HPNP 2019 - 4th International workshop on `Higgs as a probe of new physics 2019

Pursuing exotic decay channels of a charged Higgs boson

Jeonghyeon Song

(Konkuk University, Korea)

work in progress w/ Yeo Woong Yoon

Osaka University, 2019. 2. 20.

HPNP 2019 - 4th International workshop on `Higgs as a probe of new physics 2019

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

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Charged Higgs boson in the 2HDM

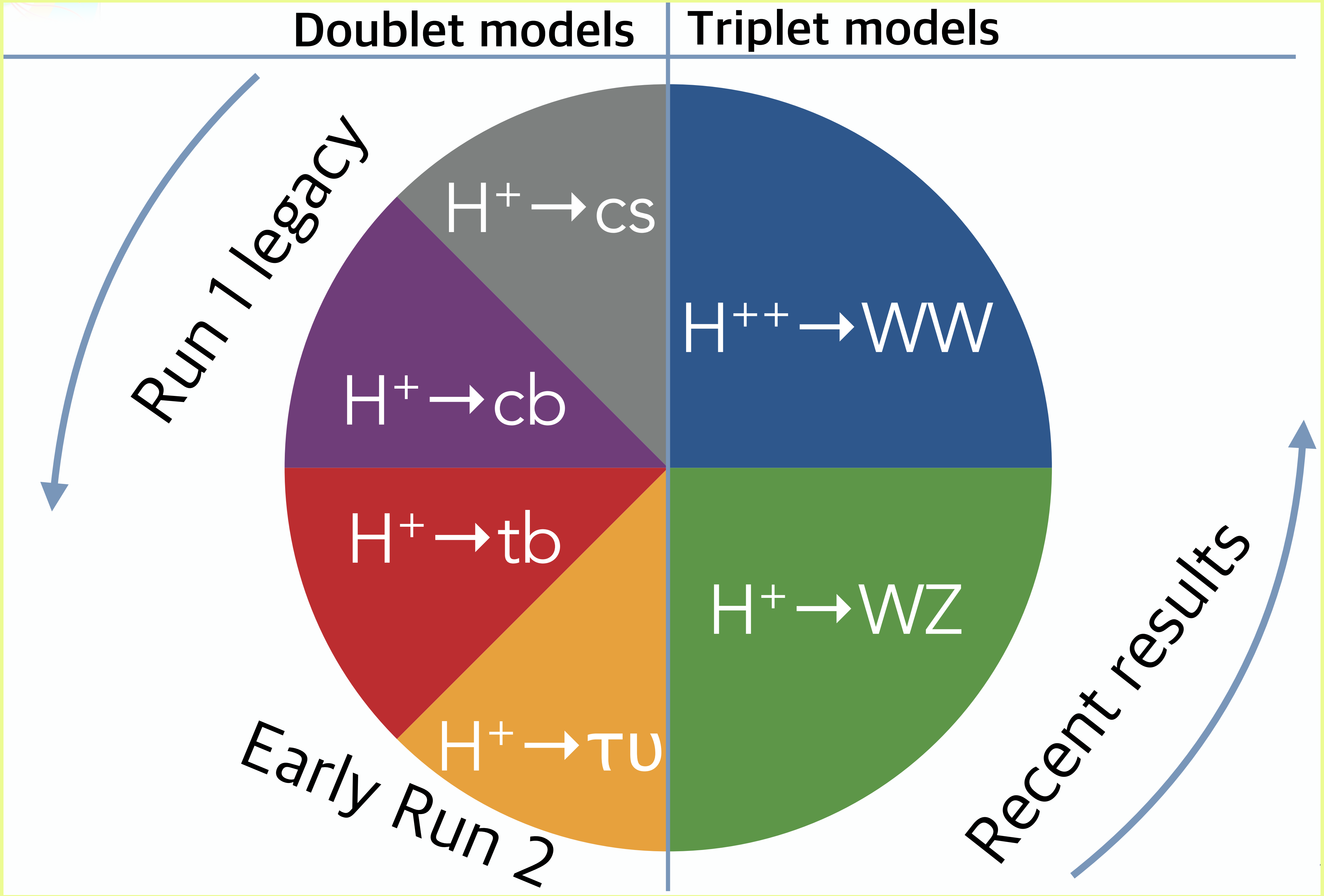
$$\Phi_1 \text{ and } \Phi_2$$

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

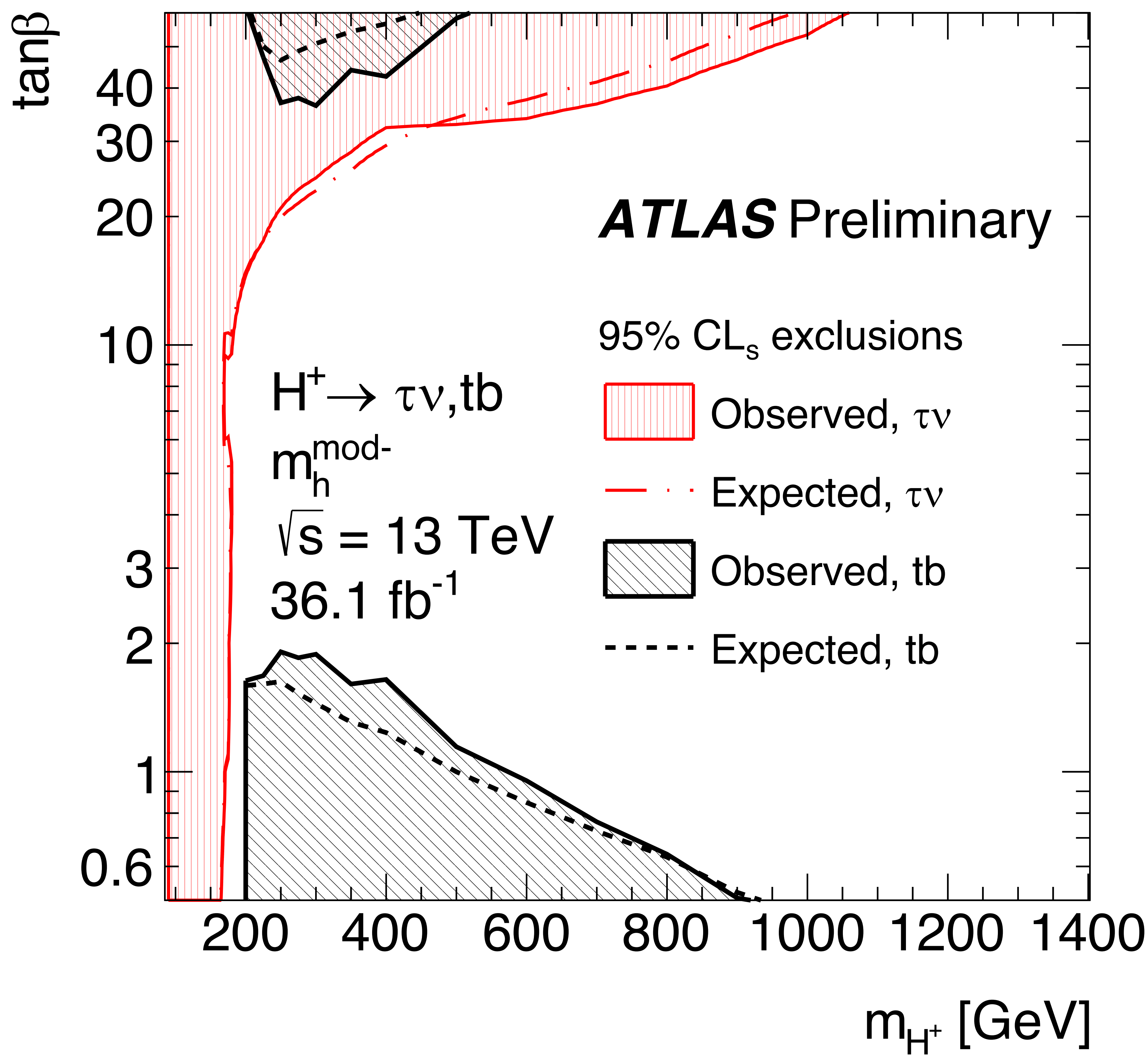
Five physical Higgs bosons

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

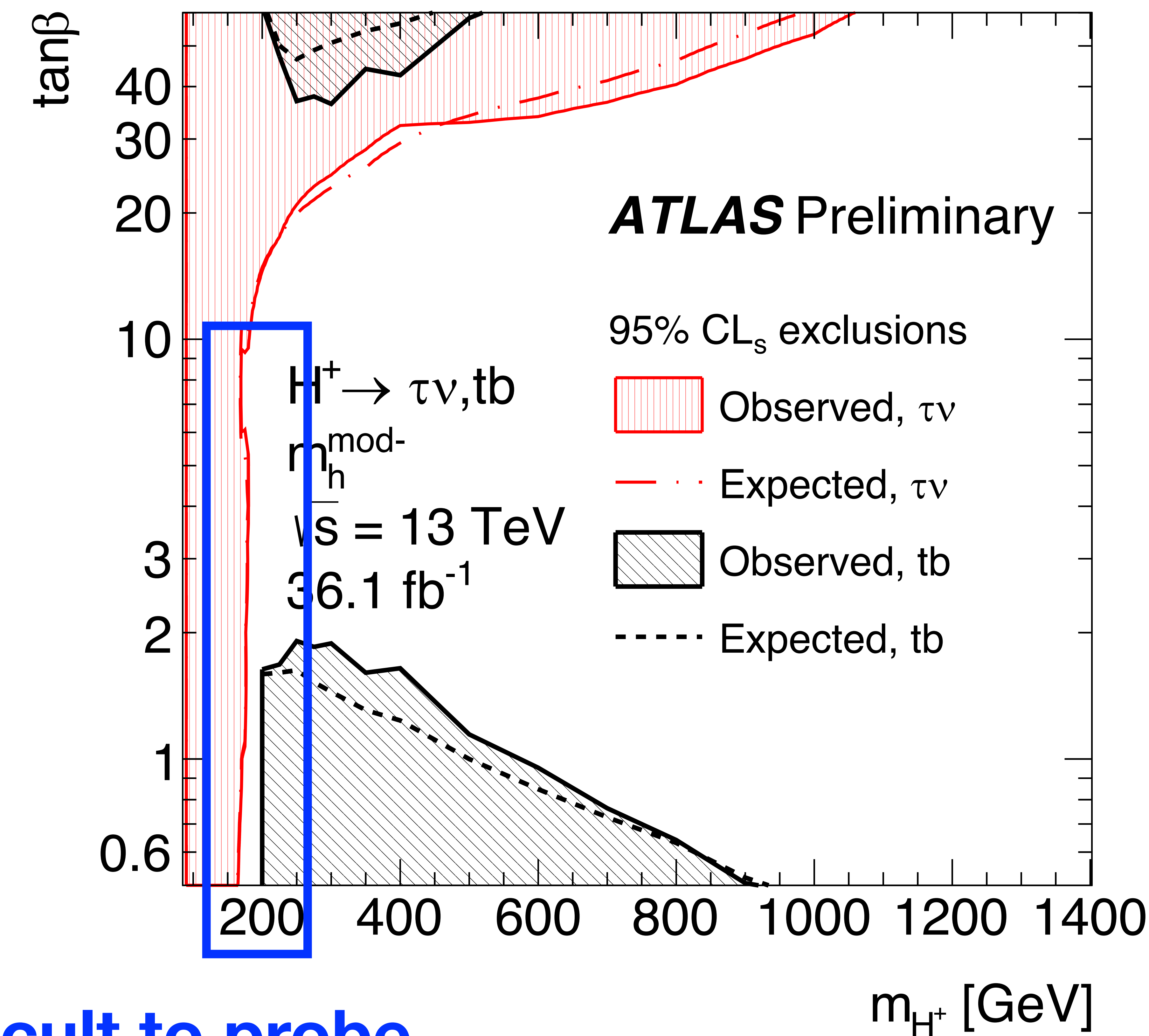
Search for H+ at the LHC



$H^+ \to tb$ and $H^+ \to \tau\nu$ superposition



$H^+ \rightarrow tb$ and $H^+ \rightarrow \tau\nu$ superposition



Very difficult to probe

Possible?

