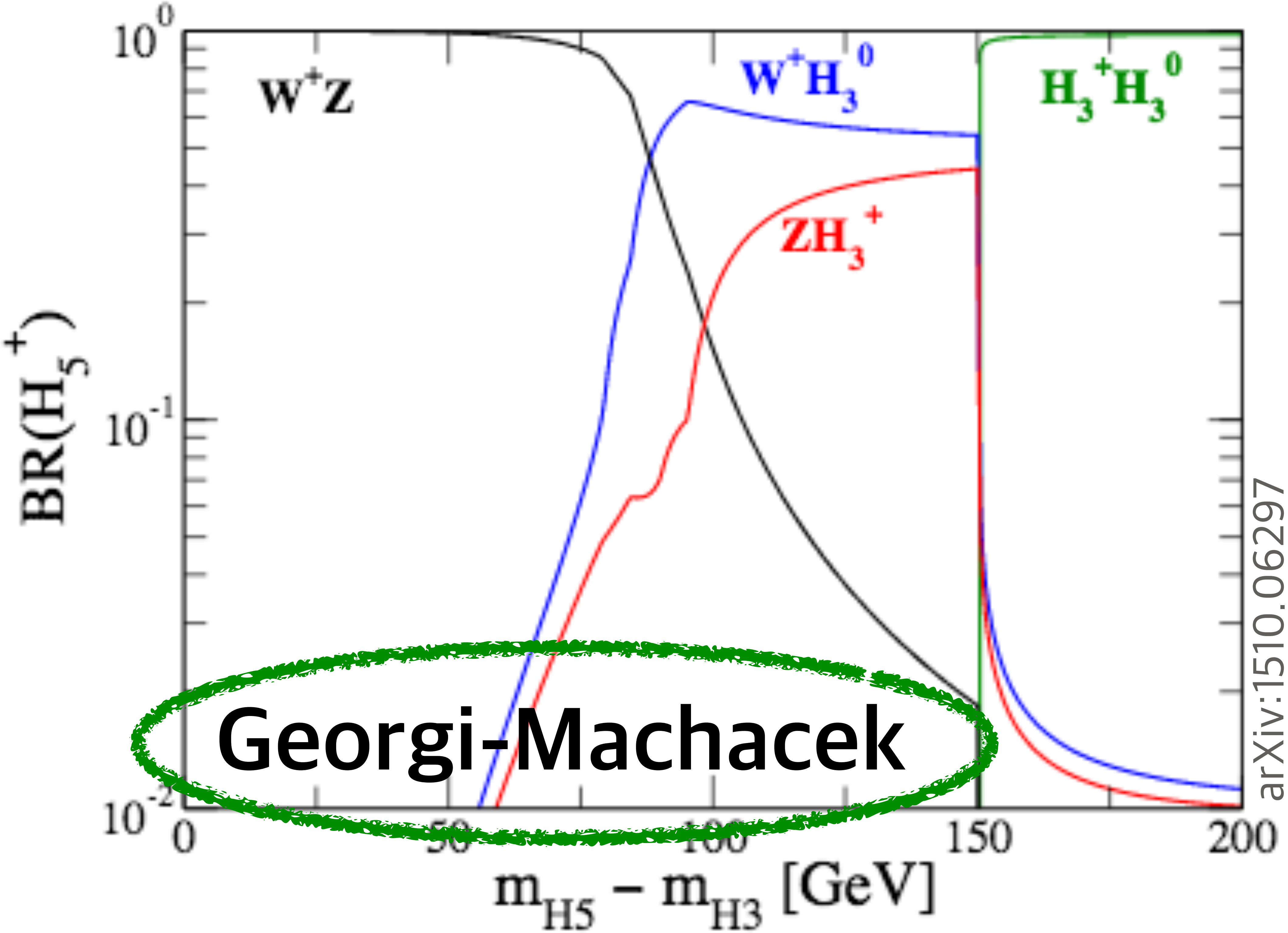

Type I
mH+=150 GeV, sin(β−α)=1
Type X
mH+=150 GeV, sin(β−α)=1
BR(H+→X)
10^0
10^−1
10^−2
10^−3
10^−4
10^−5
τν
cs
cb
μν
1
10
tanβ



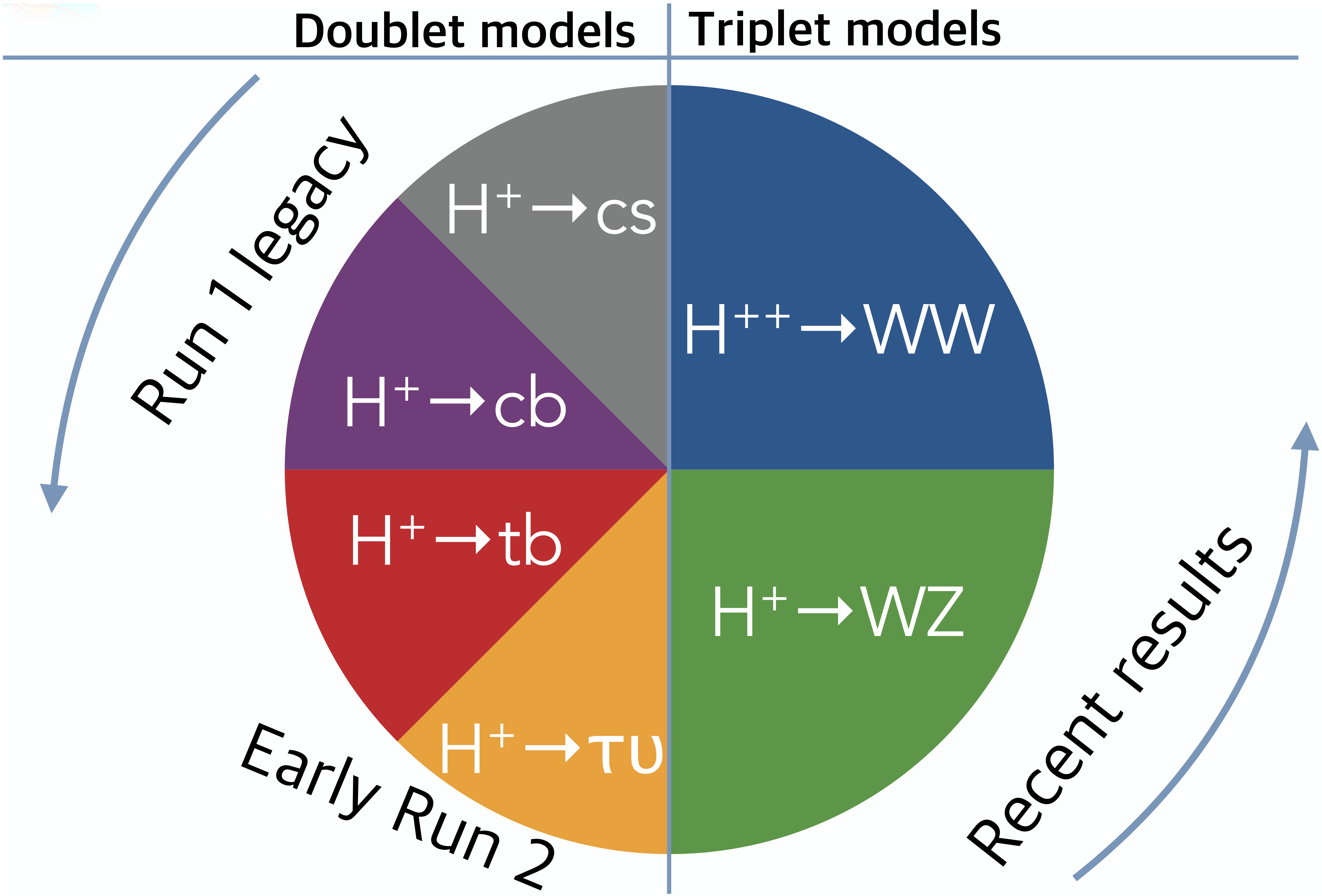
Type II (MSSM)
LHC Higgs XS WG 2013
H+→tb
H+ →τυ
m_h^mod+, tanβ = 10
BR(H± -> tb)
BR(H -> cs)
BR(H -> τ ν_τ)
BR(H -> μ ν_μ)
BR(H+-)
M_H+- [GeV]
10^0
10^-1
10^-2
10^-3
10^-4
100
200
300
400
500
600



Type II (MSSM)
H+→tb
H+ →τυ
EXCLUDED by FCNC
m_h^{mod+}, tanβ = 10
BR(H± -> tb)
BR(H -> cs)
BR(H -> τ ν_τ)
BR(H -> μ ν_μ)
BR(H+-)
M_H+- [GeV]
LHC Higgs XS WG 2013



W+Z
W+H3 0
ZH3 +
H3 +H3 0
BR(H5 +)
10^0
10^-1
10^-2
0
50
100
150
200
mH5 – mH3 [GeV]
Georgi-Machacek
arXiv:1510.06297

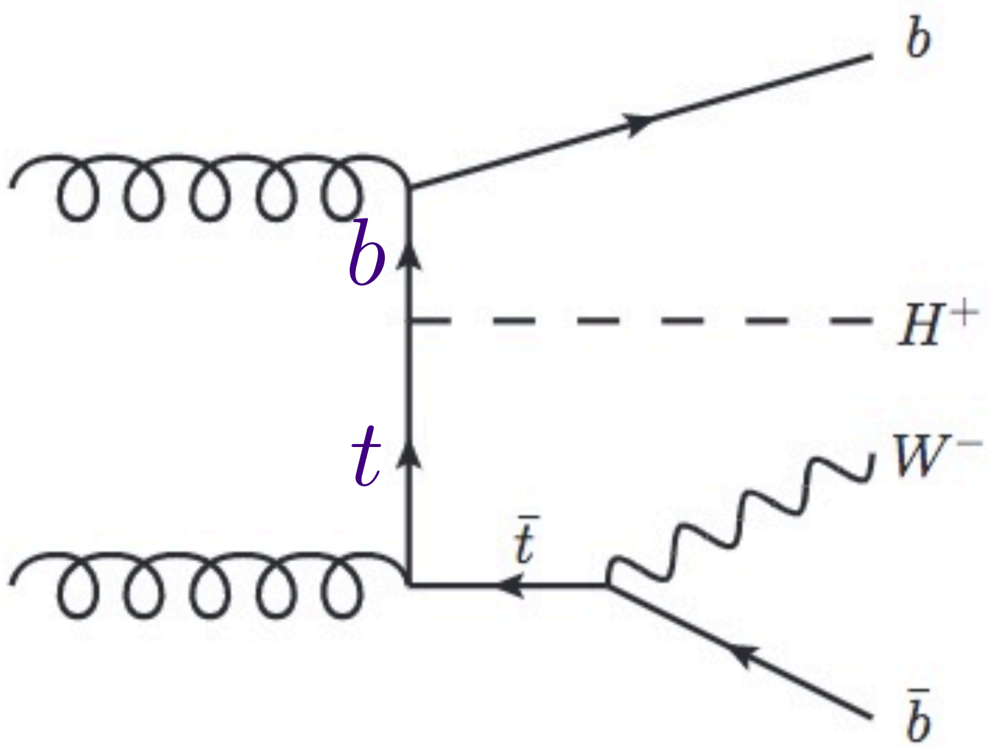

Doublet models
Triplet models
Run 1 legacy
Early Run 2
Recent results
$H^+ \to cs$
$H^+ \to cb$
$H^+ \to tb$
$H^+ \to \tau\nu$
$H^{++} \to WW$
$H^+ \to WZ$