$$M_{H^\pm} \simeq m_t$$

Two Higgs doublets

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

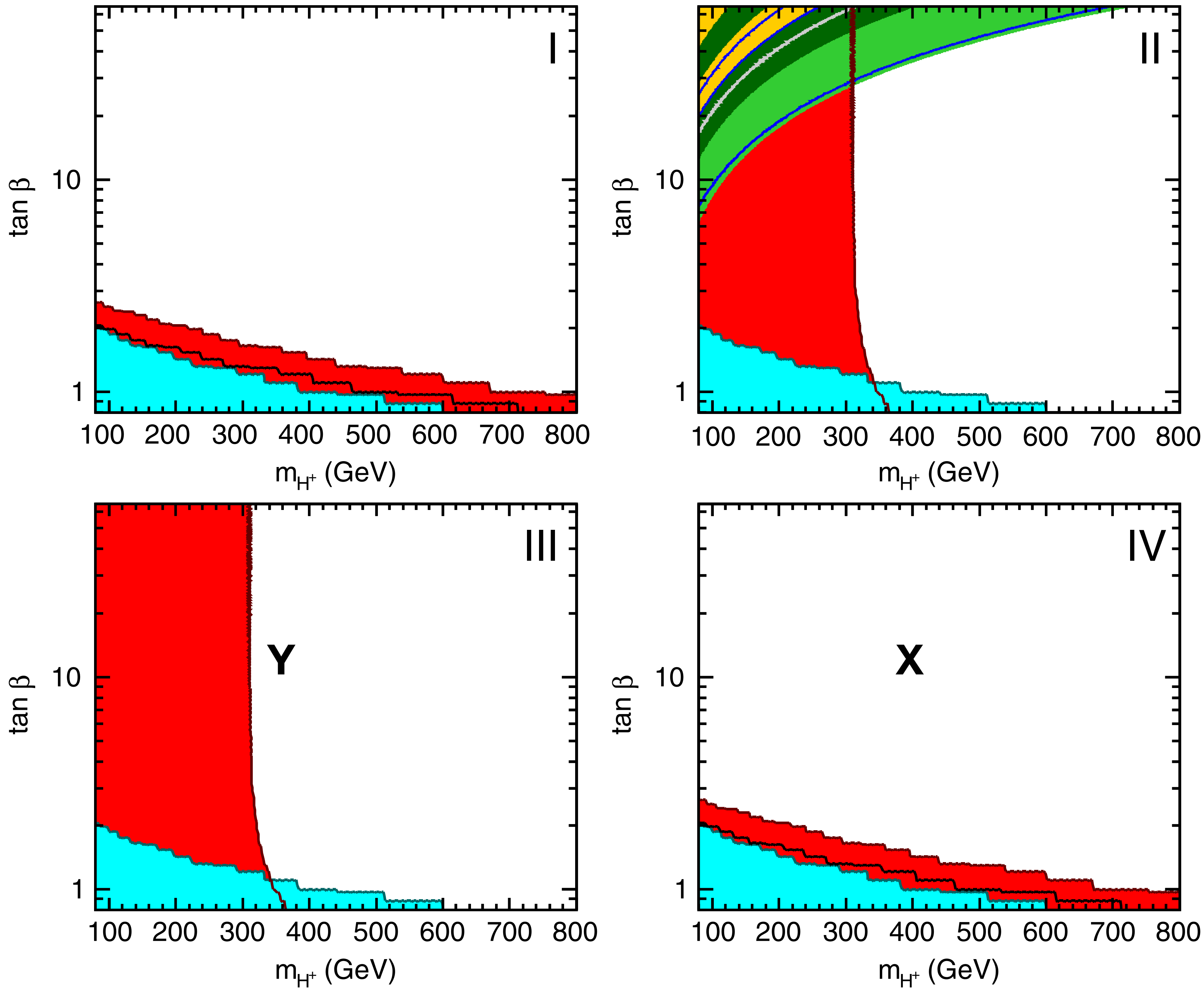
In order to suppress FCNC at tree level, we impose Z2 symmetry

$$\Phi_1 \rightarrow \Phi_1 \quad \text{and} \quad \Phi_2 \rightarrow -\Phi_2$$

4 types
according to Z2 parities

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

FCNC constraint

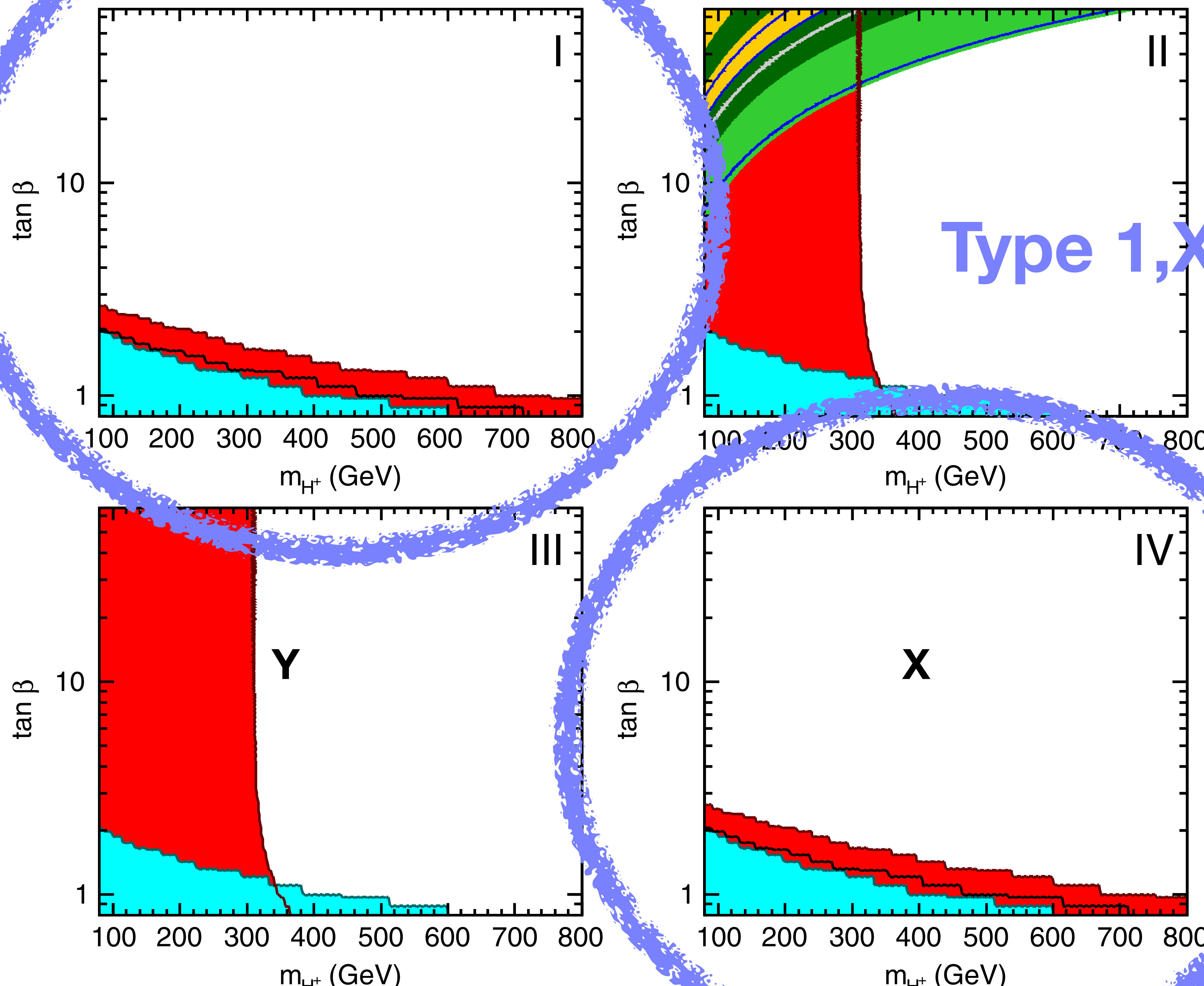


Cyan: ΔM_{bd}

Red: $b \to s\gamma$

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

FCNC constraint

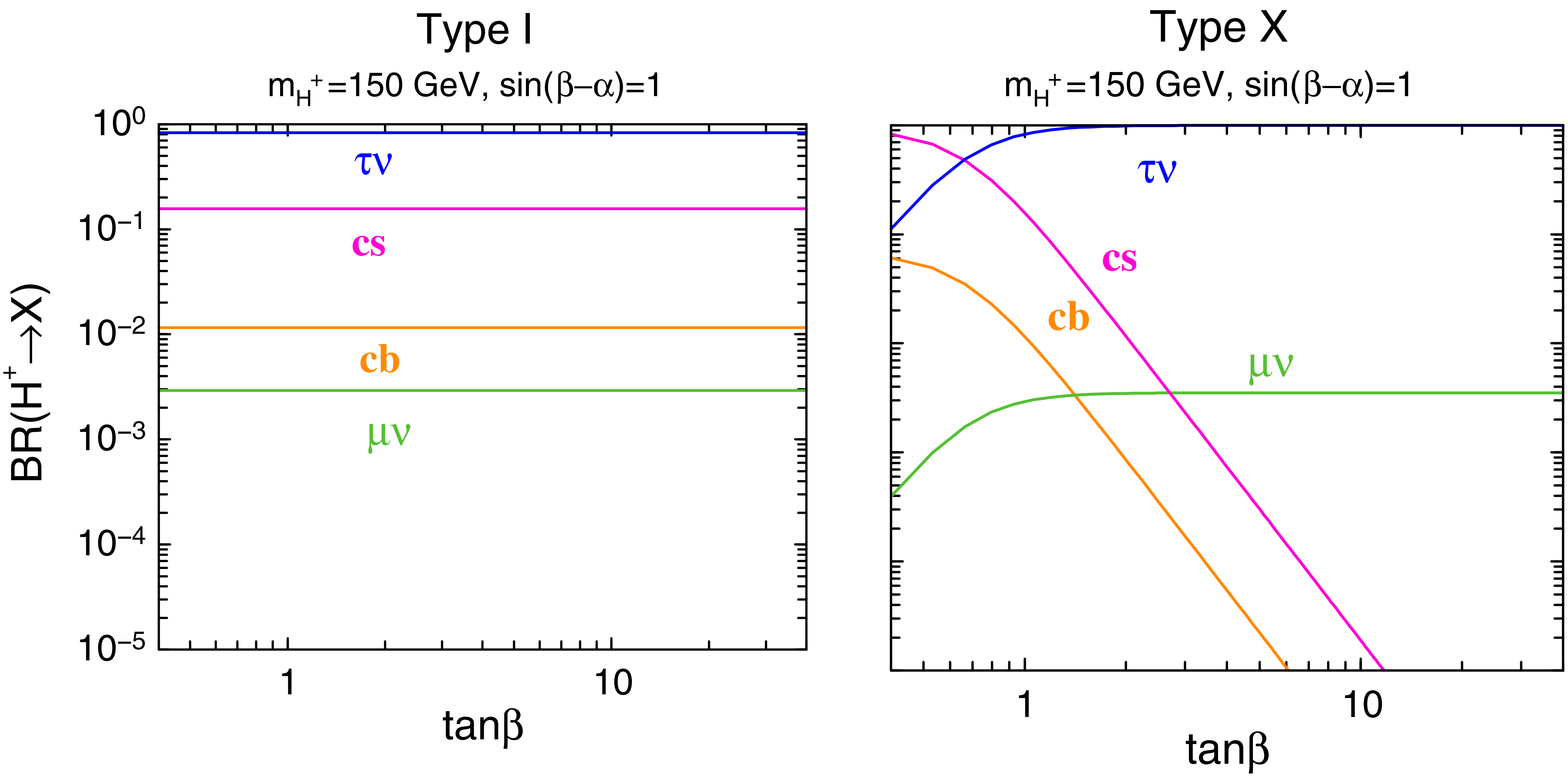


Type 1,X: light H+

Cyan: ΔM_{bd}

Red: $b \to s\gamma$

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



Aoki et.al. PRD 80 (2009)

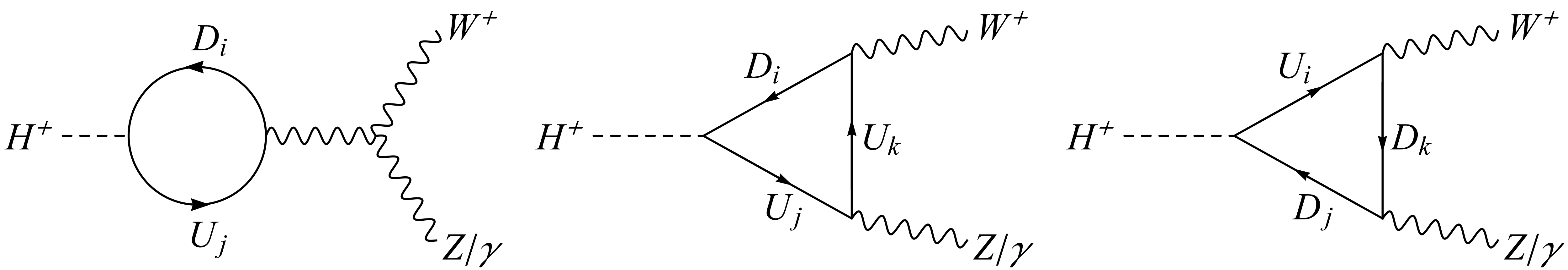
Question
New search channel
for this tricky H+?

$$M_{H^{\pm}} \simeq m_t$$

Possible!

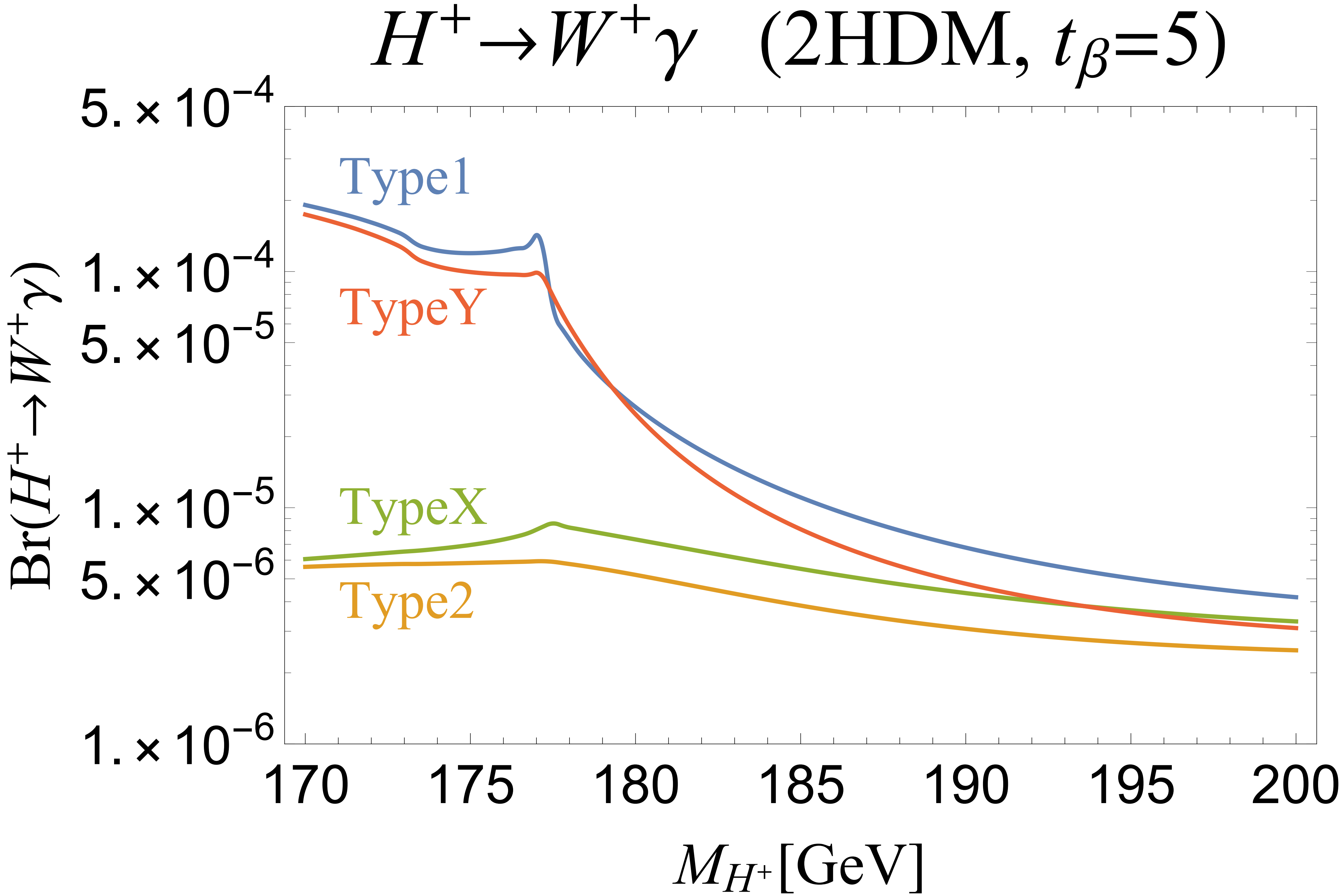
$H^{\pm} \to W^{\pm}\gamma$

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



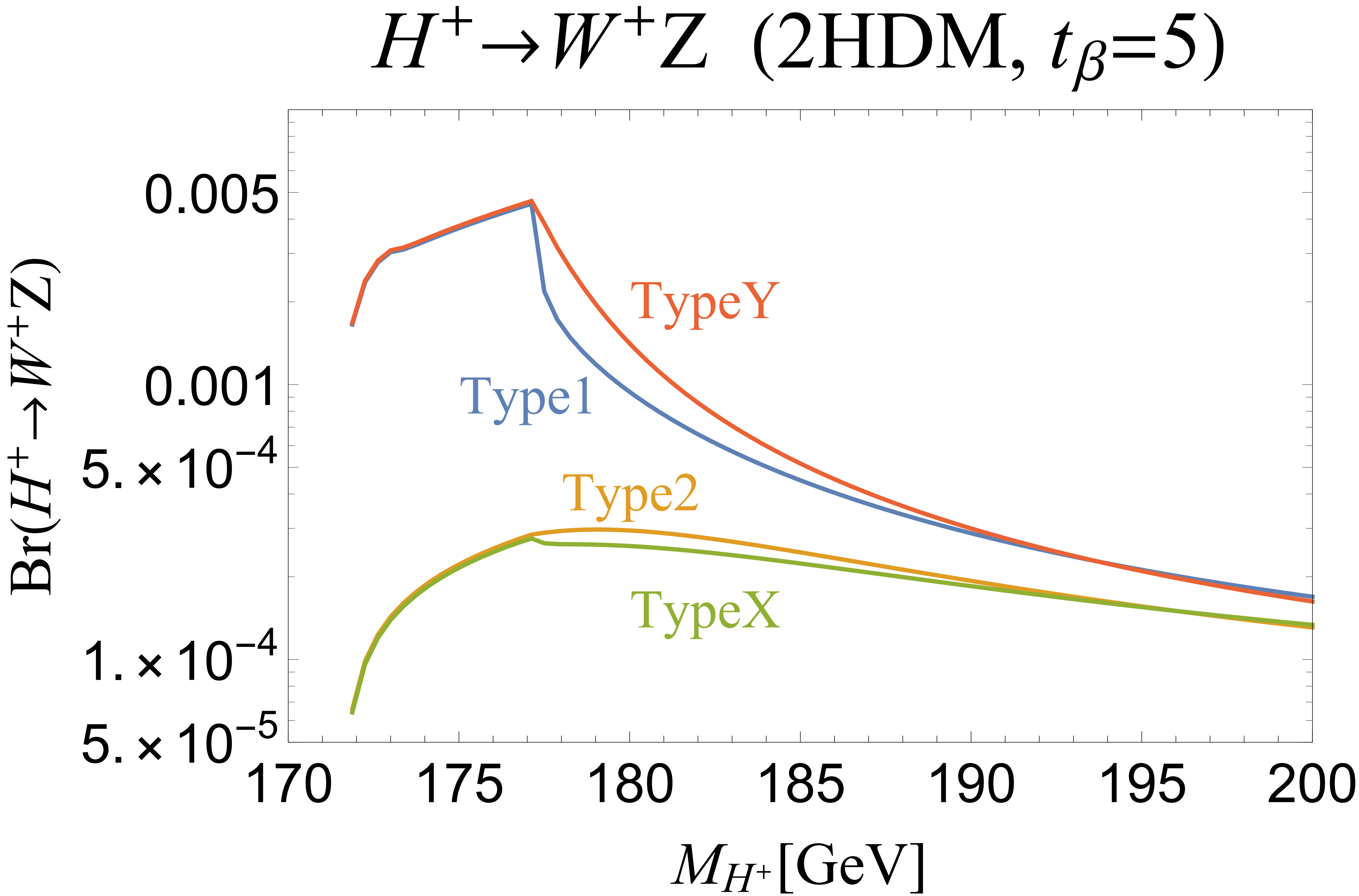
(a) (b) (c)

In a pure 2HDM,
the branching ratio is
too small!



At most 10^{-4}

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



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

Let’s add new fermions in the loop: Vector-like fermions (VLF)

VLF

Introduce both doublet and singlet

$$\text{VLF doublet}: \quad \mathcal{Q}_L = \begin{pmatrix} \mathcal{U}'_L \\ \mathcal{D}'_L \end{pmatrix}, \; \mathcal{Q}_R = \begin{pmatrix} \mathcal{U}'_R \\ \mathcal{D}'_R \end{pmatrix},$$

$$\text{VLF singlets}: \quad \mathcal{U}_L, \quad \mathcal{U}_R, \quad \mathcal{D}_L, \quad \mathcal{D}_R\,.$$

Crucial to allow the Higgs Yukawa couplings

Strategy to enhance

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

SM	$Q_L,\ L_L$	u_R	$d_R,\ \ell_R$
type-I	$+$	$-$	$-$

VLF	$\mathcal{Q}_{L,R}$	$\mathcal{U}_{L,R}$	$\mathcal{D}_{L,R}$
type-II	$+$	$-$	$+$

Yukawa Lagrangian

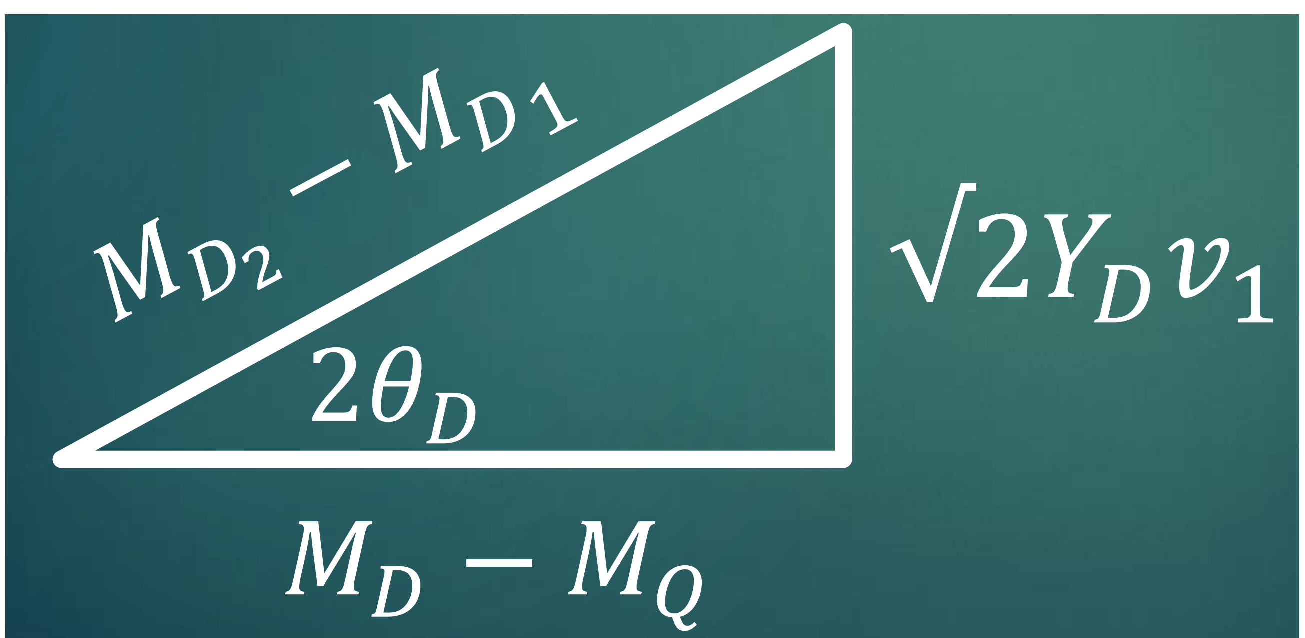
$$
\begin{aligned}
-\mathcal{L}_{\rm Yuk} =\ & M_{\mathcal{F}} \overline{\mathcal{Q}} \mathcal{Q} + M_{\mathcal{U}} \overline{\mathcal{U}} \mathcal{U} + M_{\mathcal{D}} \overline{\mathcal{D}} \mathcal{D} \\
& + \left[Y_{\mathcal{D}} \overline{\mathcal{Q}} \Phi_1 \mathcal{D} + Y_{\mathcal{U}} \overline{\mathcal{Q}}\, \widetilde{\Phi}_2 \mathcal{U} + \text{h.c.} \right]
\end{aligned}
$$

For simplicity, we assume

$$
Y_{\mathcal{U}}^{L} = Y_{\mathcal{U}}^{R} \equiv Y_{\mathcal{U}}
$$

Mixing b/w doublet and singlet

$$\mathbb{M}_{\mathcal{D}} = \begin{pmatrix} M_{\mathcal{Q}} & \frac{1}{\sqrt{2}} Y_{\mathcal{D}} v c_\beta \\ \frac{1}{\sqrt{2}} Y_{\mathcal{D}} v c_\beta & M_{\mathcal{D}} \end{pmatrix}, \quad \mathbb{M}_{\mathcal{U}} = \begin{pmatrix} M_{\mathcal{Q}} & \frac{1}{\sqrt{2}} Y_{\mathcal{U}} v s_\beta \\ \frac{1}{\sqrt{2}} Y_{\mathcal{U}} v s_\beta & M_{\mathcal{U}} \end{pmatrix}.$$