Production of H+

Key parameter: MH+

$$\text{Heavy } M_{H^\pm} > m_t$$
$$\text{Light } M_{H^\pm} < m_t$$

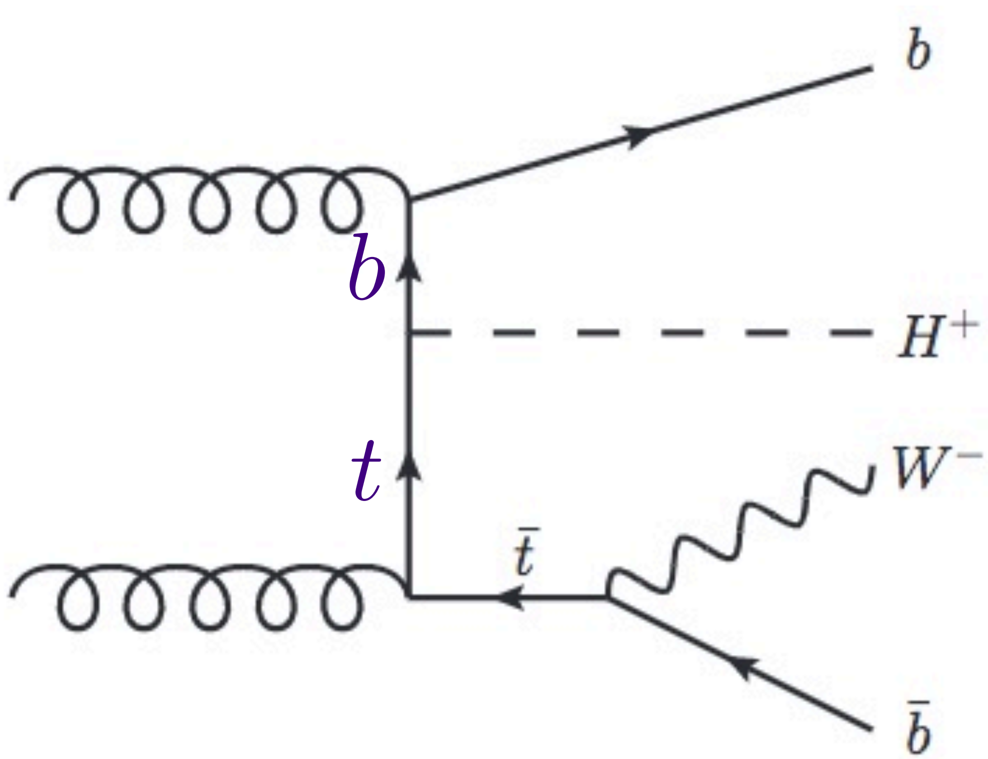
Heavy $M_{H^\pm} > m_t$



tb

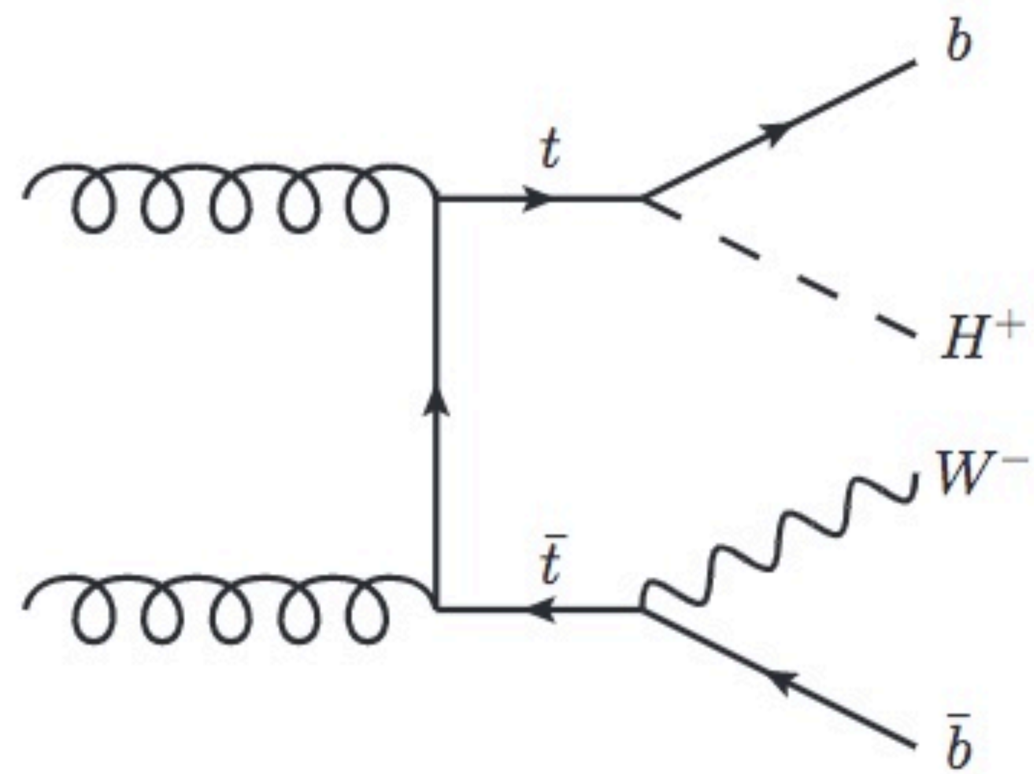
single-resonant top

Heavy $M_{H^\pm} > m_t$ Light $M_{H^\pm} < m_t$



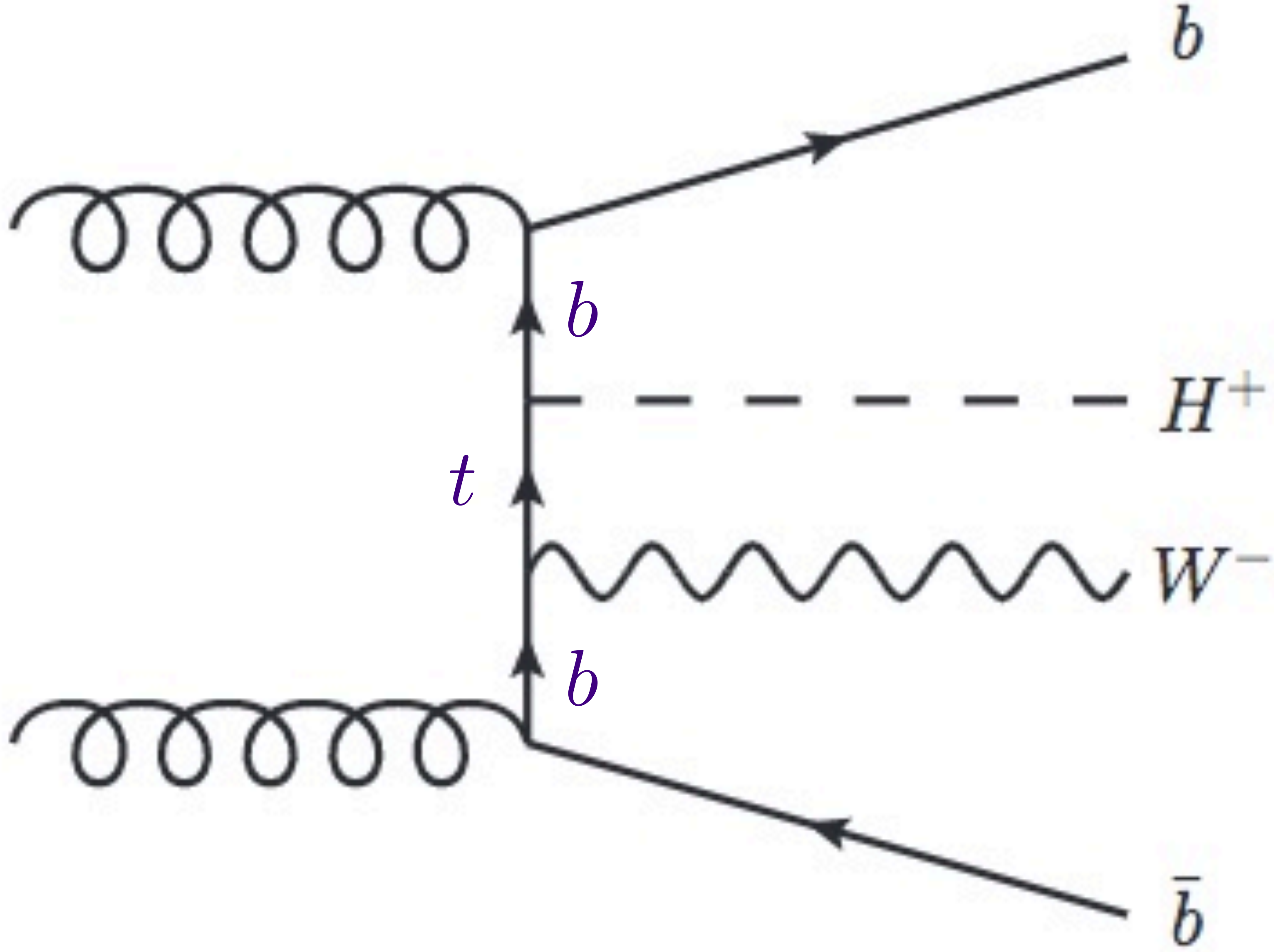
tb

single-resonant top



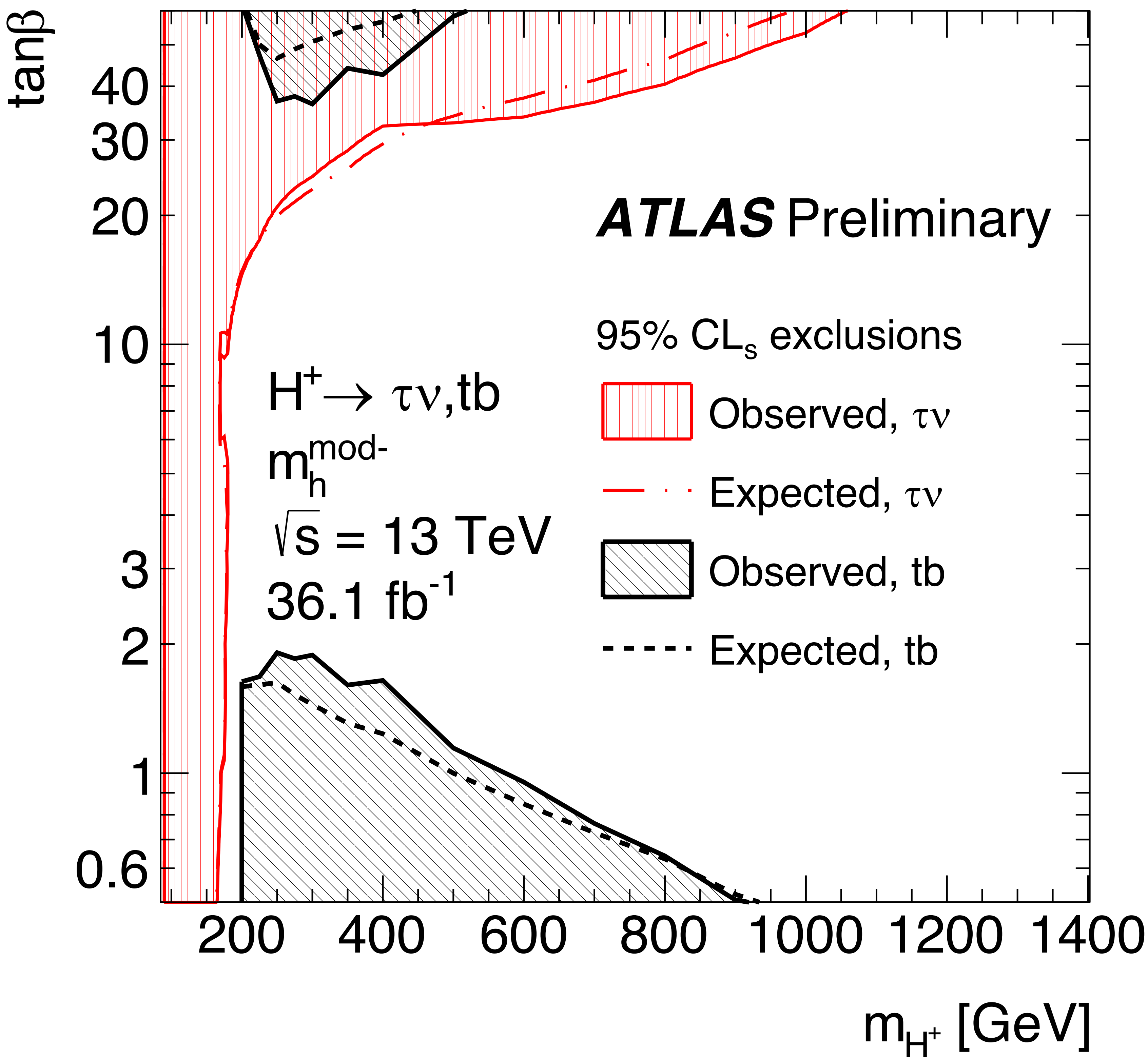
$\tau\nu$

double-resonant top

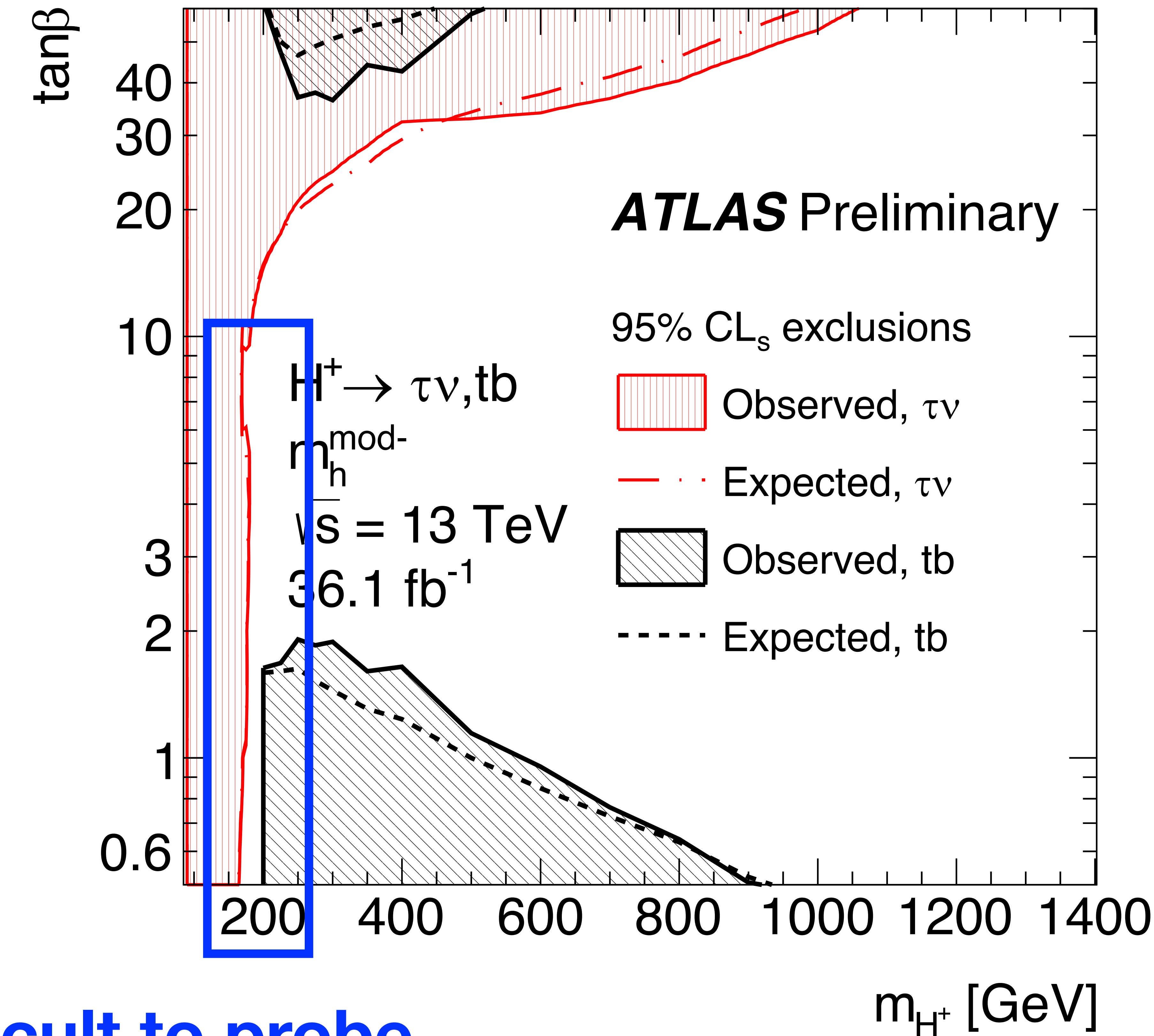


non-resonant

H+ → tb and H+ → τν superposition



H⁺ → tb and H⁺ → τν superposition



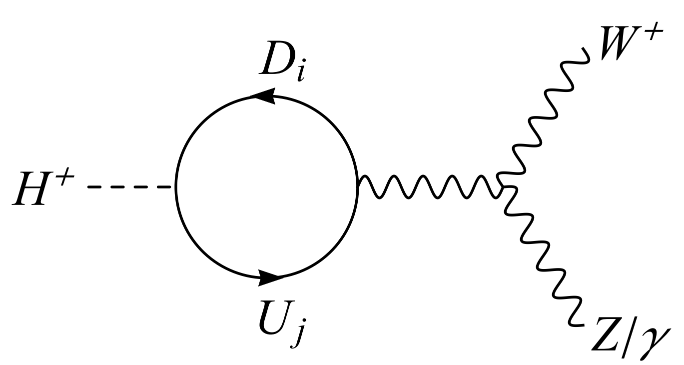
Very difficult to probe

Question
New search channel
for this tricky H+?