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

Higgs couplings with the VLF mass eigenstates

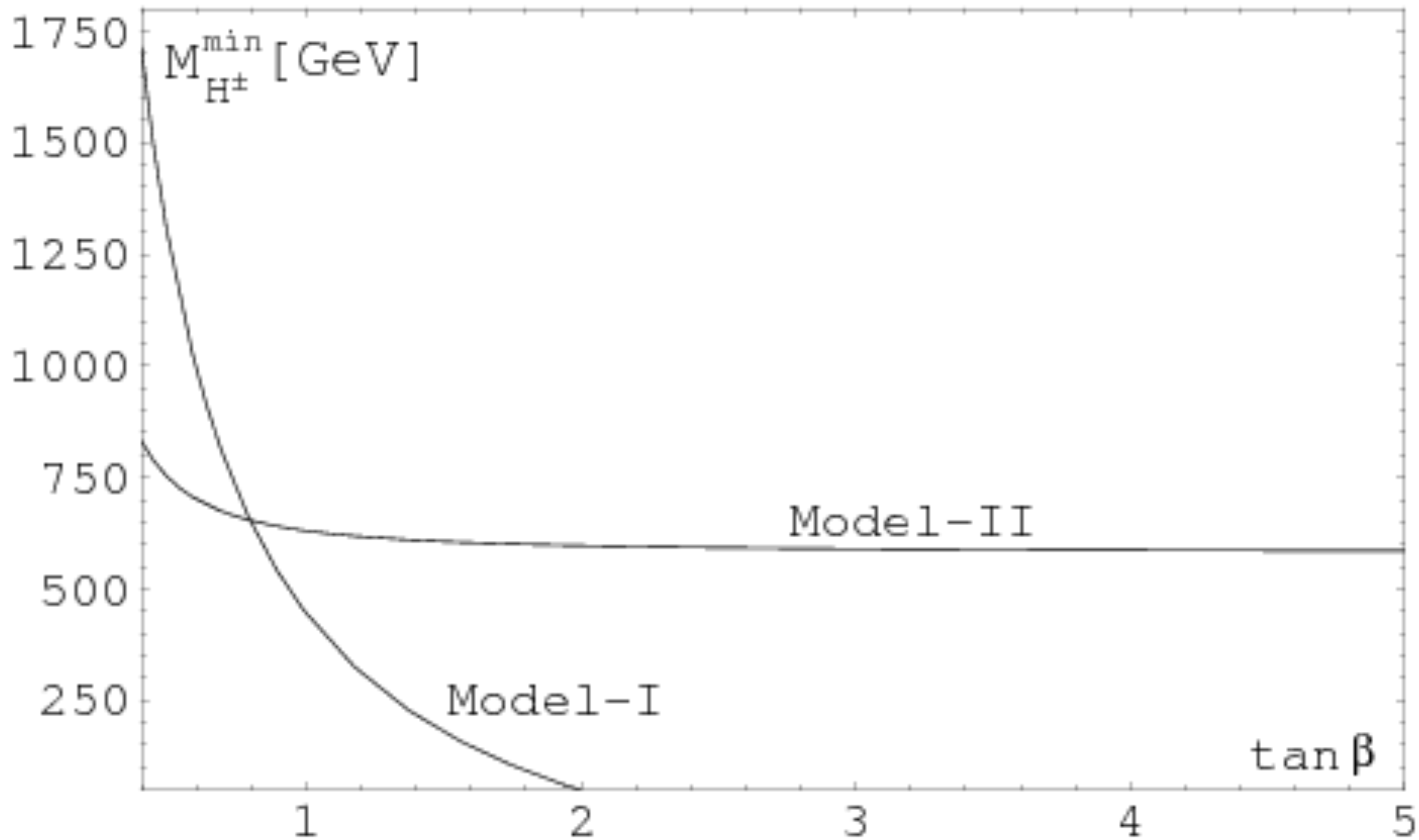
$$y^{\phi}_{\mathcal{F}_1\mathcal{F}_1} = -y^{\phi}_{\mathcal{F}_2\mathcal{F}_2} = -\frac{1}{\sqrt{2}}\, Y_{\mathcal{F}} \xi^{\mathcal{F}}_{\phi}\, s_{2\mathcal{F}},$$

$$y^{\phi}_{\mathcal{F}_1\mathcal{F}_2} = y^{\phi}_{\mathcal{F}_2\mathcal{F}_1} = \frac{1}{\sqrt{2}}\, Y_{\mathcal{F}} \xi^{\mathcal{F}}_{\phi}\, c_{2\mathcal{F}},$$

Where $\mathcal{F} = \mathcal{U}, \mathcal{D}, \;\; \phi = h, H$

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

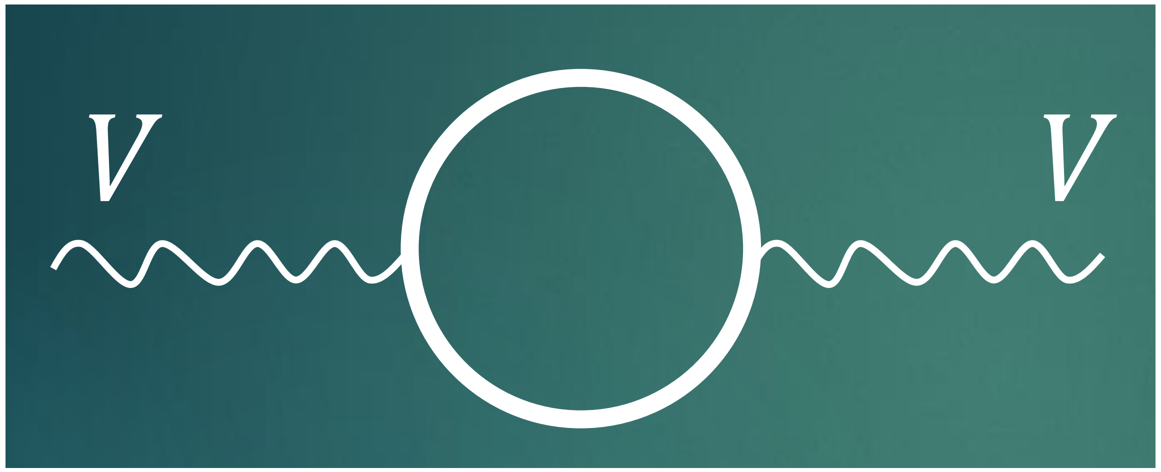
$$0.6 < |\kappa_g| < 1.12\,.$$

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

$$y^{\phi}_{\mathcal{F}_1\mathcal{F}_1} = -y^{\phi}_{\mathcal{F}_2\mathcal{F}_2}$$

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)

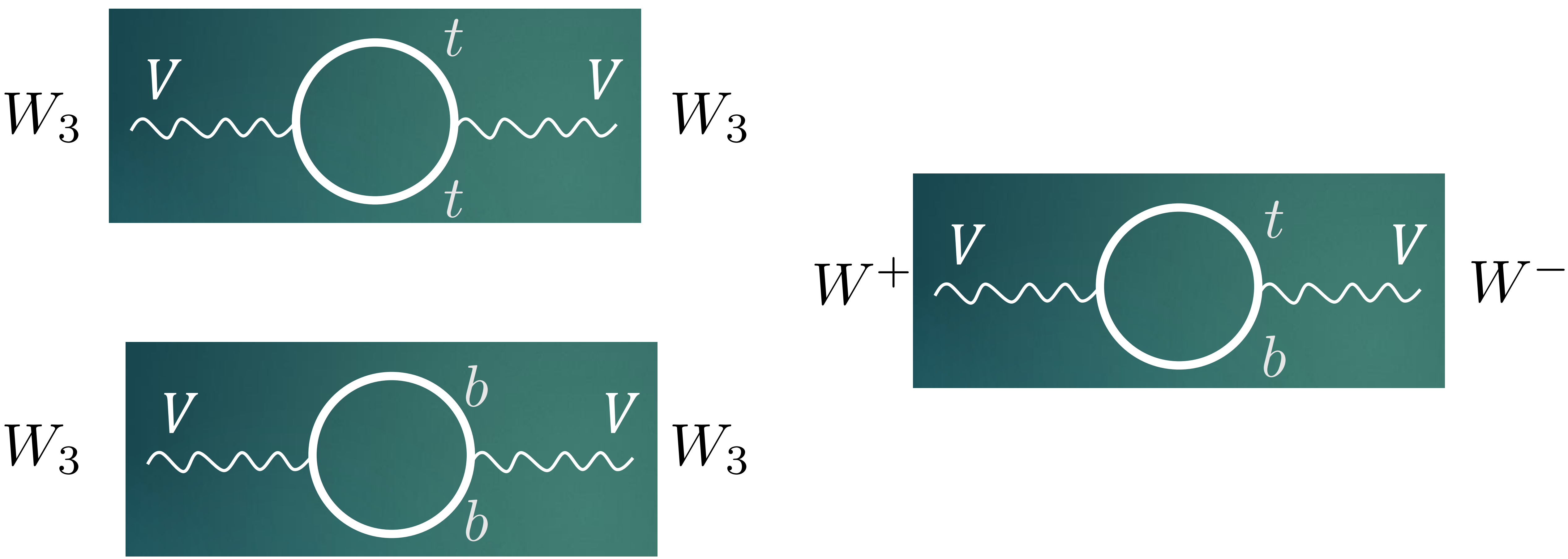
Later we shall consider large mass difference like 500 GeV

Why is this allowed in our model?

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

SM?

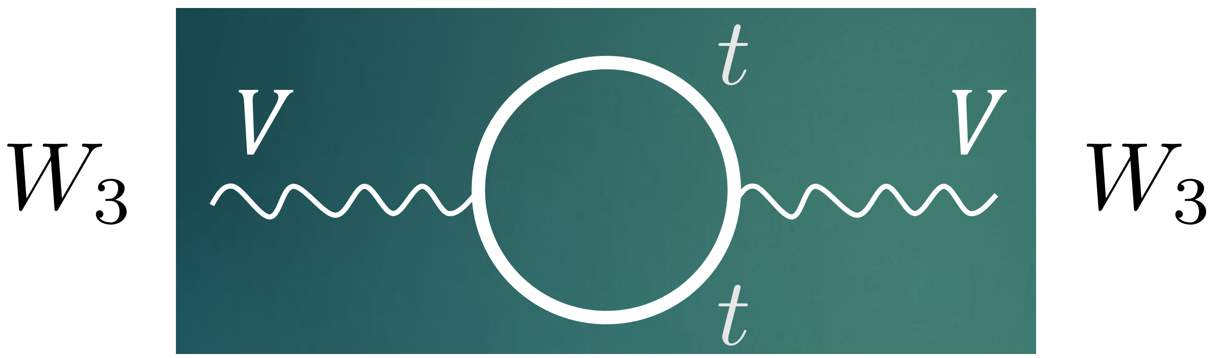
$$M_W^2 \hat{T} = \Pi_{W_3 W_3}(0) - \Pi_{W^+ W^-}(0),$$

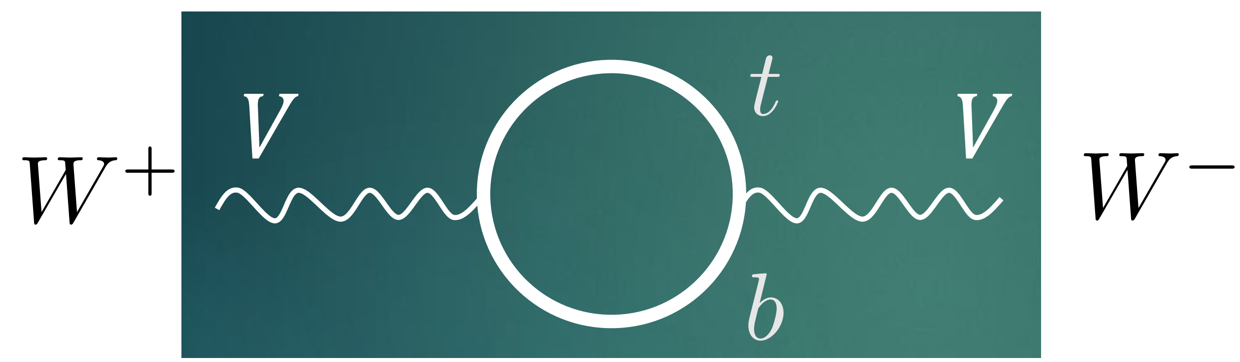


SM?

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

$$\Delta M = 0 \to \Pi_{VV}(0) = 0$$





0 $\quad \propto \Delta M^2$

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

One VLQ doublet + one VLQ singlet

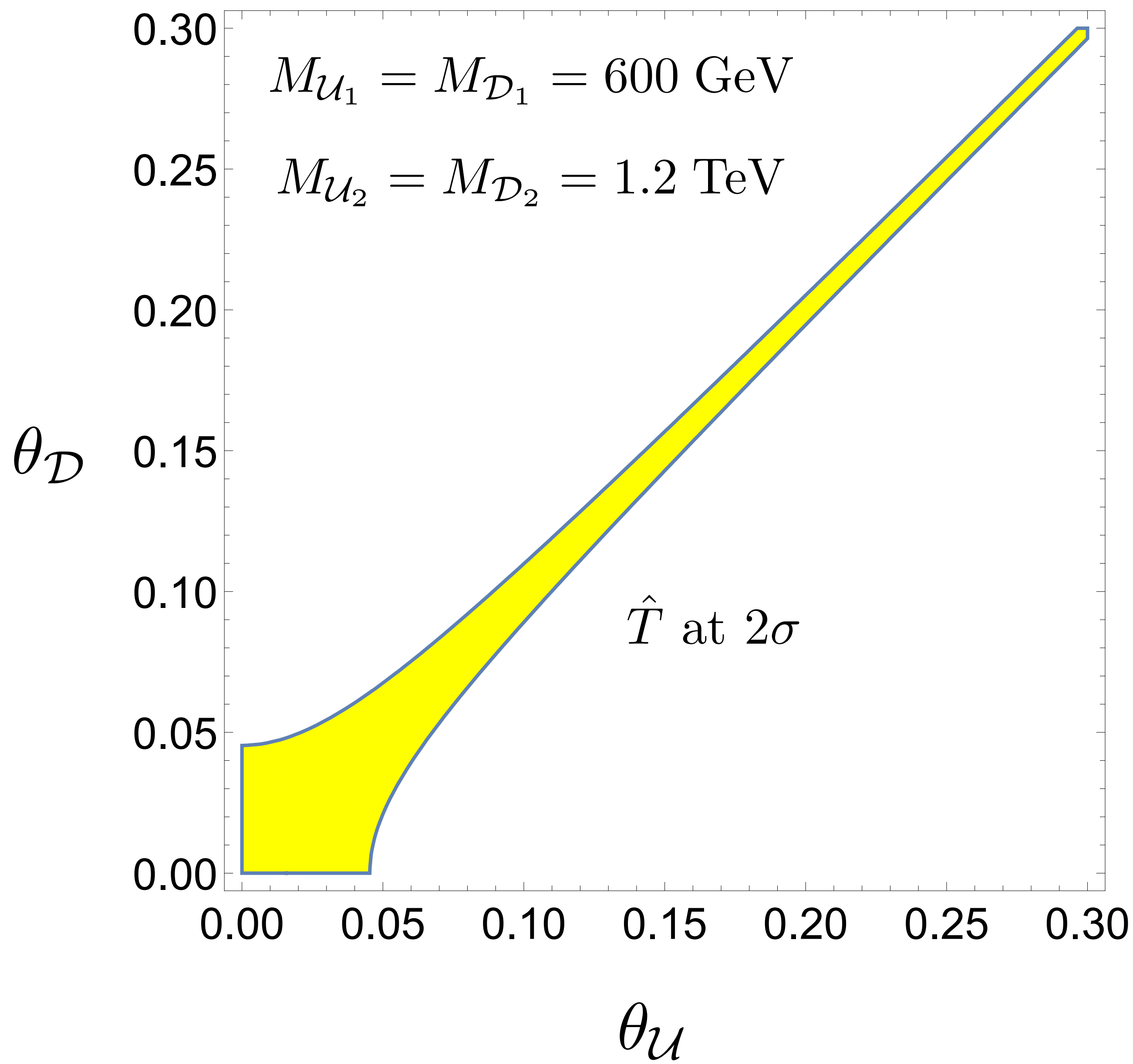
Mixing

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

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

Cancellation!

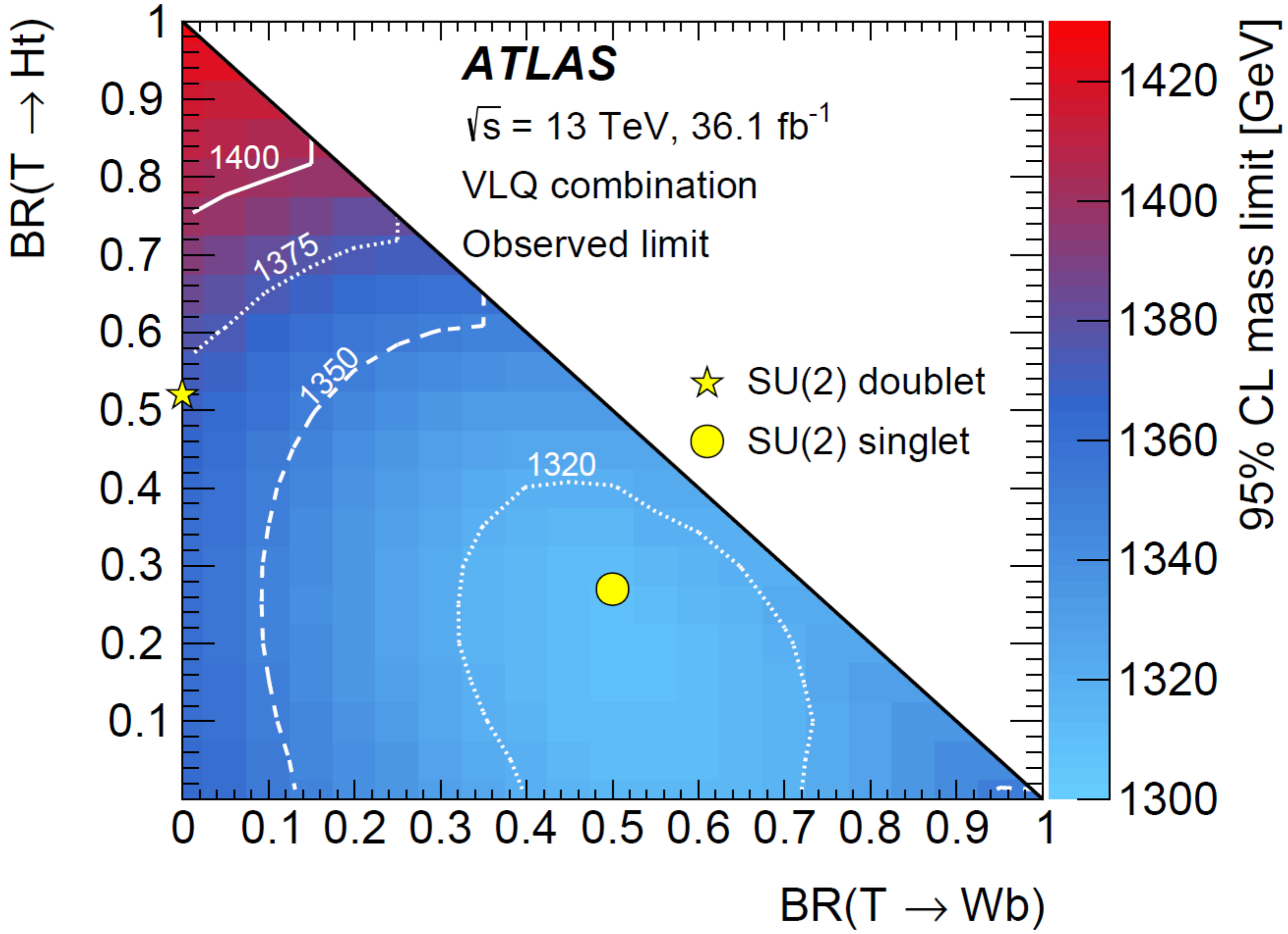
Cancellation happens when

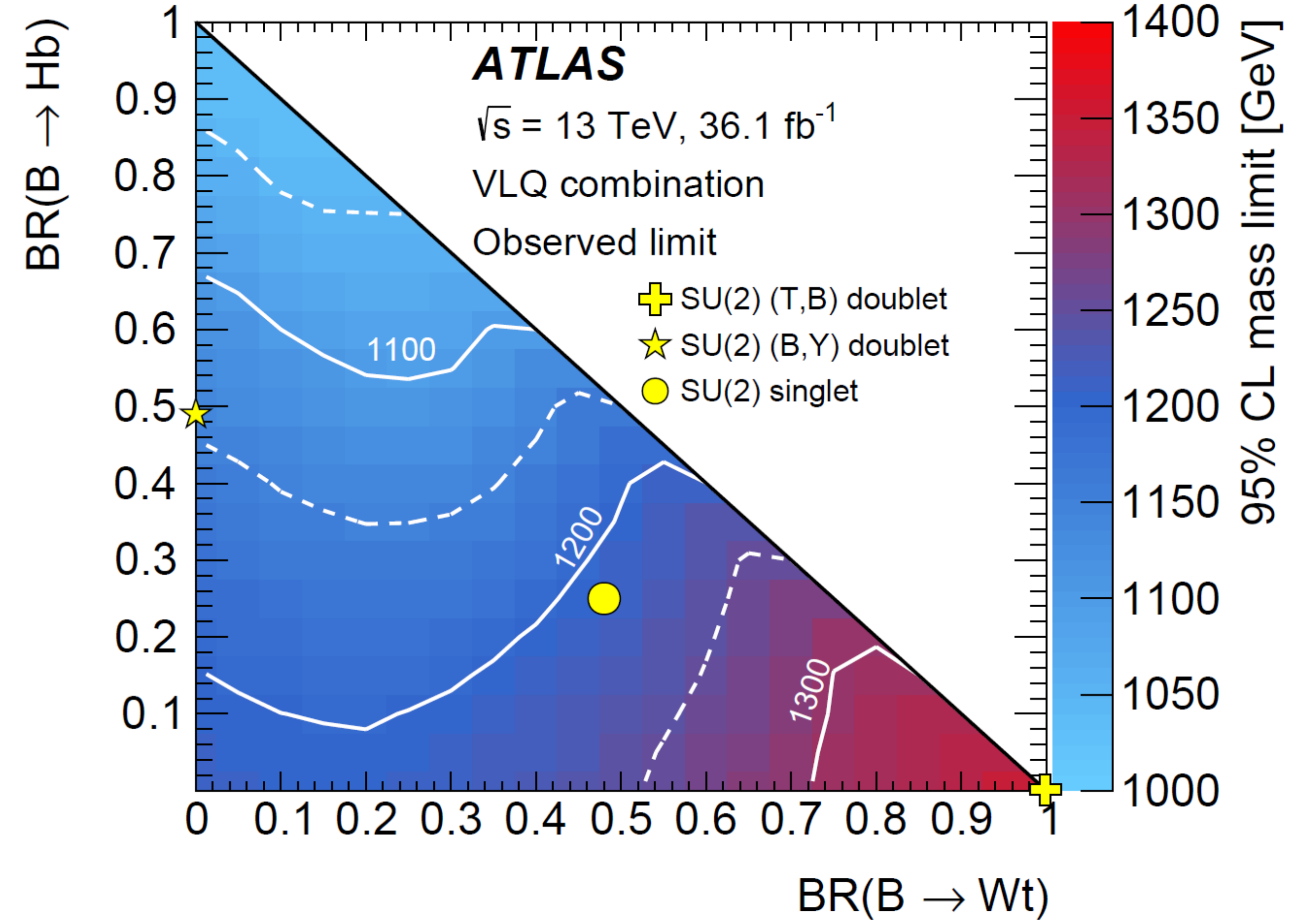


$$M_{\mathcal{U}_1} = M_{\mathcal{D}_1}, \quad M_{\mathcal{U}_2} = M_{\mathcal{D}_2}, \quad \theta_{\mathcal{U}} = \theta_{\mathcal{D}}.$$