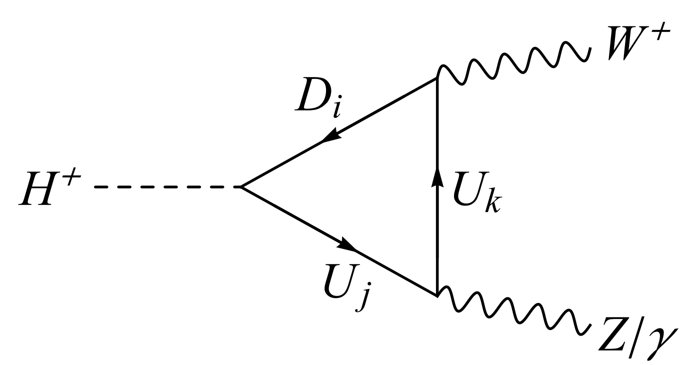
Kinematically

$H^{\pm} \to W^{\pm}\gamma$

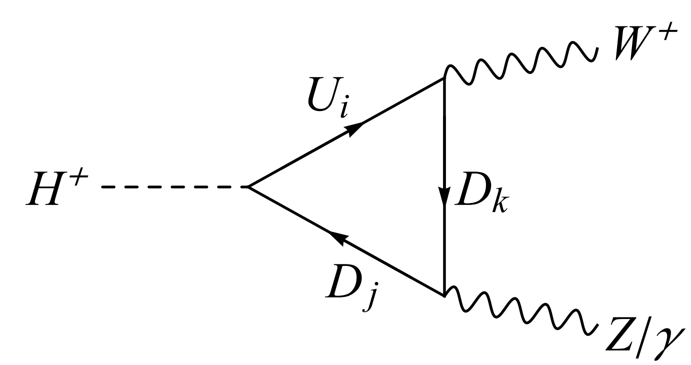
$H^{\pm} \to W^{\pm}Z^{(*)}$



(a)

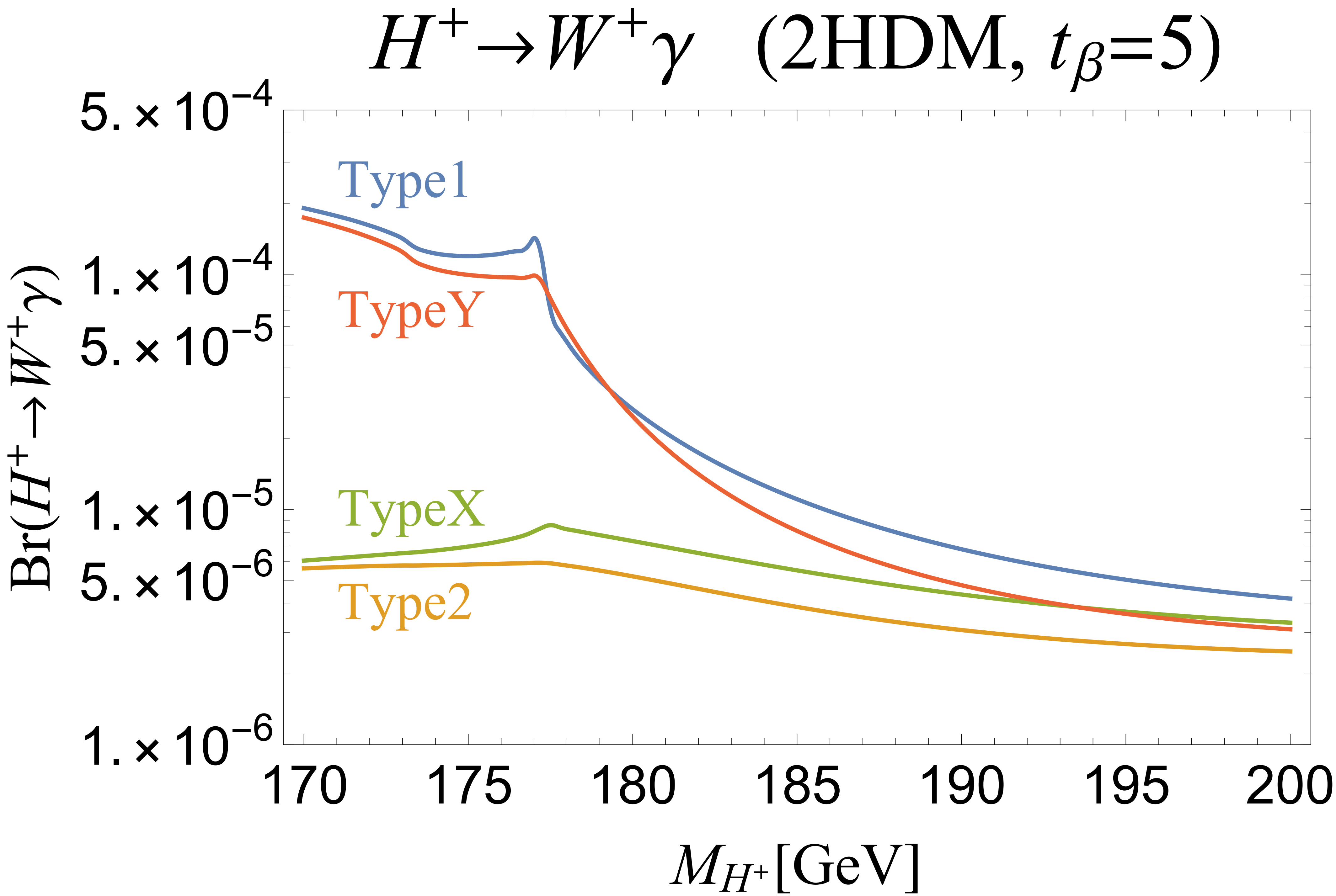


(b)



(c)

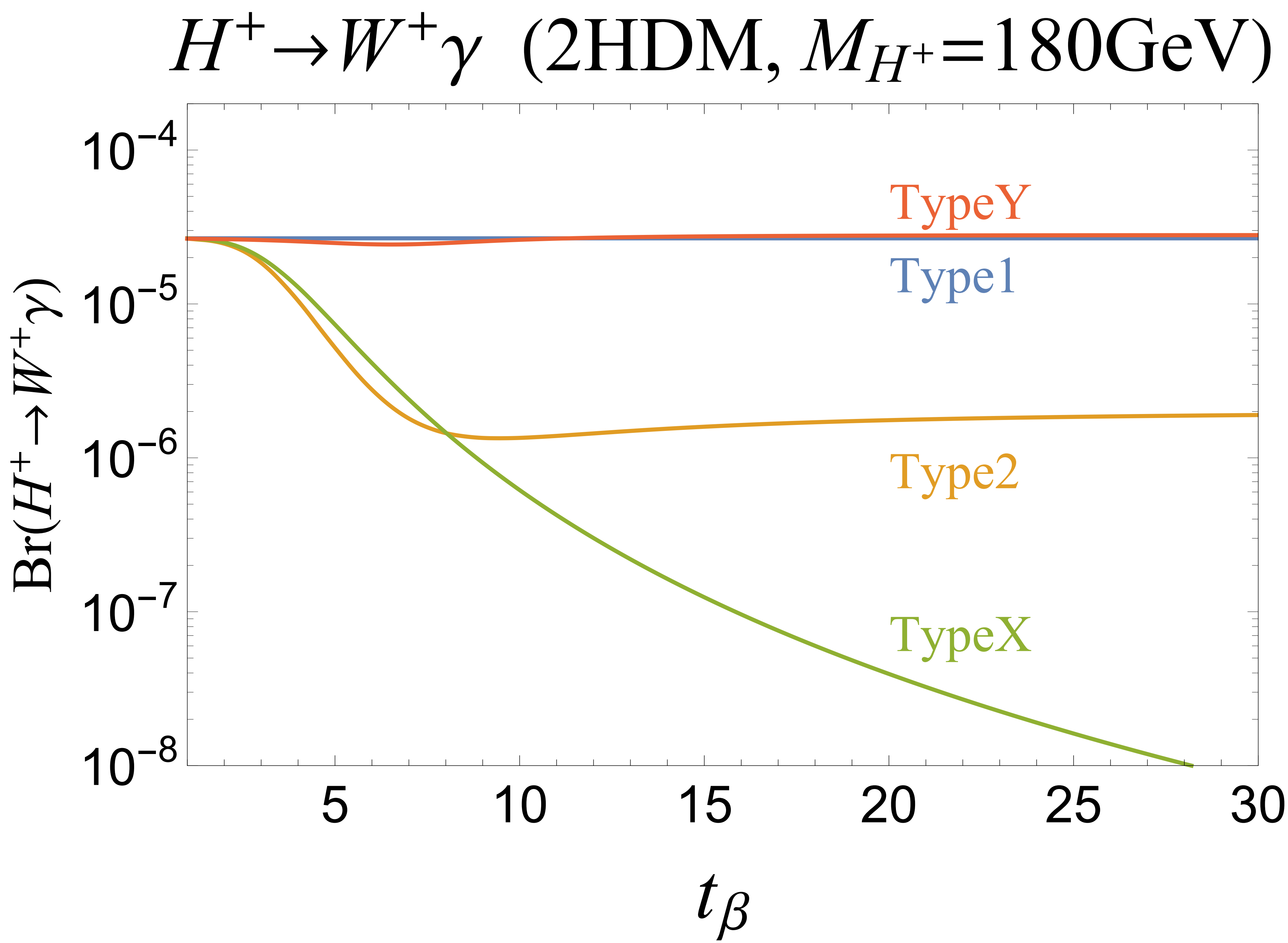
Pure 2HDM is not enough!

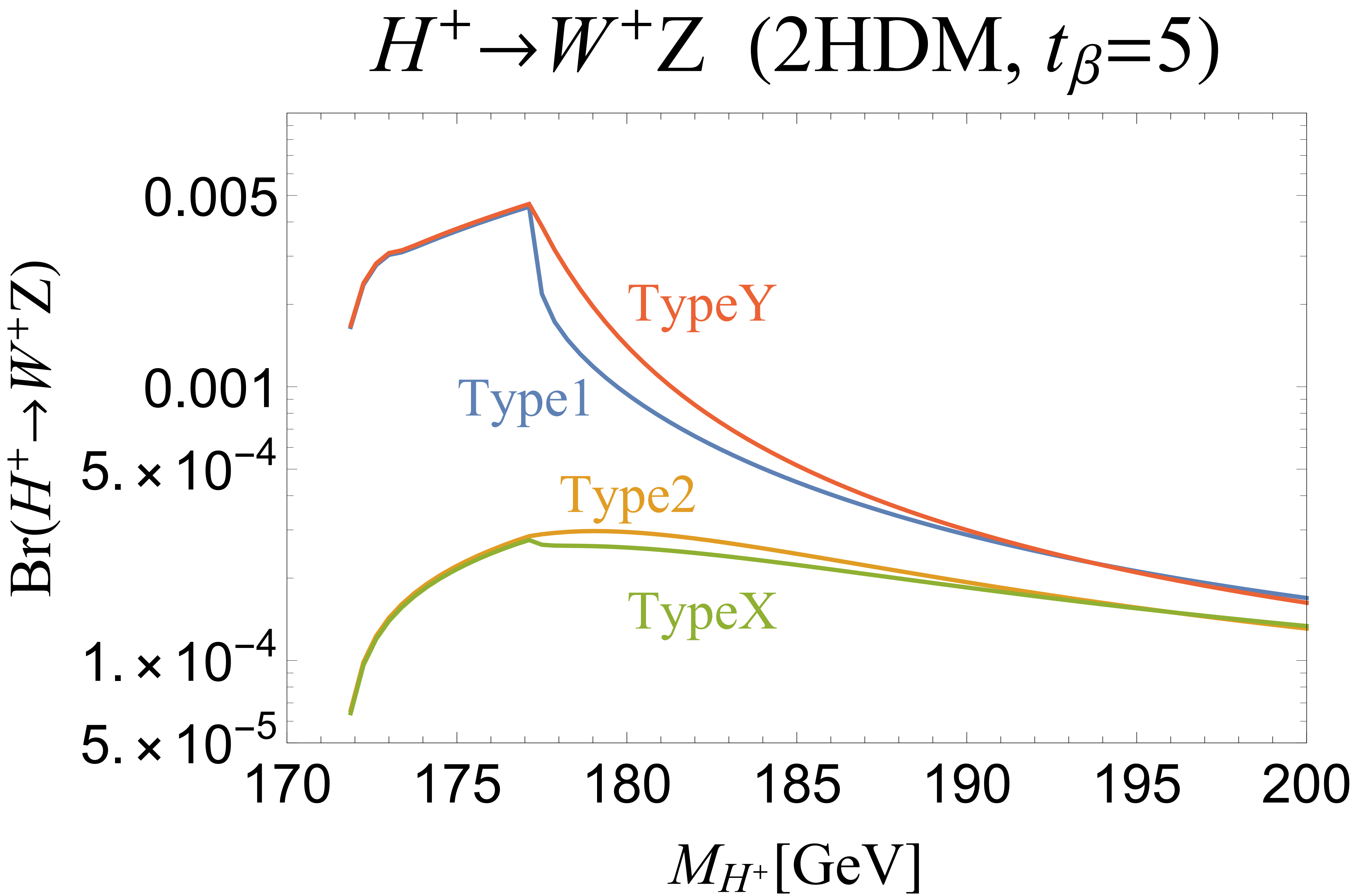


At most 10^{-4}

After $M_{H^\pm} > m_t + m_b$, 10^{-5}

t_β dependence





Further suppression if we want $Z \to \ell\ell$

Let’s add new fermions in the loop: VL fermions

VLQ

- If the scalar sector only includes SU(2) doublets, new VLQ coupling to the SM ones with renormalizable couplings allow only