Direct constraints on the VL fermion masses

ATLAS, 1808.02343



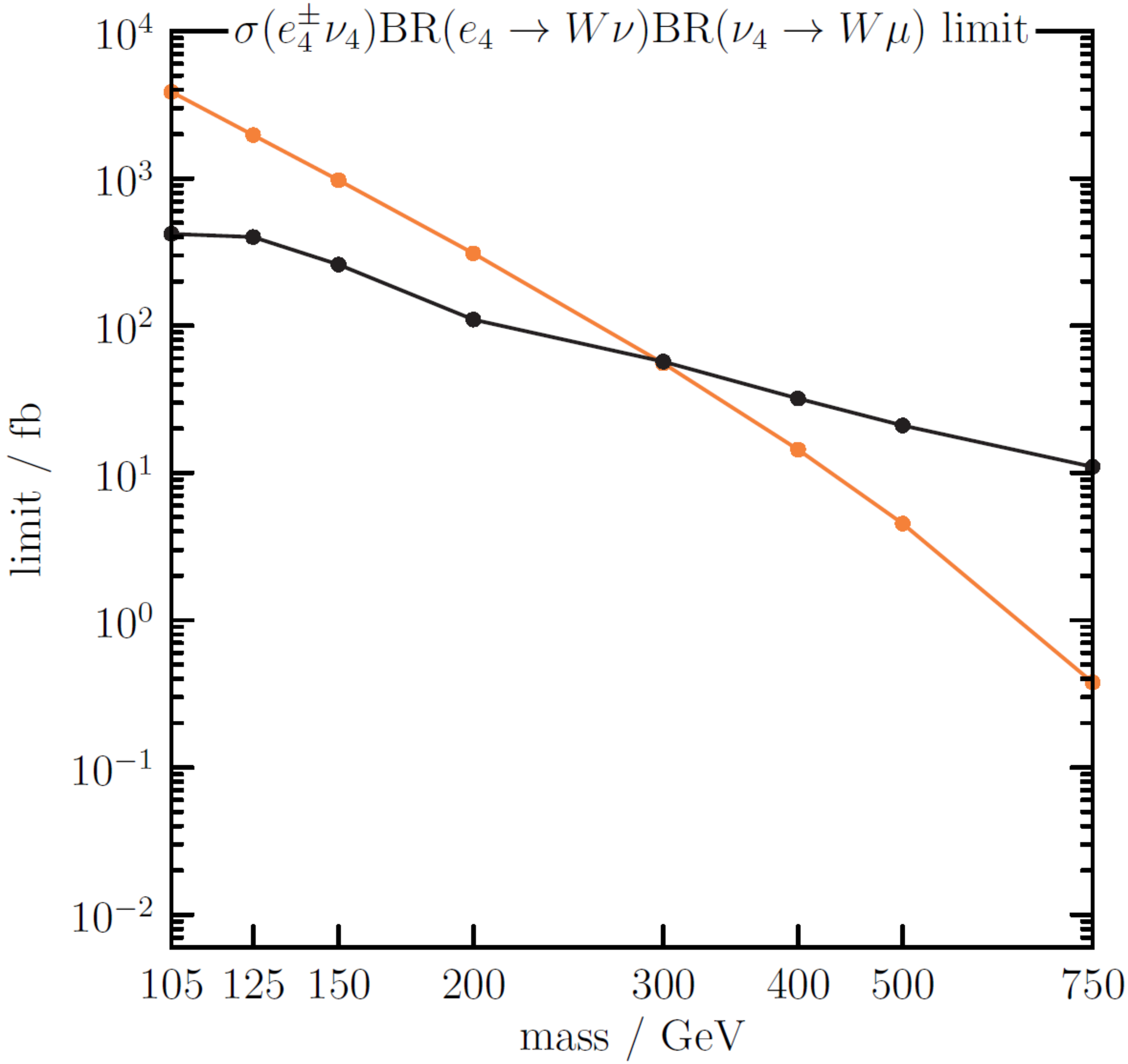


$M_T > 1.31\text{TeV}$ $M_B > 1.03\text{TeV}$

$T \to Zt/Wb/Ht$ $B \to Hb/Zb/Wt$

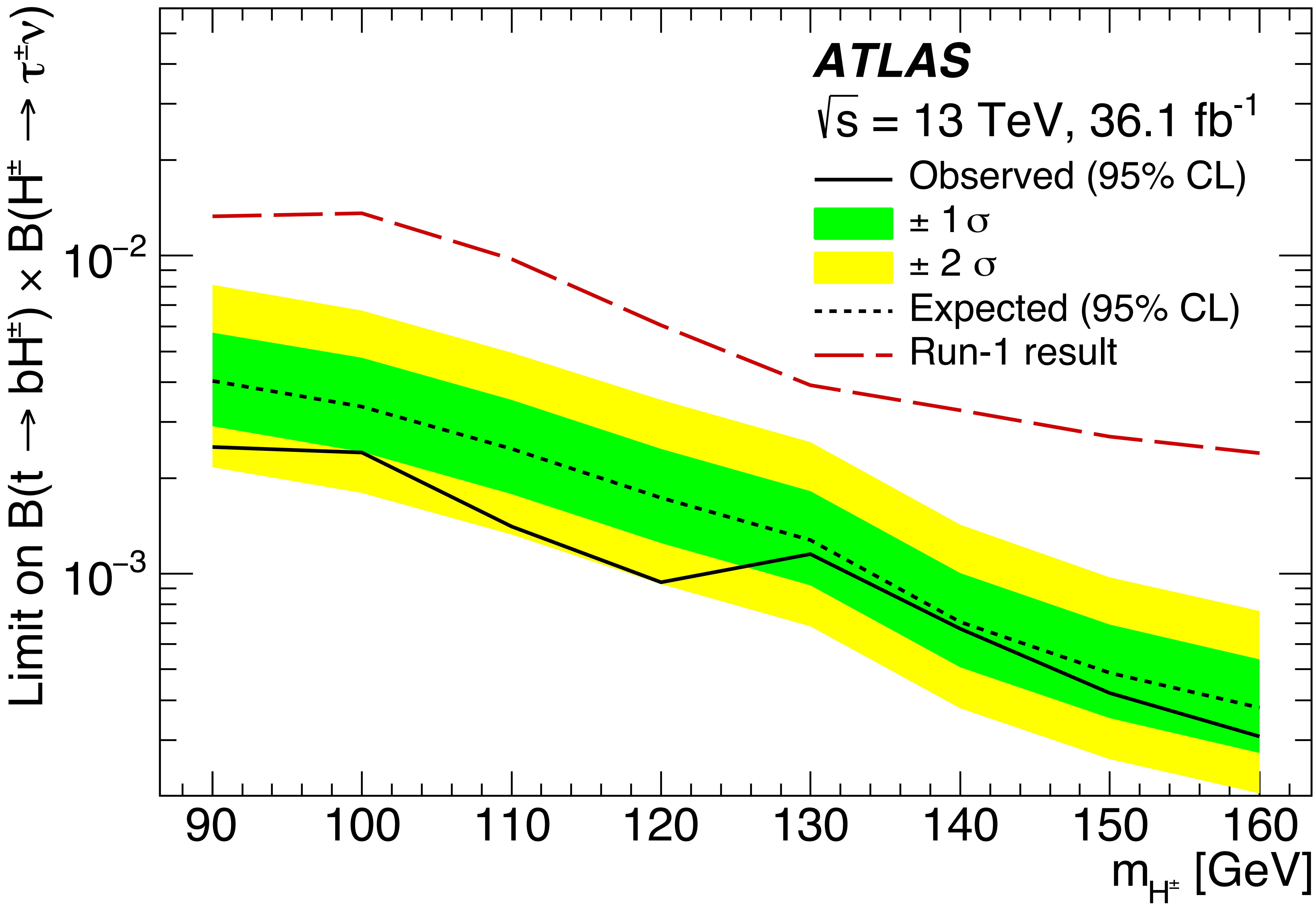
The bounds can be relaxed if the VLQs decay into light quarks.

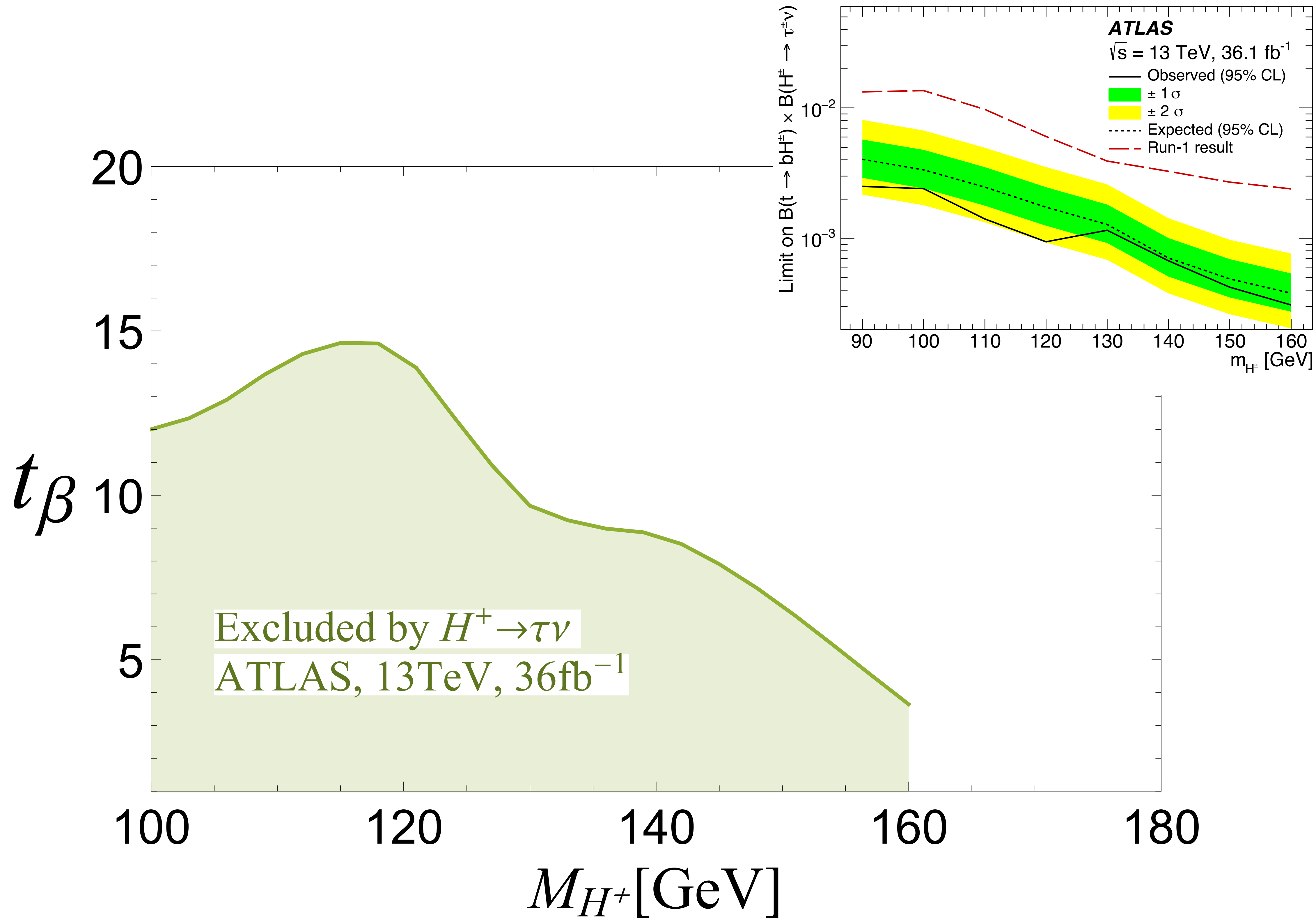
Dermisek, Hall, Lunghi, Shin, 1408.3123



$M_E > 300\text{GeV}$

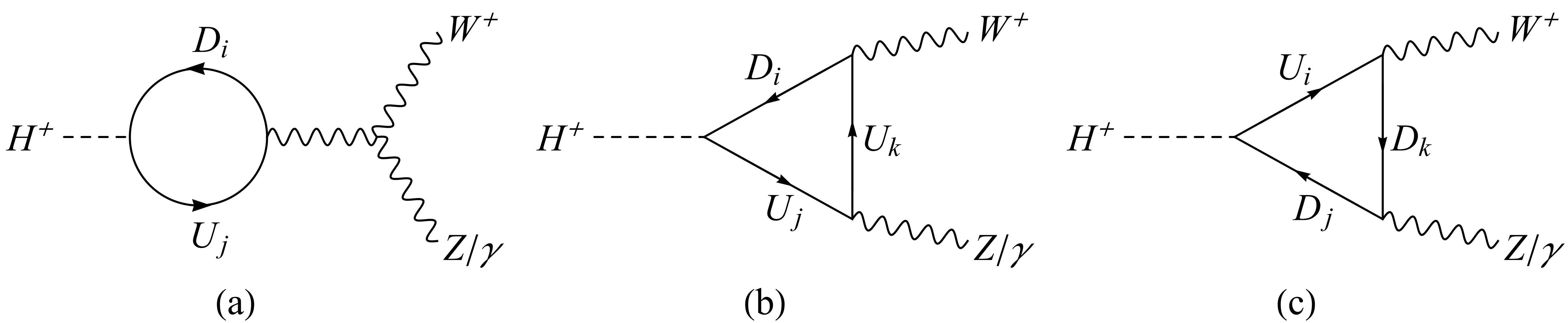
Constraints from the direct searches for the charged Higgs boson at the LHC


ATLAS
√s = 13 TeV, 36.1 fb-1
Observed (95% CL)
± 1 σ
± 2 σ
Expected (95% CL)
Run-1 result
Limit on B(t → bH±) × B(H± → τ±ν)
10−2
10−3
90
100
110
120
130
140
150
160
mH± [GeV]



20
15
10
5
t_β
100
120
140
160
180
M_{H^+}[GeV]
Excluded by $H^+ \to \tau\nu$
ATLAS, 13TeV, 36fb^{-1}
ATLAS
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
Observed (95% CL)
± 1σ
± 2 σ
Expected (95% CL)
Run-1 result
Limit on B(t → bH$^\pm$) × B(H$^\pm$ → τ$^\pm$ν)
10^{-2}
10^{-3}
90
100
110
120
130
140
150
160
$m_{H^\pm}$ [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 $p_2^\nu M_{\mu\nu} = 0$