$$
\begin{aligned}
& T^0_{L,R}, \quad B^0_{L,R} \quad \text{(singlets)}, \\
& \boxed{(X T^0)_{L,R}, \quad (T^0 B^0)_{L,R},} \quad (B^0 Y)_{L,R} \quad \text{(doublets)}, \\
& (X T^0 B^0)_{L,R}, \quad (T^0 B^0 Y)_{L,R} \quad \text{(triplets)}.
\end{aligned}
$$

Introduce both doublet and singlet

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

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

Crucial to allow the Higgs Yukawa couplings

Then we can write down the Yukawa couplings

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

Strategy to enhance W+photon

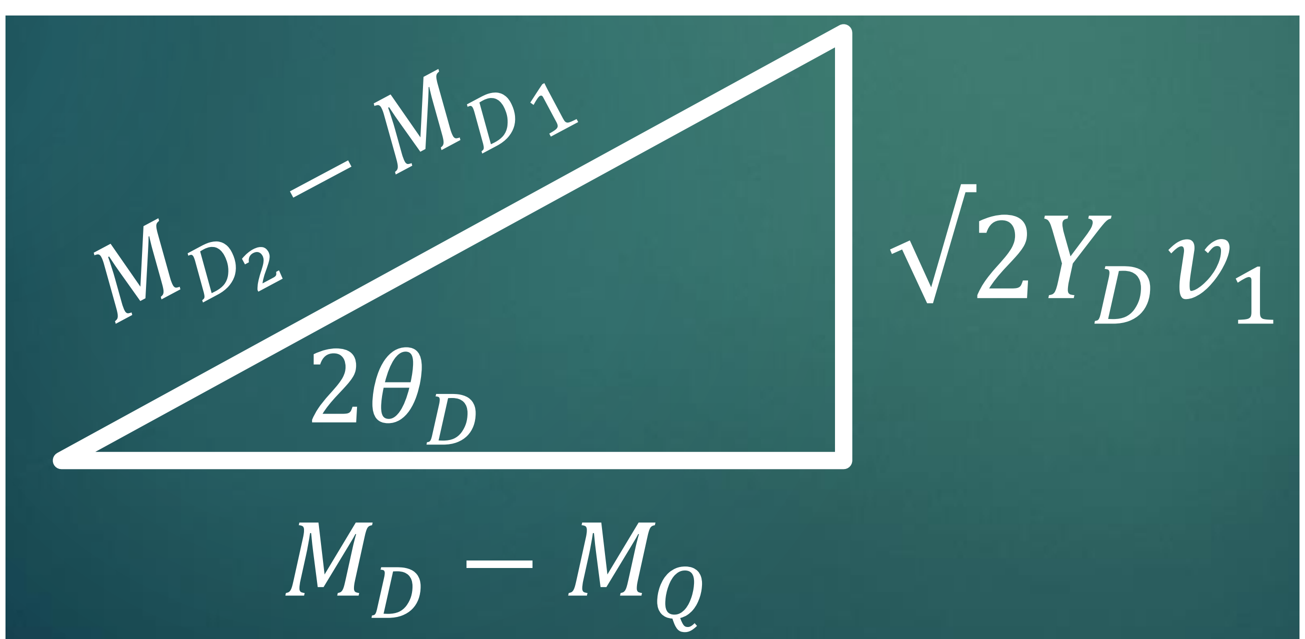
- SM fermions: Type-1
- VLQs: Type-2

$$Y_U \equiv Y_{U_2},\ Y_{U_1} = 0\,,$$

$$Y_D \equiv Y_{D_1},\ Y_{D_2} = 0\,.$$

Mixing b/w doublet and singlet

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



$$V_D = \begin{pmatrix} \cos\theta_D & -\sin\theta_D \\ \sin\theta_D & \cos\theta_D \end{pmatrix}$$

Interactions in terms of mass eigenstates

$$
\begin{aligned}
y_{hD_1D_1} &= -Y_D \xi_h^D s_{2D}/\sqrt{2}\,, \\
y_{hD_1D_2} &= Y_D \xi_h^D c_{2D}/\sqrt{2}\,, \\
y_{hD_2D_1} &= Y_D \xi_h^D c_{2D}/\sqrt{2}\,, \\
y_{hD_2D_2} &= Y_D \xi_h^D s_{2D}/\sqrt{2}\,,
\end{aligned}
$$

If $\theta_D \ll 1$

$$y_{hD_1D_1} = -Y_D \xi_h^D s_{2D}/\sqrt{2}\,, \longrightarrow 0$$

$$y_{hD_1D_2} = Y_D \xi_h^D c_{2D}/\sqrt{2}\,,$$

$$y_{hD_2D_1} = Y_D \xi_h^D c_{2D}/\sqrt{2}\,,$$

$$y_{hD_2D_2} = Y_D \xi_h^D s_{2D}/\sqrt{2}\,, \longrightarrow 0$$

Gauge couplings

$$g_{WD_1U_1} = c_U c_D \, , \;\; g_{WD_1U_2} = s_U c_D$$

$$g_{WD_2U_1} = c_U s_D \, , \;\; g_{WD_2U_2} = s_U s_D$$

$$g_{ZU_1U_1} = g_V^U c_U^2 + g_V^u s_U^2 \, , \quad g_{ZU_2U_2} = g_V^U s_U^2 + g_V^u c_U^2 \, ,$$

$$g_{ZU_1U_2} = g_{ZU_2U_1} = (g_V^U - g_V^u) s_U c_U \, ,$$

$$g_V^F = \frac{1}{2} T_F^3 - Q_F s_W^2$$

W/Z couplings with mixed VLQs

$$g_{WD_1U_1} = c_U c_D \,, \quad g_{WD_1U_2} = s_U c_D$$

$$g_{WD_2U_1} = c_U s_D \,, \quad g_{WD_2U_2} = s_U s_D$$

$$g_{ZU_1U_1} = g_V^U c_U^2 + g_V^u s_U^2 \,, \quad g_{ZU_2U_2} = g_V^U s_U^2 + g_V^u c_U^2 \,,$$

$$g_{ZU_1U_2} = g_{ZU_2U_1} = (g_V^U - g_V^u) s_U c_U ,$$

$$g_V^F = \frac{1}{2} T_F^3 - Q_F s_W^2$$

If $\theta_D \ll 1$

$$g_{WD_1U_1} = c_U c_D \,, \quad g_{WD_1U_2} = s_U c_D \quad \rightarrow \quad \mathbf{0}$$

$$g_{WD_2U_1} = c_U s_D \,, \quad g_{WD_2U_2} = s_U s_D \quad \rightarrow \quad \mathbf{0}$$

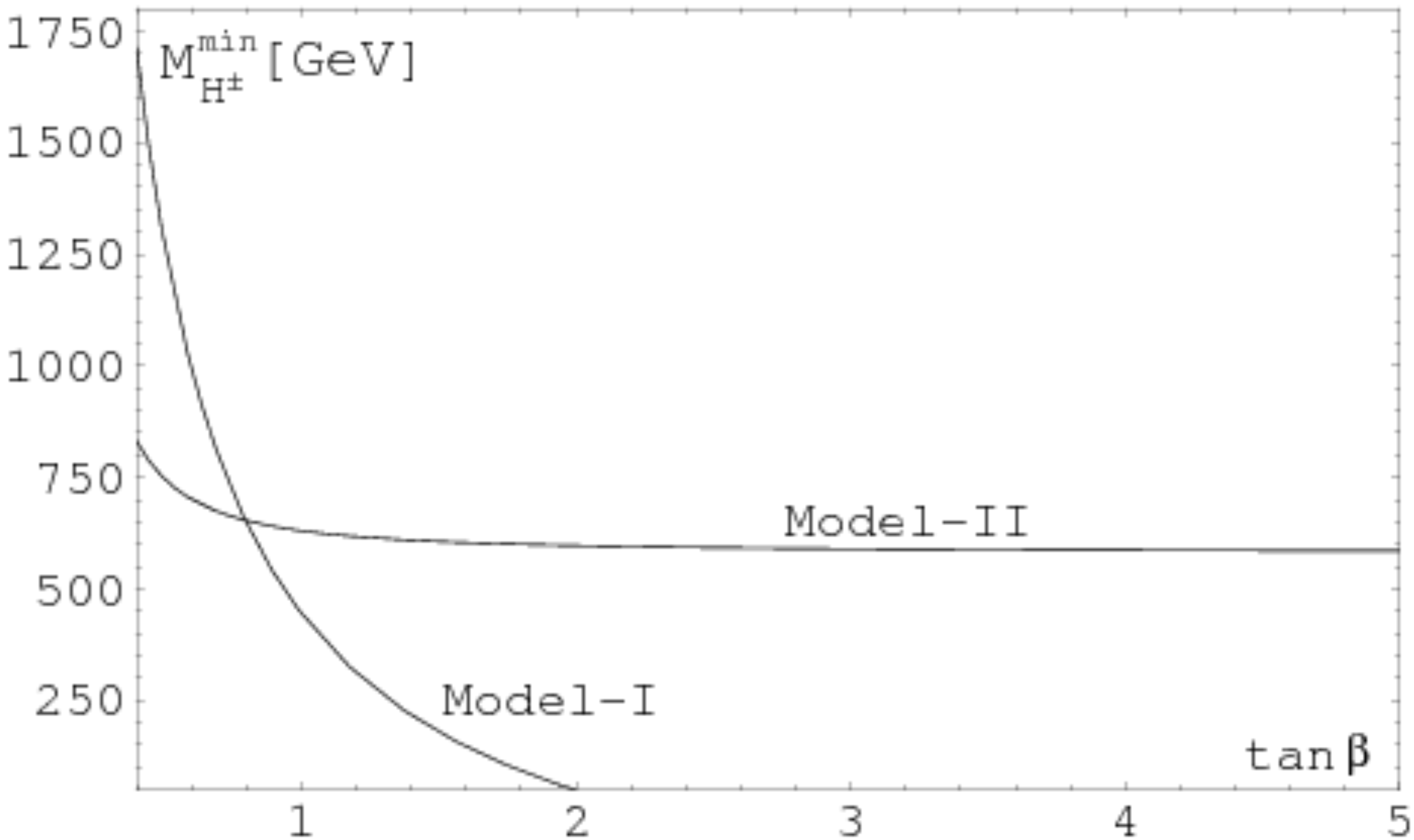
$$g_{ZU_1U_1} = g_V^U c_U^2 + g_V^u s_U^2 \,, \quad g_{ZU_2U_2} = g_V^U s_U^2 + g_V^u c_U^2 \,,$$

$$g_{ZU_1U_2} = g_{ZU_2U_1} = (g_V^U - g_V^u) s_U c_U \,, \quad \rightarrow \quad \mathbf{0}$$

W/Z couplings: no mixed VLQs

Constraints

A. Constraints from $b \to s\gamma$.



For $t_\beta > 2$, $M_{H^\pm} \sim m_t$ is possible in Type I

B. Constraints from Higgs precision

$$0.6 < |\kappa_g| < 1.12\,.$$

$$\kappa_g = 1 + \frac{\sum_{q=VLQs} y_{hqq}\, v/m_q\, A^H_{1/2}(\tau_q)}{A^H_{1/2}(\tau_t)}$$

OK!

B. Constraints from Higgs precision

$$0.6 < |\kappa_g| < 1.12\,.$$

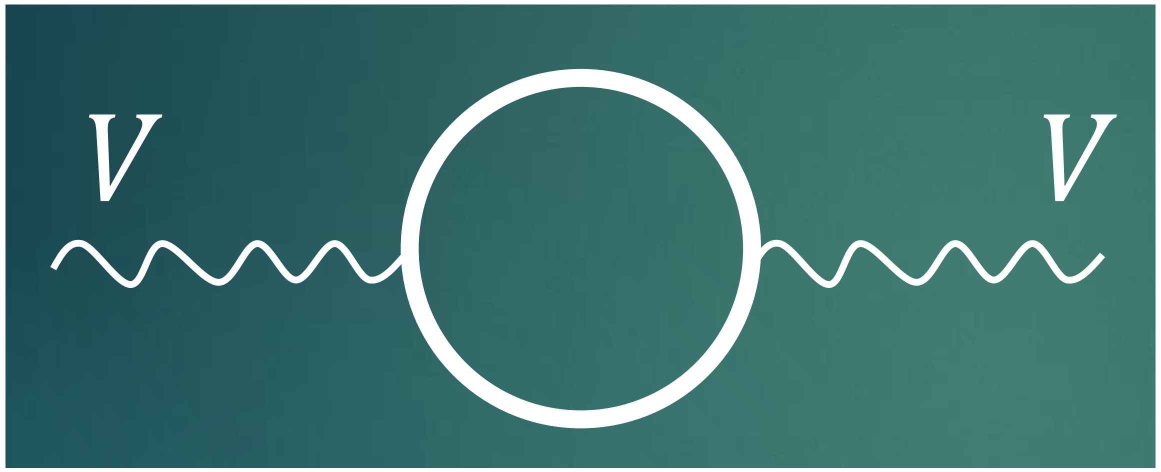
$$\kappa_g = 1 + \frac{\sum_{q=VLQs} y_{hqq}\, v/m_q\, A^H_{1/2}(\tau_q)}{A^H_{1/2}(\tau_t)}$$

$$y_{hD_1D_1} = -Y_D \xi^D_h s_{2D}/\sqrt{2}\,,$$

$$y_{hD_2D_2} = Y_D \xi^D_h s_{2D}/\sqrt{2}\,.$$

Cancellation!

C. Constraints from $\hat{T}$ parameter



Oblique parameters: S, T, U

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

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

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

In the SM!

Peskin, Takeuchi, PRD (1992)

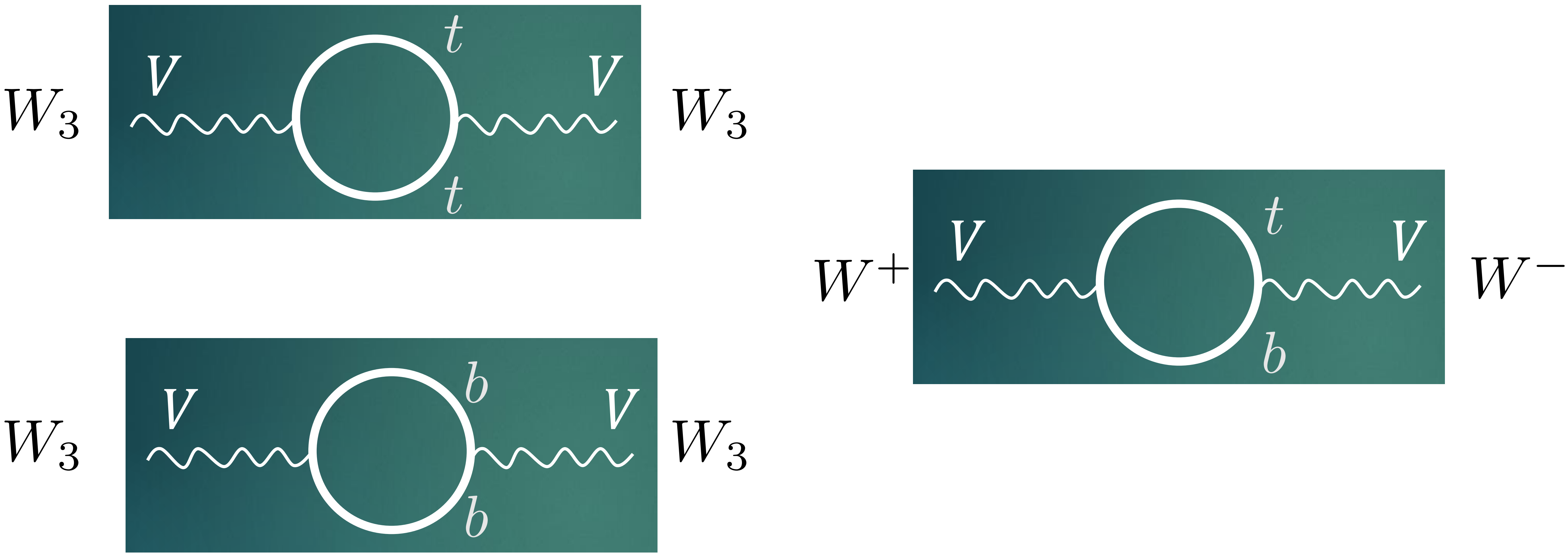
Later we shall consider large mass difference like 500 GeV

Why is this allowed by T?

SM?

$$M_W^2 \hat{T} = \Pi_{W_3 W_3}(0) - \Pi_{W^+ W^-}(0),$$

$\Delta M = 0 \rightarrow \Delta T = 0$



0

$\propto \Delta M^2$

$$M_W^2 \hat{T} = \Pi_{W_3 W_3}(0) - \Pi_{W^+ W^-}(0),$$

One VLQ doublet?

No mixing

If $\theta_D \ll 1$

$$g_{WD_1U_1} = c_U c_D \,, \; g_{WD_1U_2} = s_U c_D \rightarrow 0$$

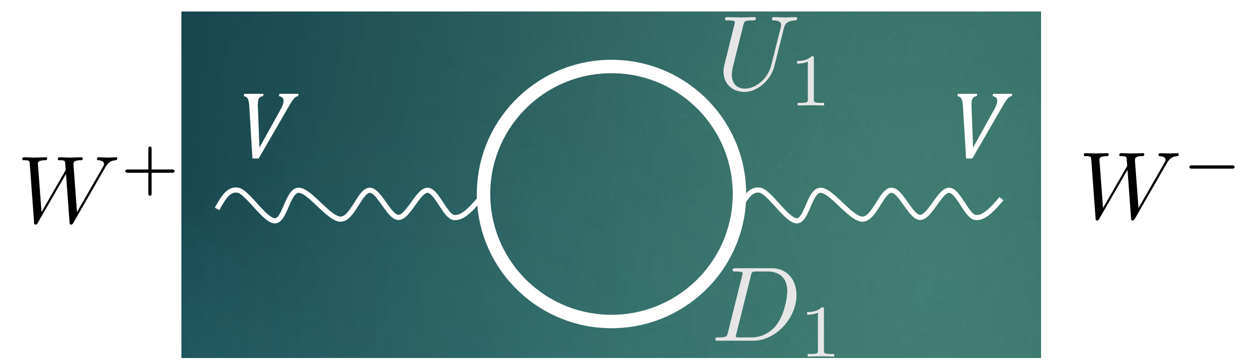
$$g_{WD_2U_1} = c_U s_D \,, \; g_{WD_2U_2} = s_U s_D \rightarrow 0$$

$$g_{ZU_1U_1} = g_V^U c_U^2 + g_V^u s_U^2 \,, \quad g_{ZU_2U_2} = g_V^U s_U^2 + g_V^u c_U^2 \,,$$

$$g_{ZU_1U_2} = g_{ZU_2U_1} = (g_V^U - g_V^u) s_U c_U \,, \rightarrow 0$$

One VLQ doublet?

No mixing



0

$\propto \Delta M^2$

$$M_W^2 \hat{T} = \Pi_{W_3 W_3}(0) - \Pi_{W^+ W^-}(0),$$

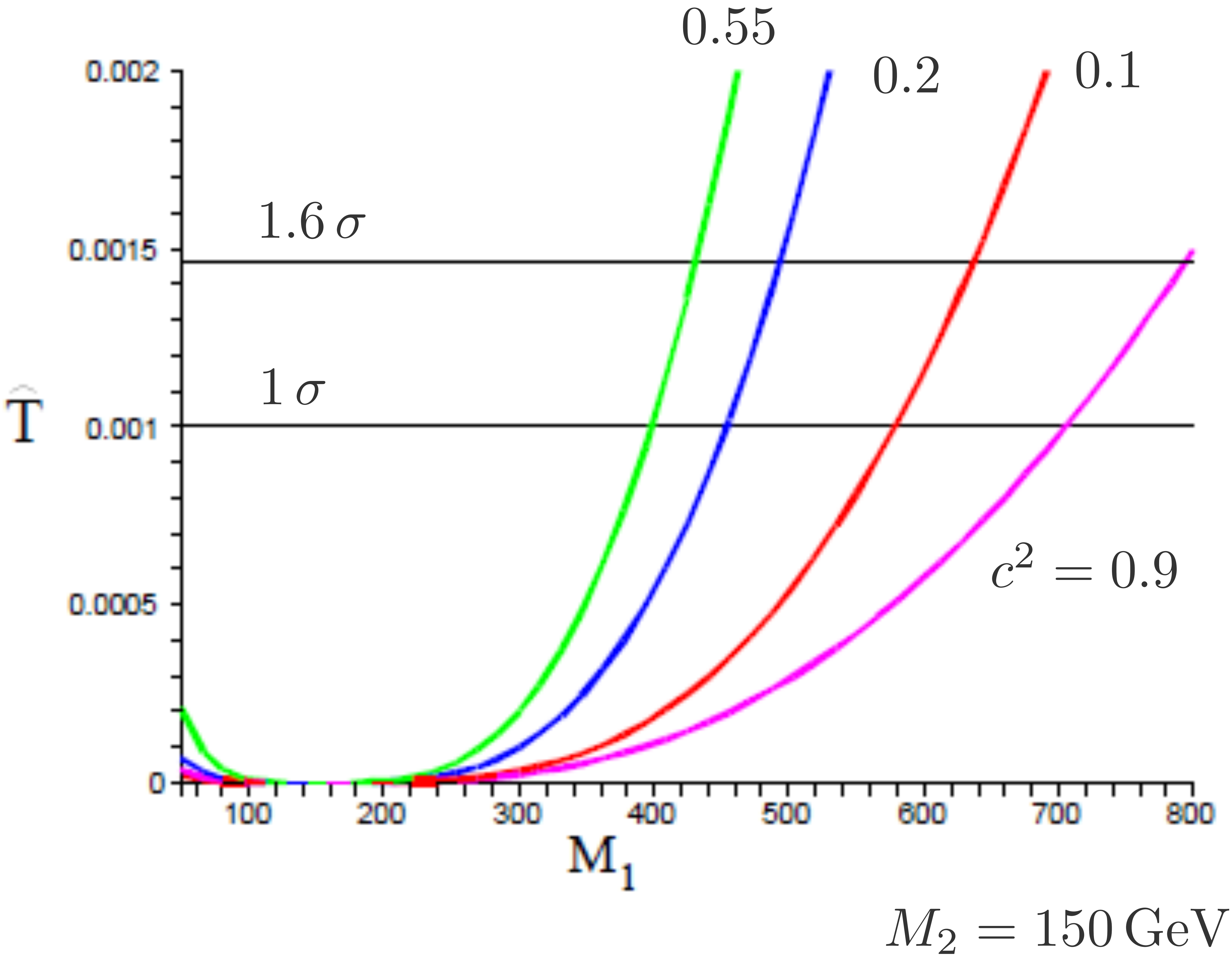
One VLQ doublet + one VLQ singlet

Mixing

$\propto \Delta M^2$ $\quad\quad$ $\propto \Delta M^2$

$$M_W^2 \hat{T} = \Pi_{W_3 W_3}(0) - \Pi_{W^+ W^-}(0),$$

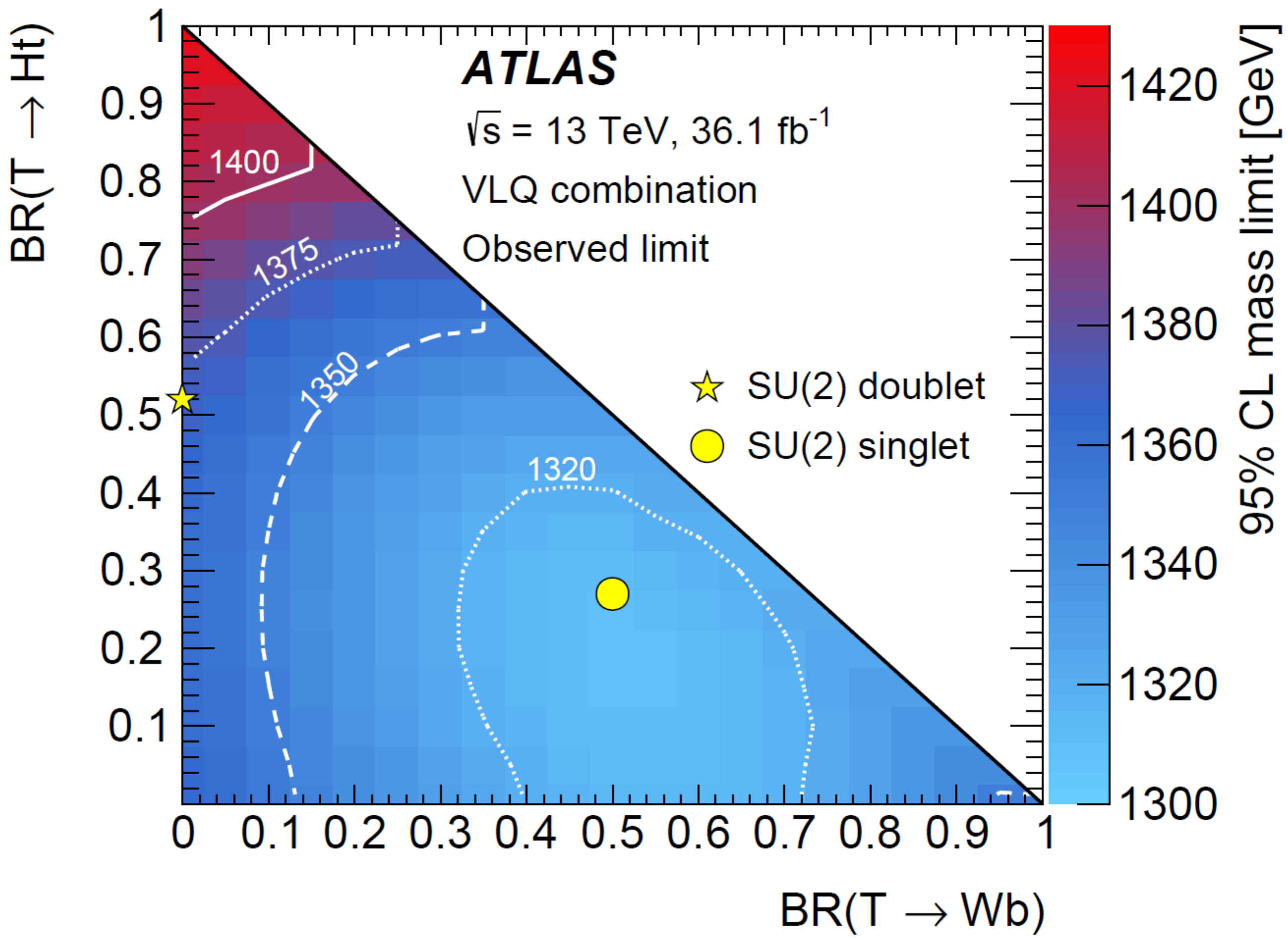
Cancellation!