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

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

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

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

Benchmark point

$$s_{\beta-\alpha} = 1, \quad \text{(alignment limit)},$$

$$M_{\mathcal{U}_1} = M_{\mathcal{D}_1} = \begin{cases} 600\,\text{GeV or 1.3 TeV}, & \text{for VLQ;} \\ 300\ \text{GeV}, & \text{for VLL,} \end{cases}$$

$$(Q_{\mathcal{U}}, Q_{\mathcal{D}}) = \begin{cases} \text{VLQ:} & \begin{bmatrix} (X,T) & : (5/3, 2/3); \\ (T,B) & : (2/3, -1/3); \\ (B,Y) & : (-1/3, -4/3); \end{bmatrix} \\ \text{VLL:} & \quad (N,E) : (0, -1), \end{cases}$$

$$\Delta M \equiv M_{\mathcal{U}_2} - M_{\mathcal{U}_1} = M_{\mathcal{D}_2} - M_{\mathcal{D}_1} \subset [0, 1.5]\ \text{TeV}$$

$$\theta_{\mathcal{U}} = \theta_{\mathcal{D}} = 0.2\,,$$

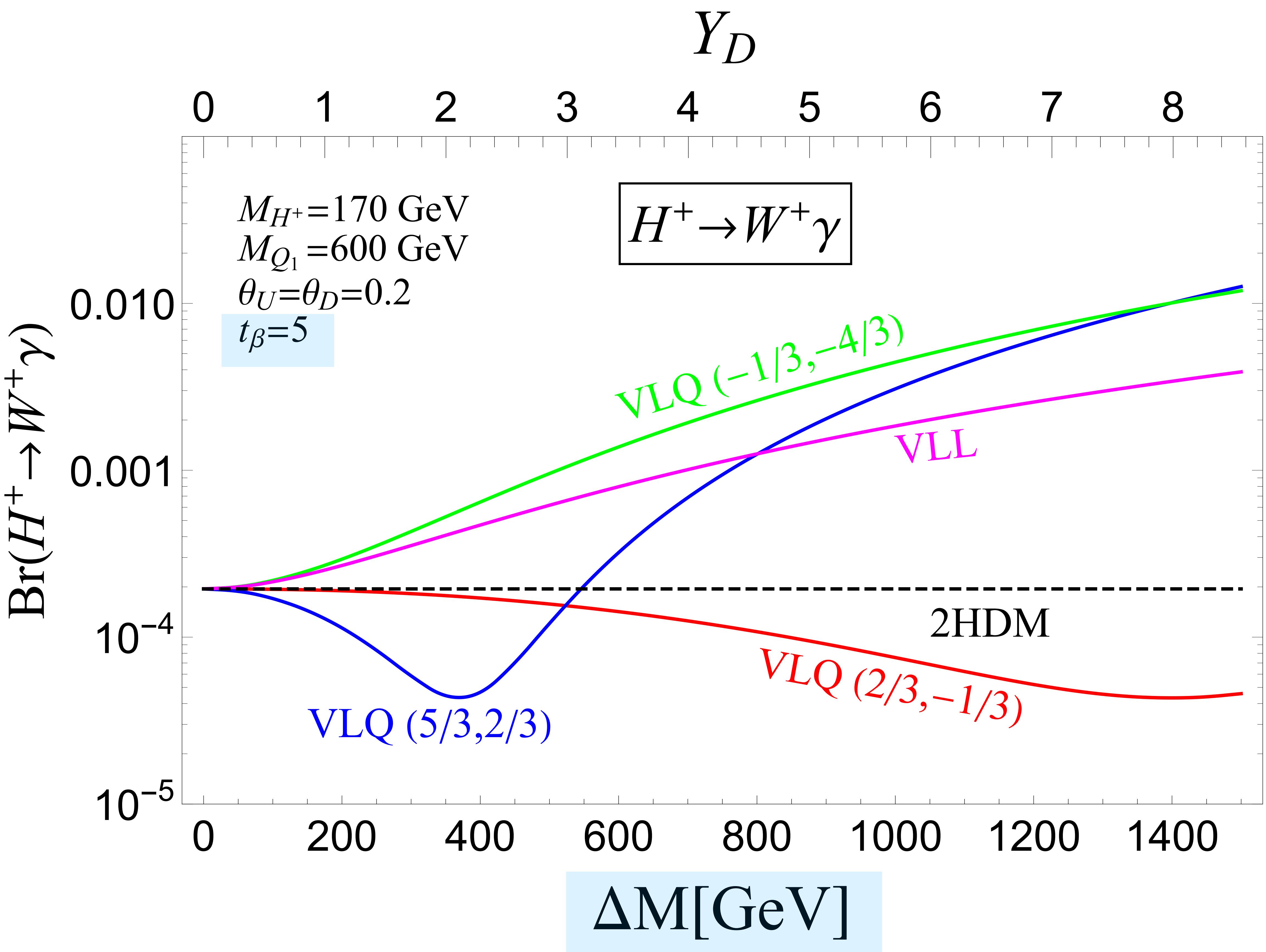
Decays of VLF (X,T)

$$-\mathscr{L} = \delta Y_{4u}\,\overline{Q}\Phi_2 u_R + \delta Y_{4d}\,\bar{Q}_L\Phi_1\mathcal{D} + h.c.,$$