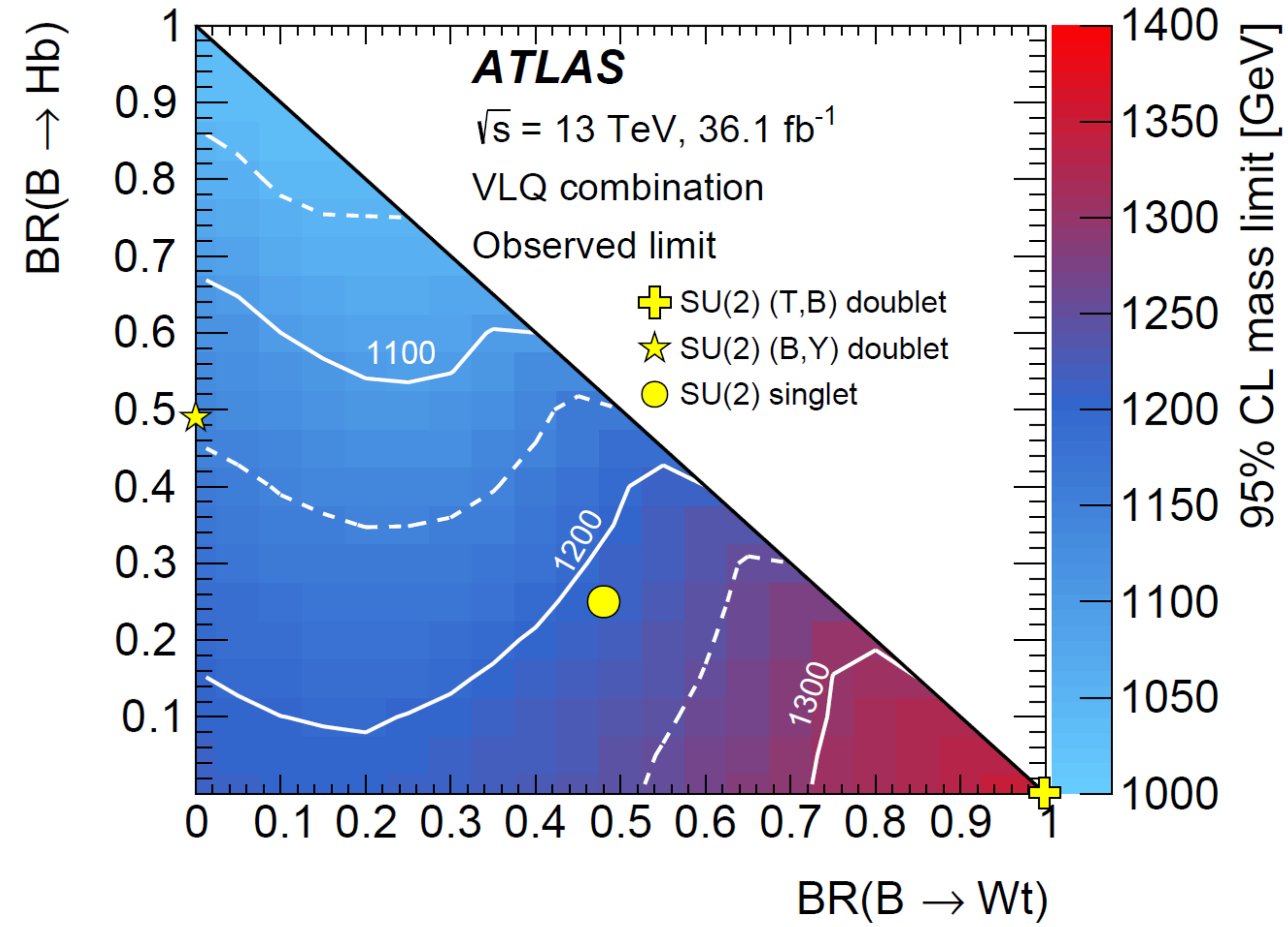


0.55
0.2
0.1
0.002
0.0015
0.001
0.0005
0
$1.6\,\sigma$
$1\,\sigma$
$\hat{T}$
$c^2 = 0.9$
100
200
300
400
500
600
700
800
M_1
$M_2 = 150\,\text{GeV}$

Direct constraints on the VL fermion masses

ATLAS, 1808.02343

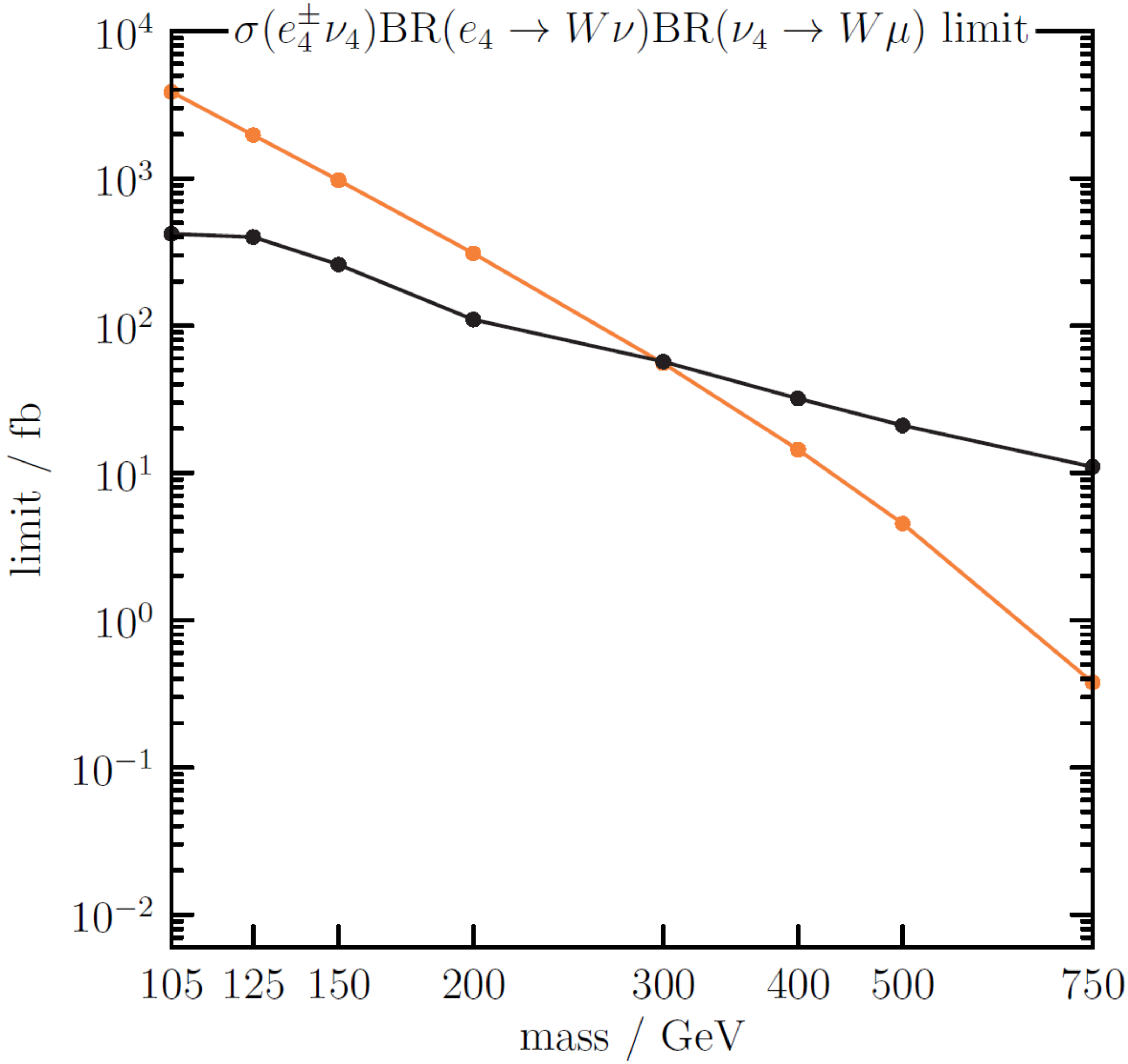




$M_T > 1.31\text{TeV}$ $M_B > 1.03\text{TeV}$

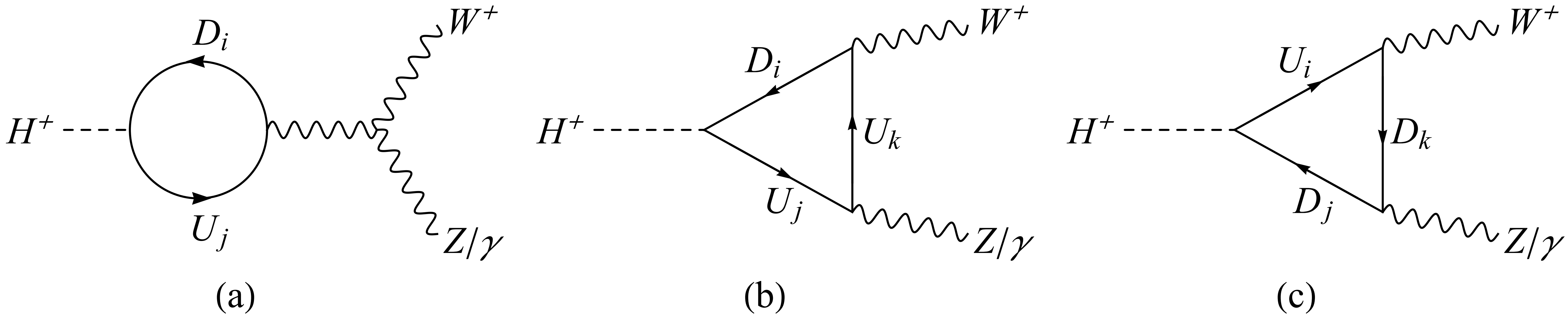
The bounds can be relaxed if the VLQs decay into light quarks.

Dermisek, Hall, Lunghi, Shin, 1408.3123



$M_E > 300\text{GeV}$

$$BR(H^{\pm} \to W^{\pm}\gamma/W^{\pm}Z)$$



$$\mathcal{M} = \frac{g^2 N_c M_{H^+}}{(16\pi^2)\sqrt{2}c_W} \epsilon_W^{\mu *} \epsilon_V^{\nu *} \mathcal{M}_{\mu\nu},$$

$$\mathcal{M}_{\mu\nu} = g_{\mu\nu}\mathcal{M}_1 + \frac{p_{2\mu}p_{1\nu}}{M_{H^-}^2}\mathcal{M}_2 + i\epsilon_{\mu\nu\rho\sigma}\frac{p_{2\rho}p_{1\sigma}}{M_{H^-}^2}\mathcal{M}_3$$

For $W^+\gamma$ decay, the Ward-identity $p_2^\nu M_{\mu\nu} = 0$

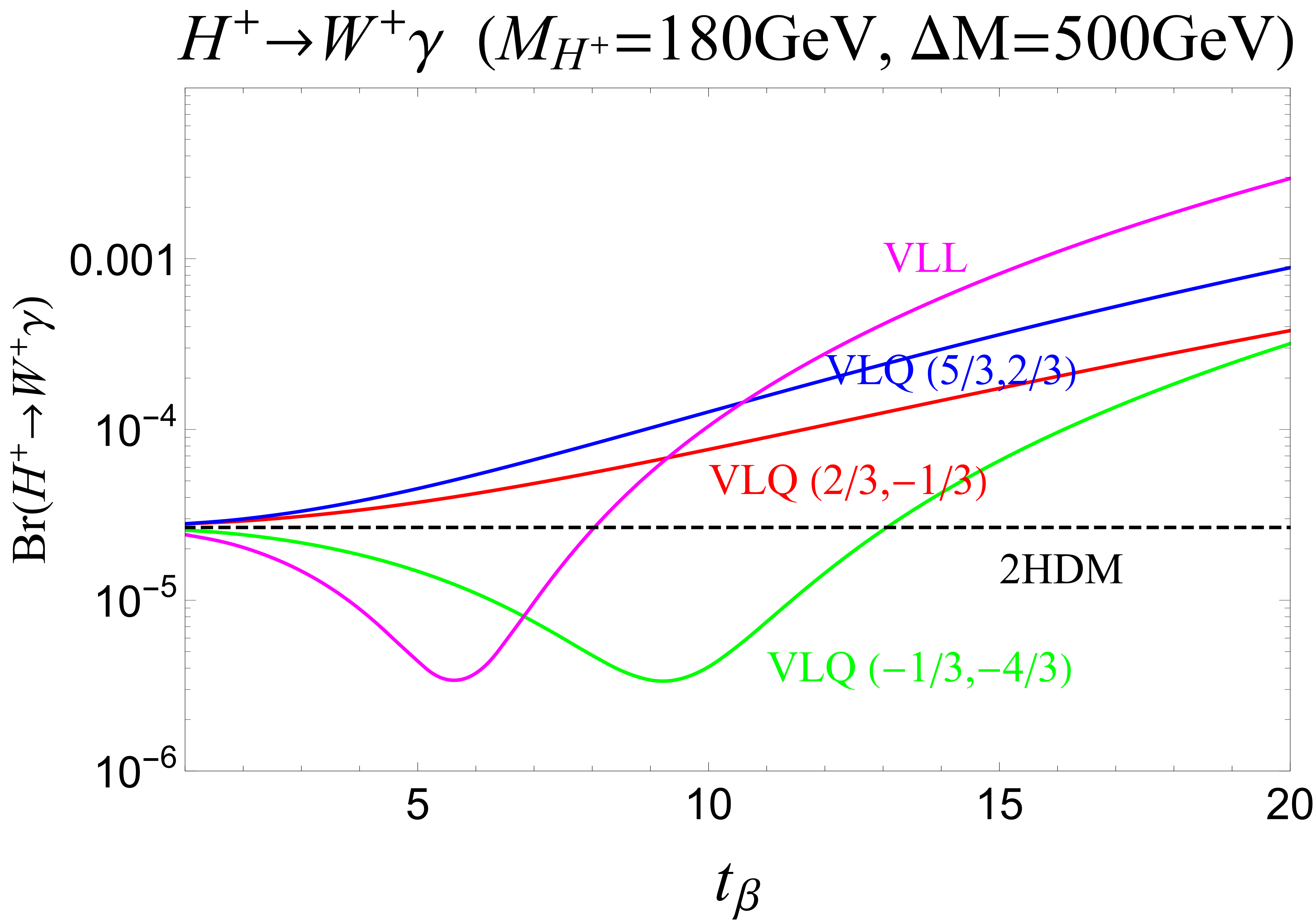
$$\mathcal{M}_1 = -\frac{1}{2}\Big(1 - \frac{m_W^2}{M_{H^+}^2}\Big)\mathcal{M}_2, \quad (\text{for } H^+ \to W^+\gamma)$$

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

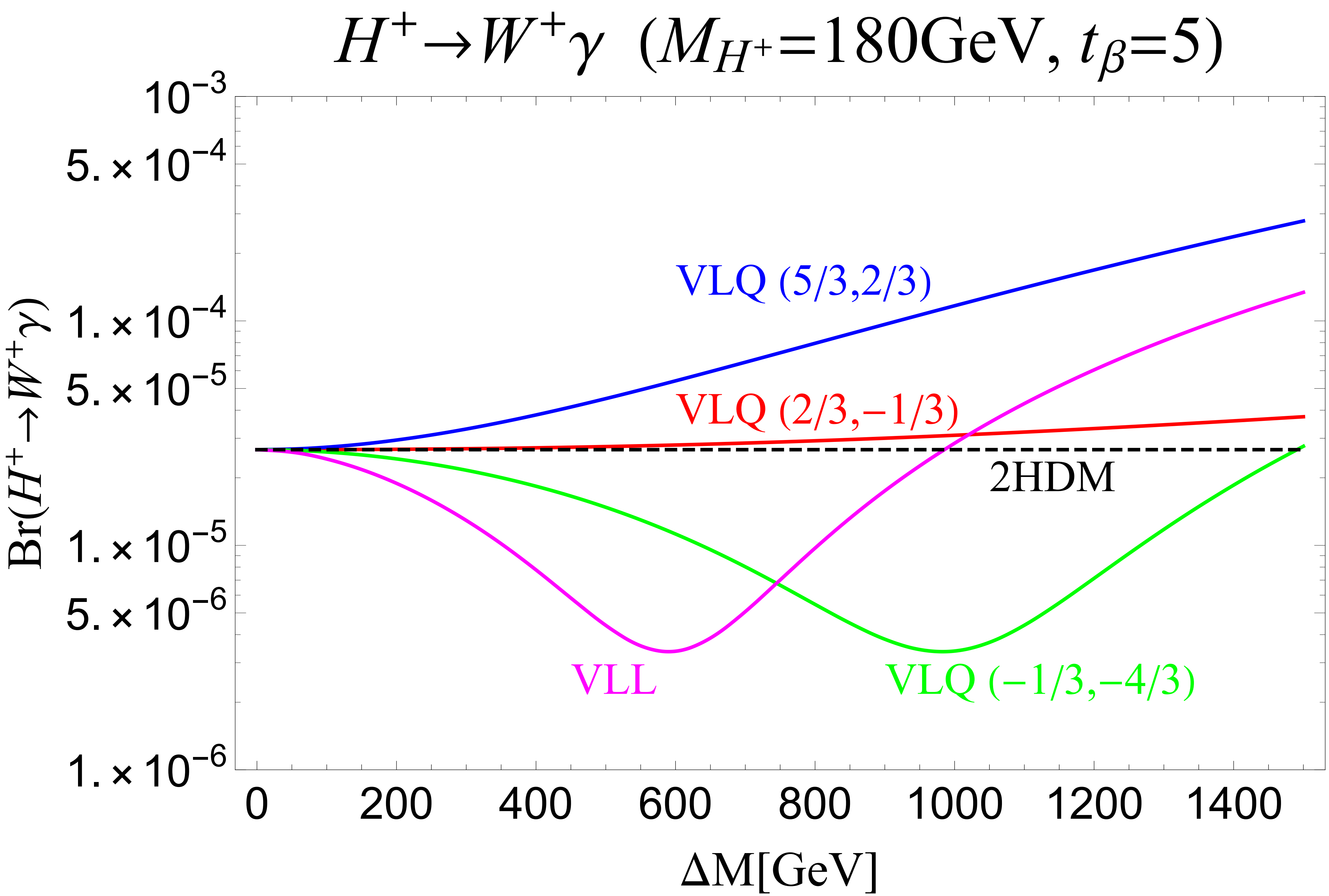
for $H^+ \to W^+ Z$

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

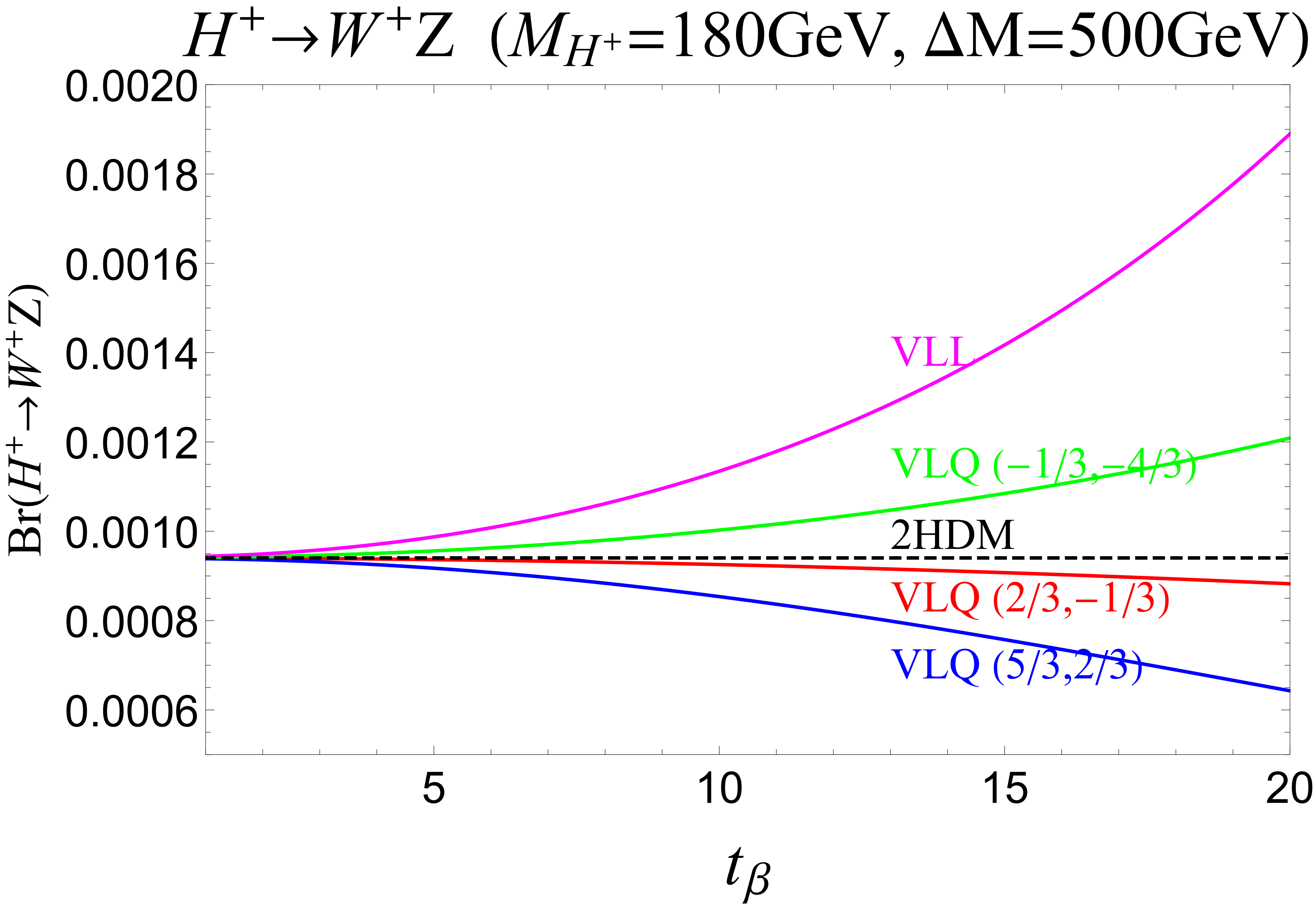
$M_{U_1} = M_{D_1} = 1.3$ TeV, $\theta_{U,D} = 0.2$



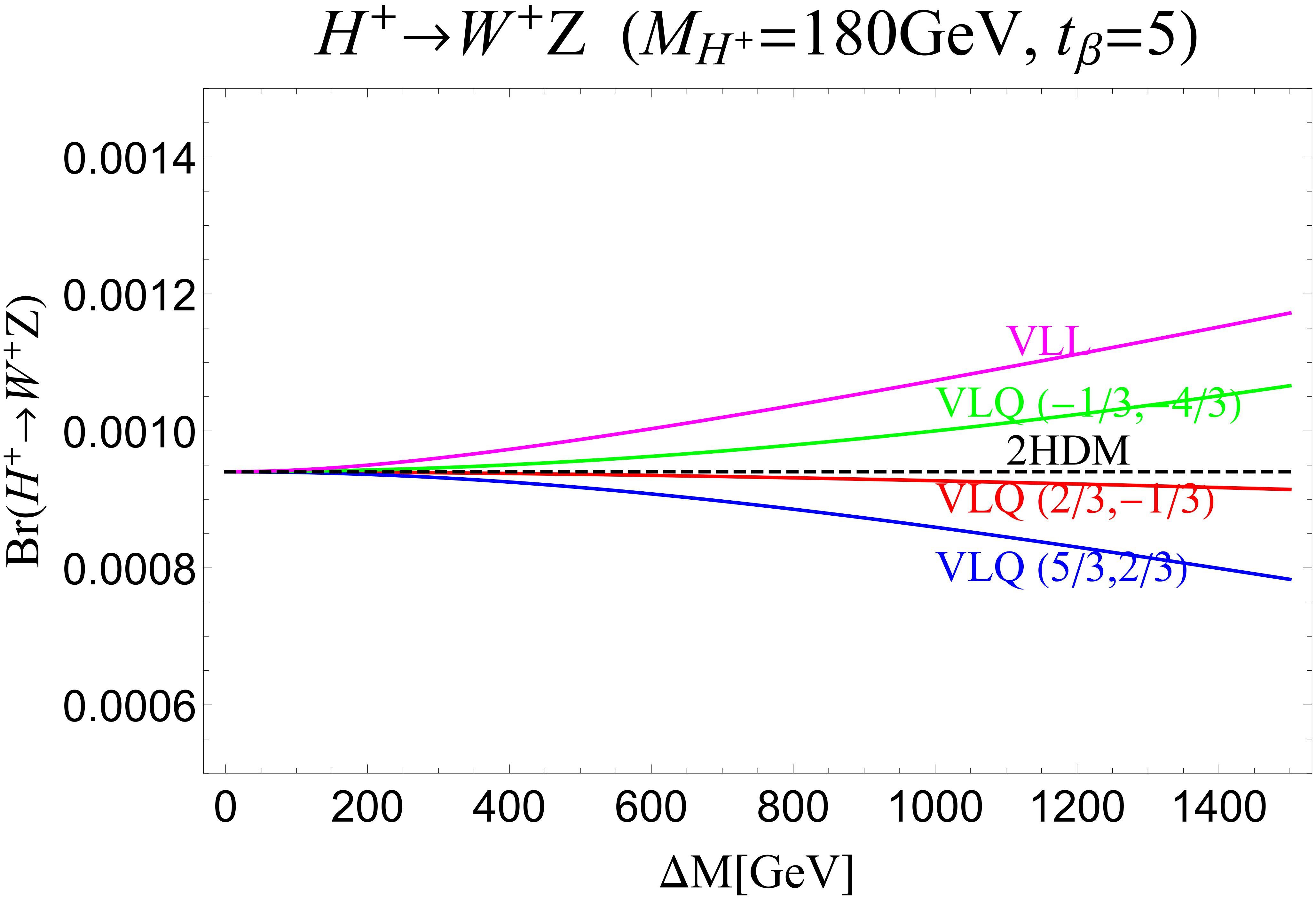
$M_{U_1} = M_{D_1} = 1.3$ TeV, $\theta_{U,D} = 0.2$



$M_{U_1} = M_{D_1} = 1.3$ TeV, $\theta_{U,D} = 0.2$

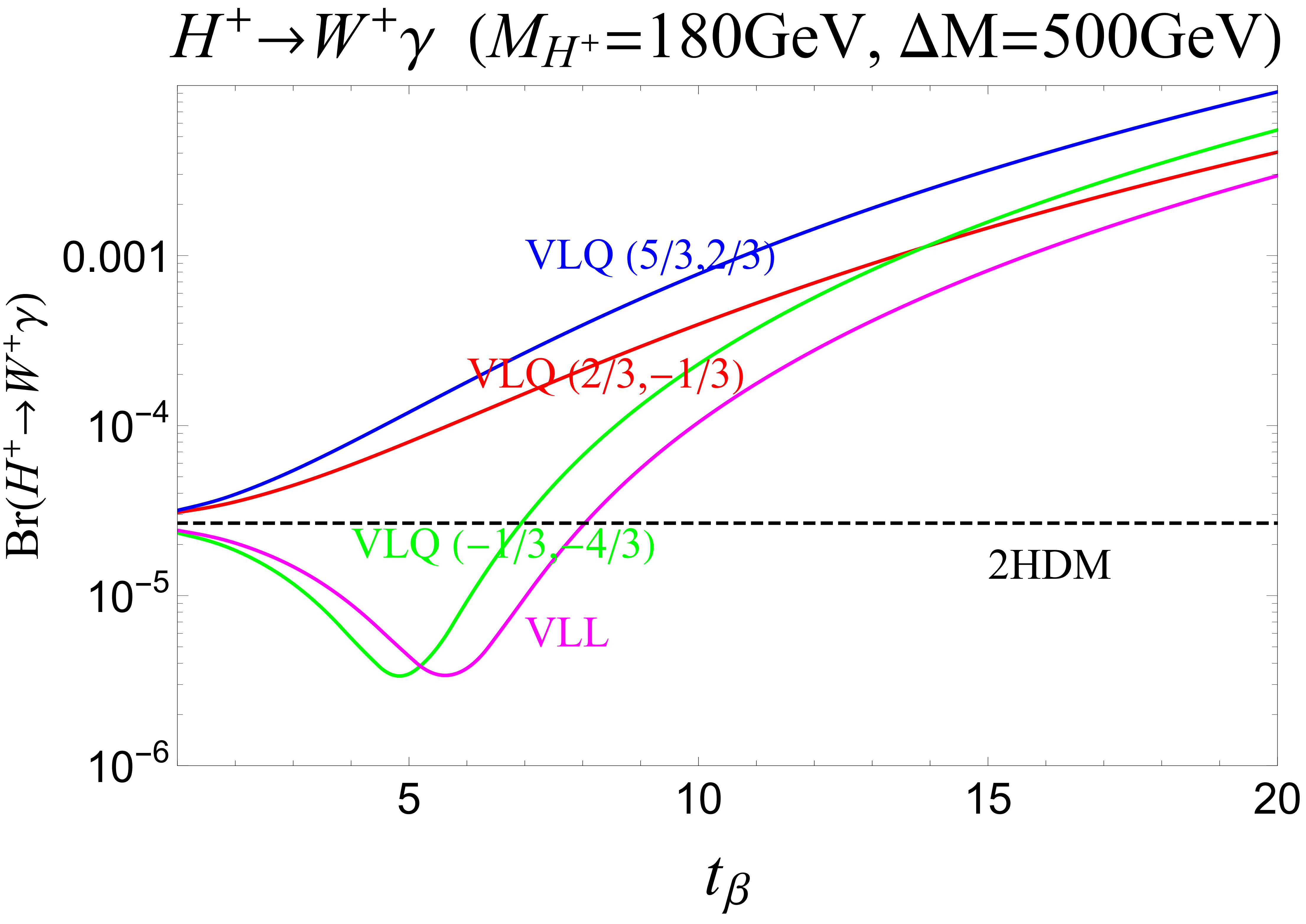


$M_{U_1} = M_{D_1} = 1.3$ TeV, $\theta_{U,D} = 0.2$

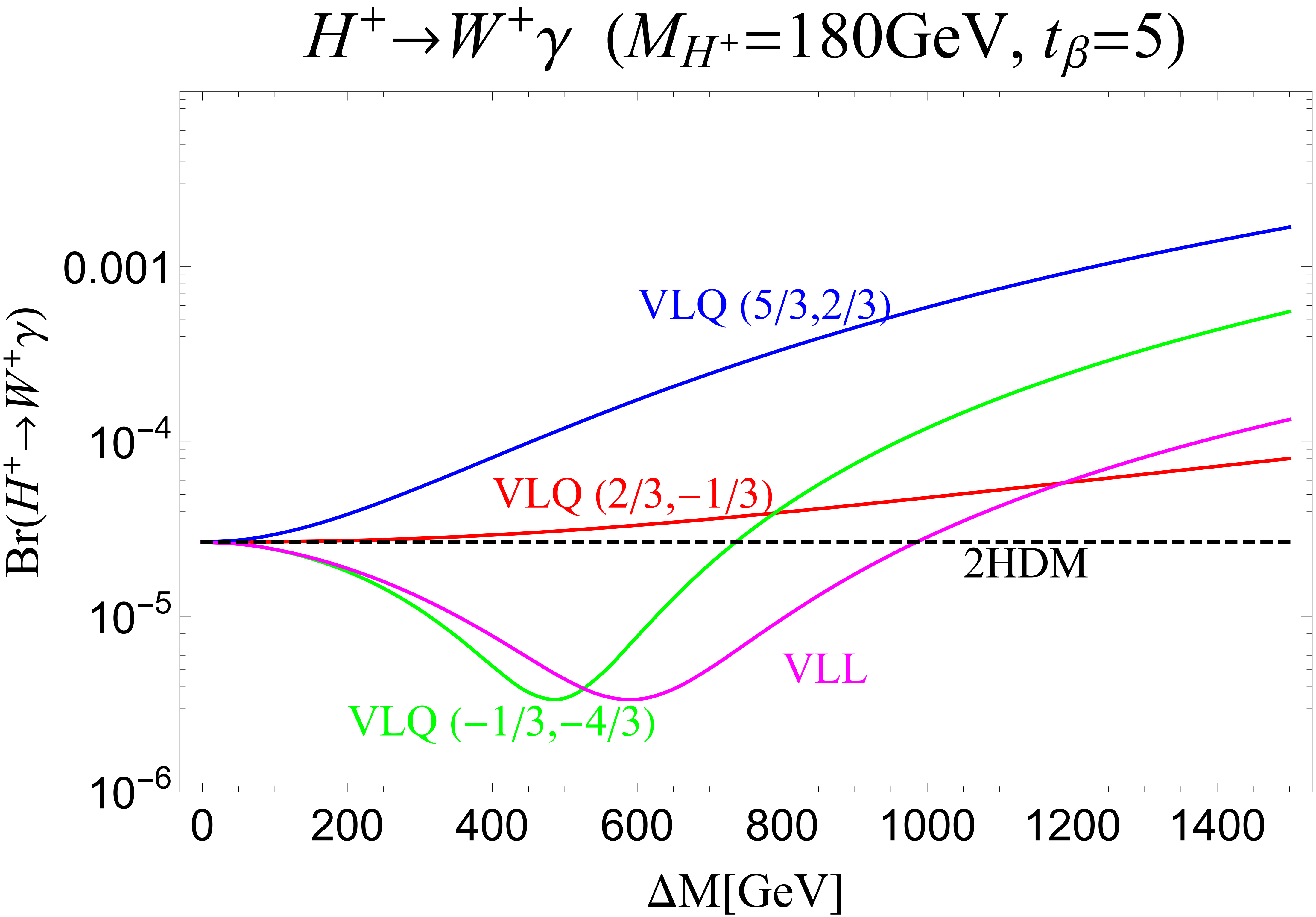


No significant enhancement

$M_{U_1} = M_{D_1} = 650$ GeV, $\theta_{U,D} = 0.2$



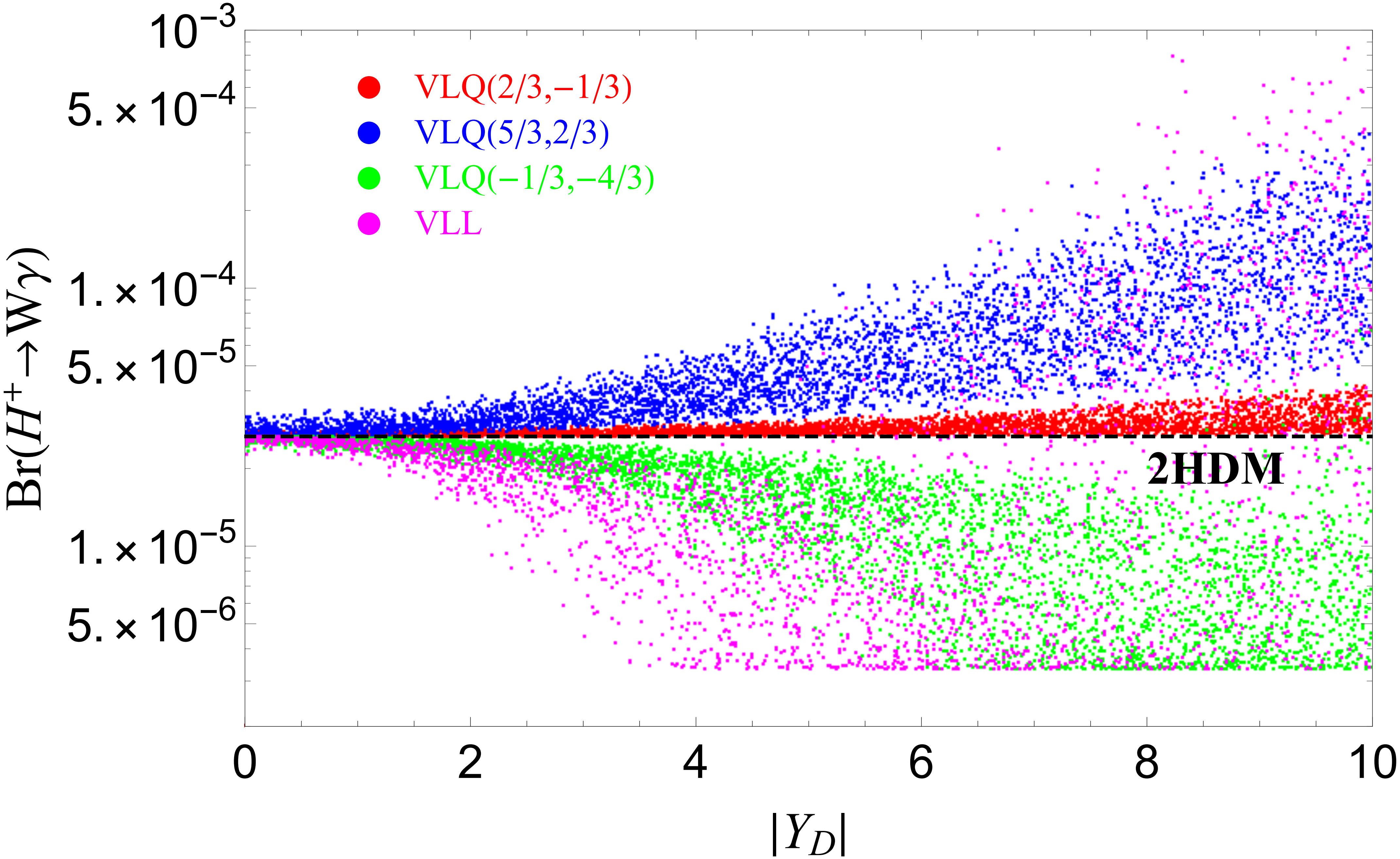
$M_{U_1} = M_{D_1} = 650$ GeV, $\theta_{U,D} = 0.2$



$$\text{VLQ}: \quad M_{U_1} = 1310\,\text{GeV},\ M_{D_1} = 1030\,\text{GeV}$$
$$M_{U_2} \subset [1310, 4000]\,\text{GeV}, \quad M_{U_2} \subset [1030, 4000]\,\text{GeV}$$
$$t_\beta \subset [1, 50], \quad \theta_U, \theta_D \subset \left[-\frac{\pi}{2}, \frac{\pi}{2}\right].$$

$$\text{VLL}: \quad M_{\nu_1} = 300\,\text{GeV},\ M_{e_1} = 300\,\text{GeV},$$
$$M_{\nu_2} \subset [300, 1000]\,\text{GeV}, \quad M_{e_2} \subset [300, 1000]\,\text{GeV}$$
$$t_\beta \subset [1, 50], \quad \theta_\nu, \theta_e \subset \left[-\frac{\pi}{2}, \frac{\pi}{2}\right].$$

$$M_{H^\pm} = 180\,\text{GeV}$$



Conclusions

- $M_{H^\pm} \simeq m_t$ is very tricky to probe.
- A new search channel is into $W^\pm\gamma$ and $W^\pm Z$.
- With the VL fermions, the branching ratio of $W^\pm\gamma$ can be enhanced by a factor of 100.
- $\mathrm{BR}(H^\pm \to W^\pm Z)$ does not show the enhancement.