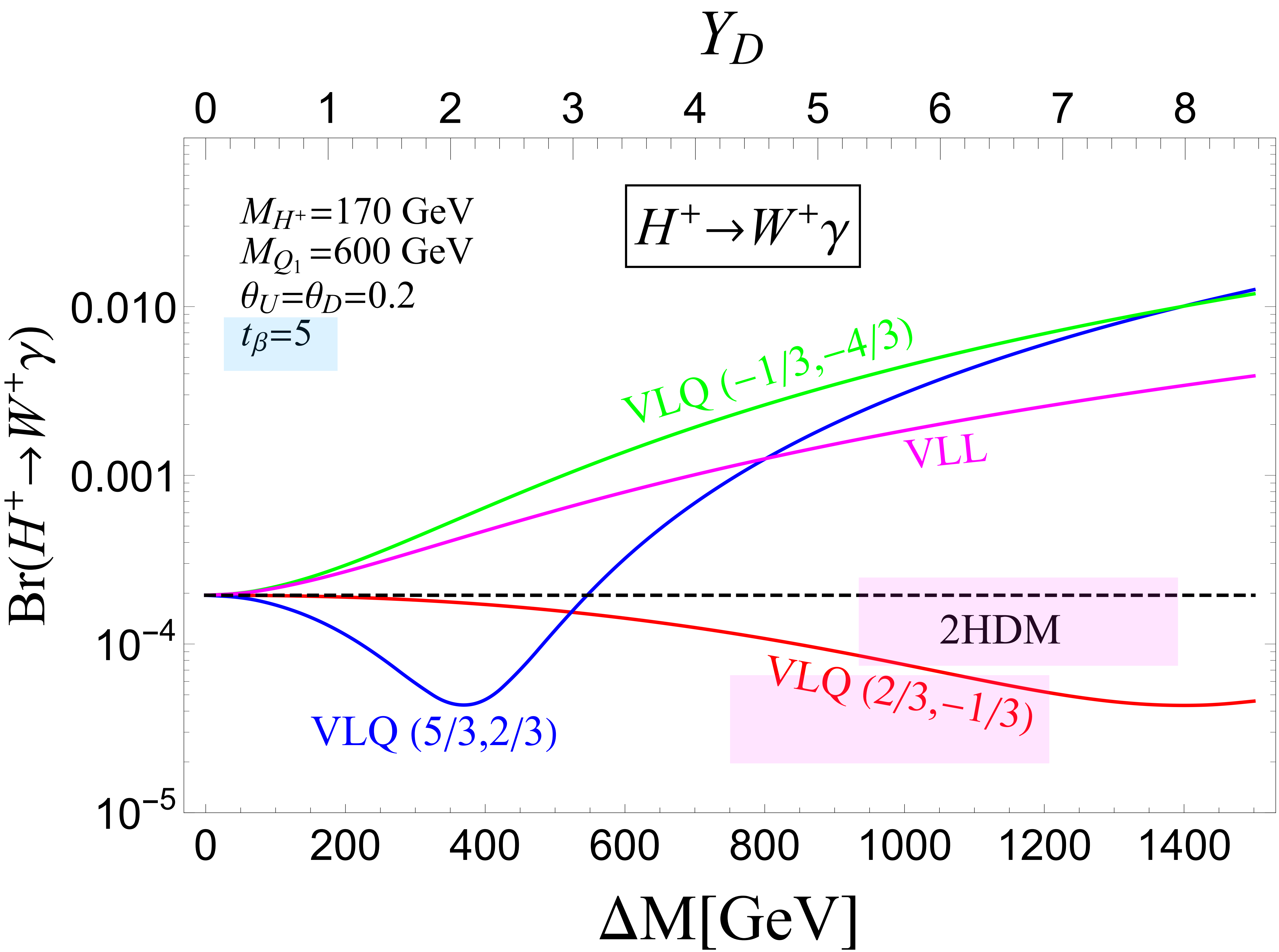
$$X \to H^+ u_i, \quad X \to W^+ u_i$$

$$Q_X = \frac{5}{3}$$

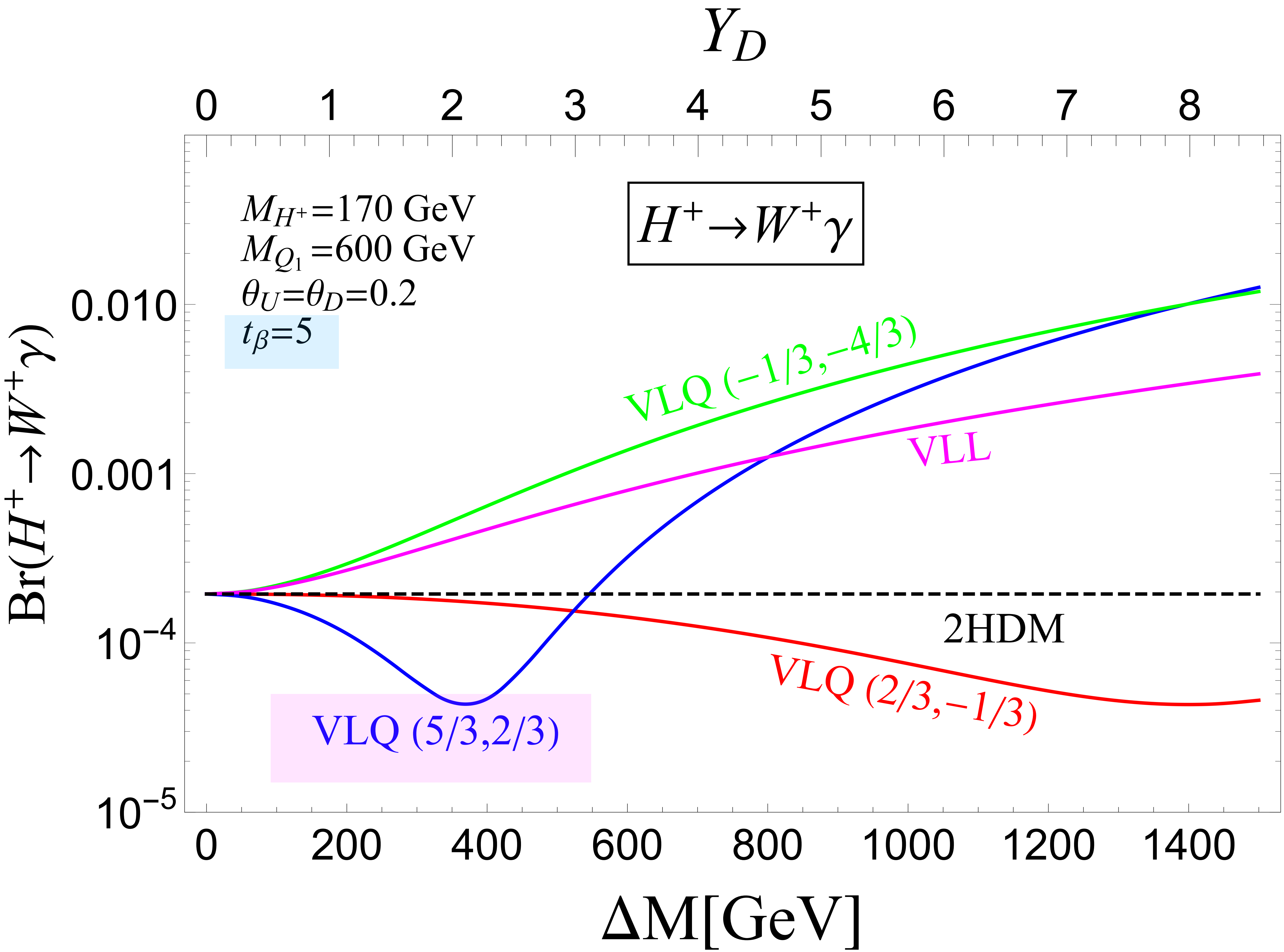
Low mass of the VLFs



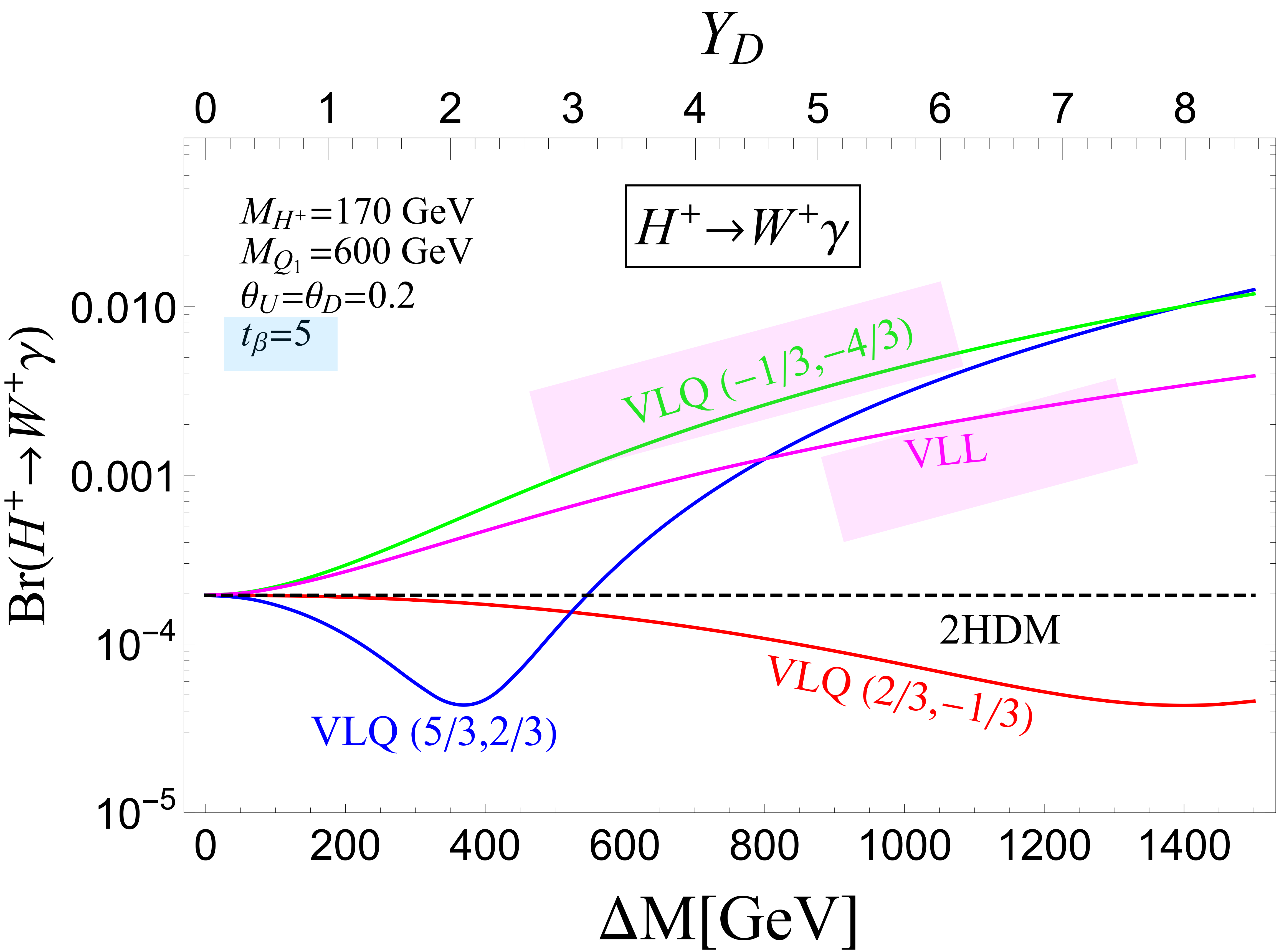
Low mass of the VLFs



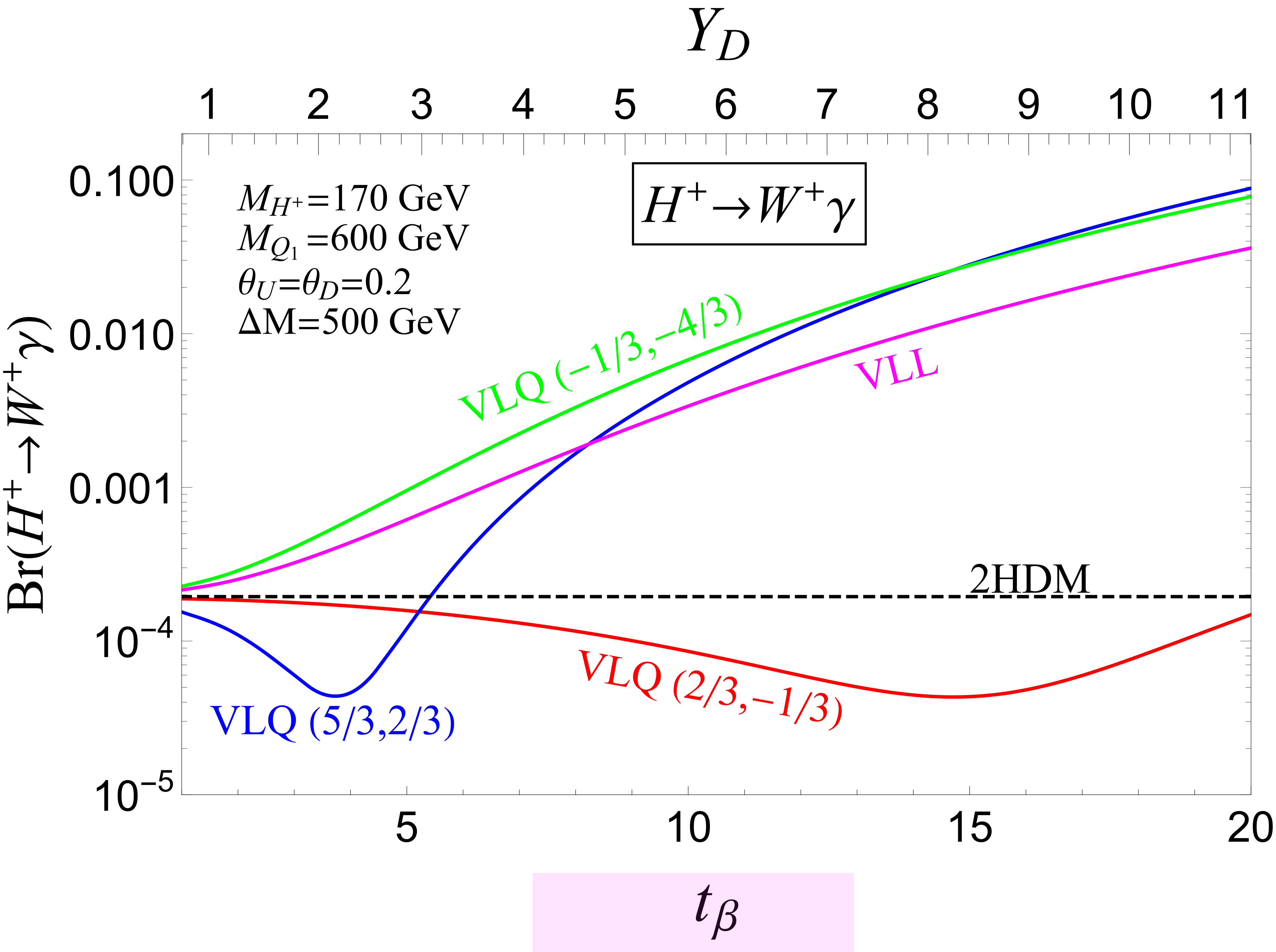
Low mass of the VLFs



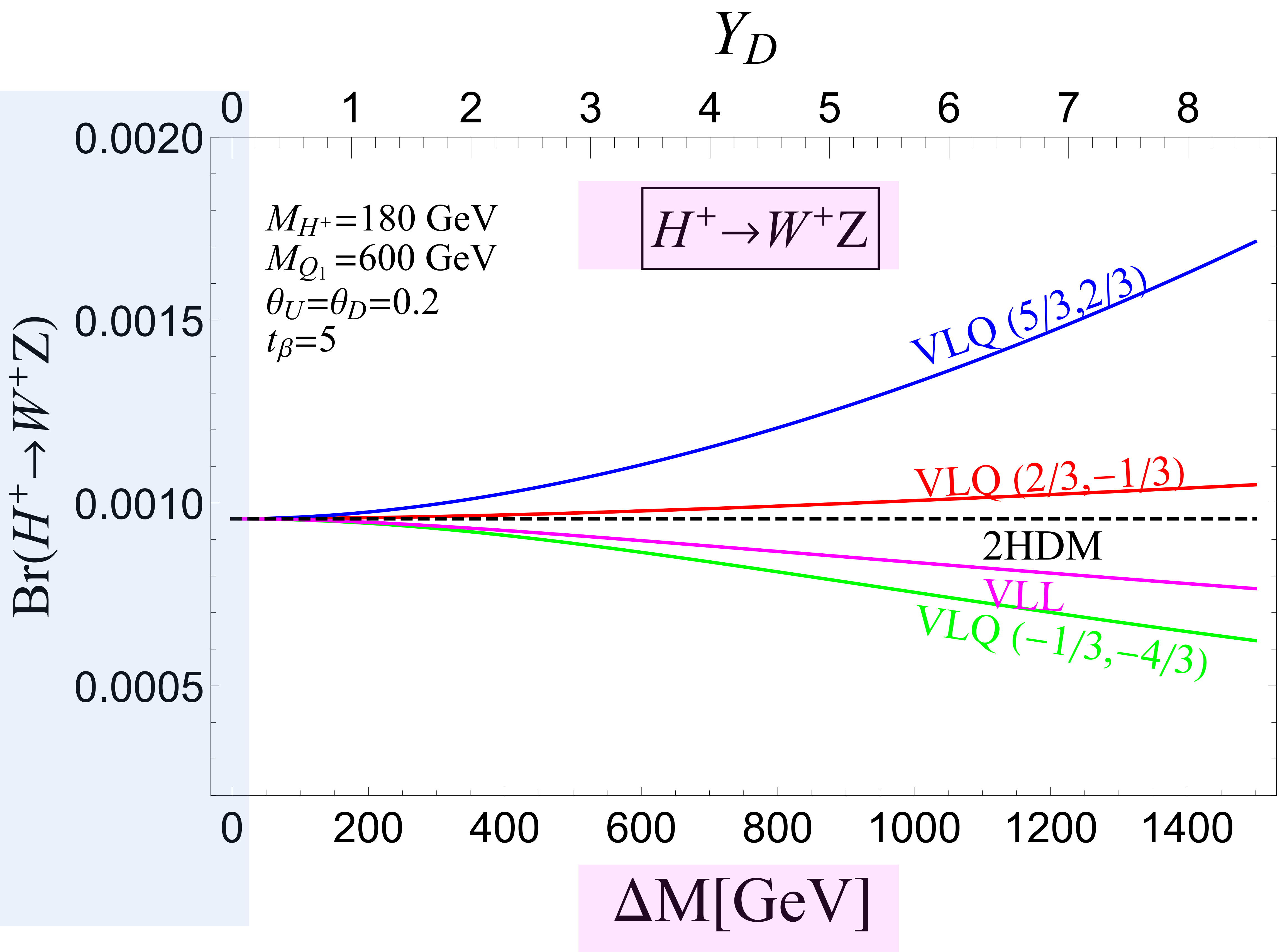
Low mass of the VLFs



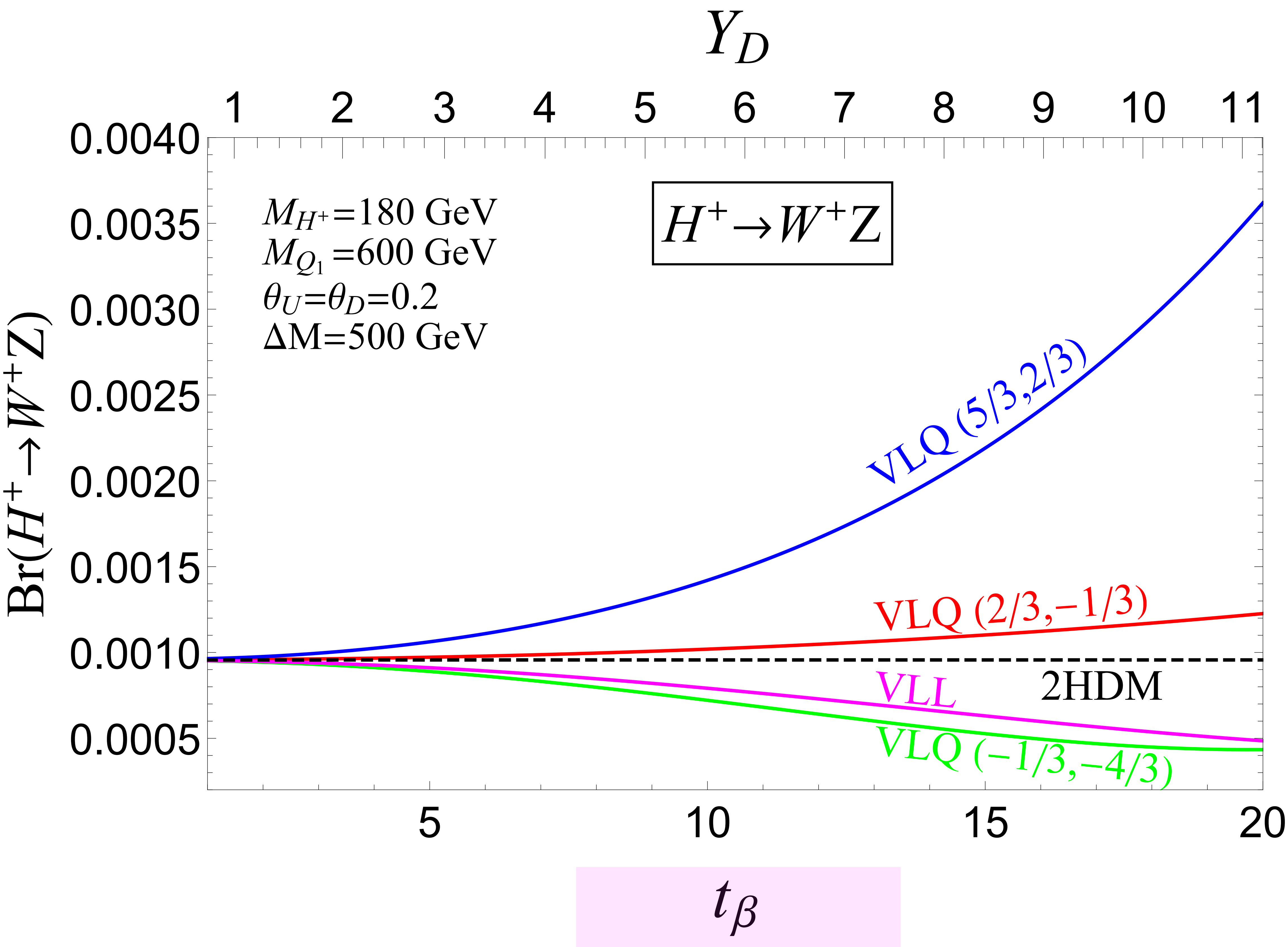
Low mass of the VLFs



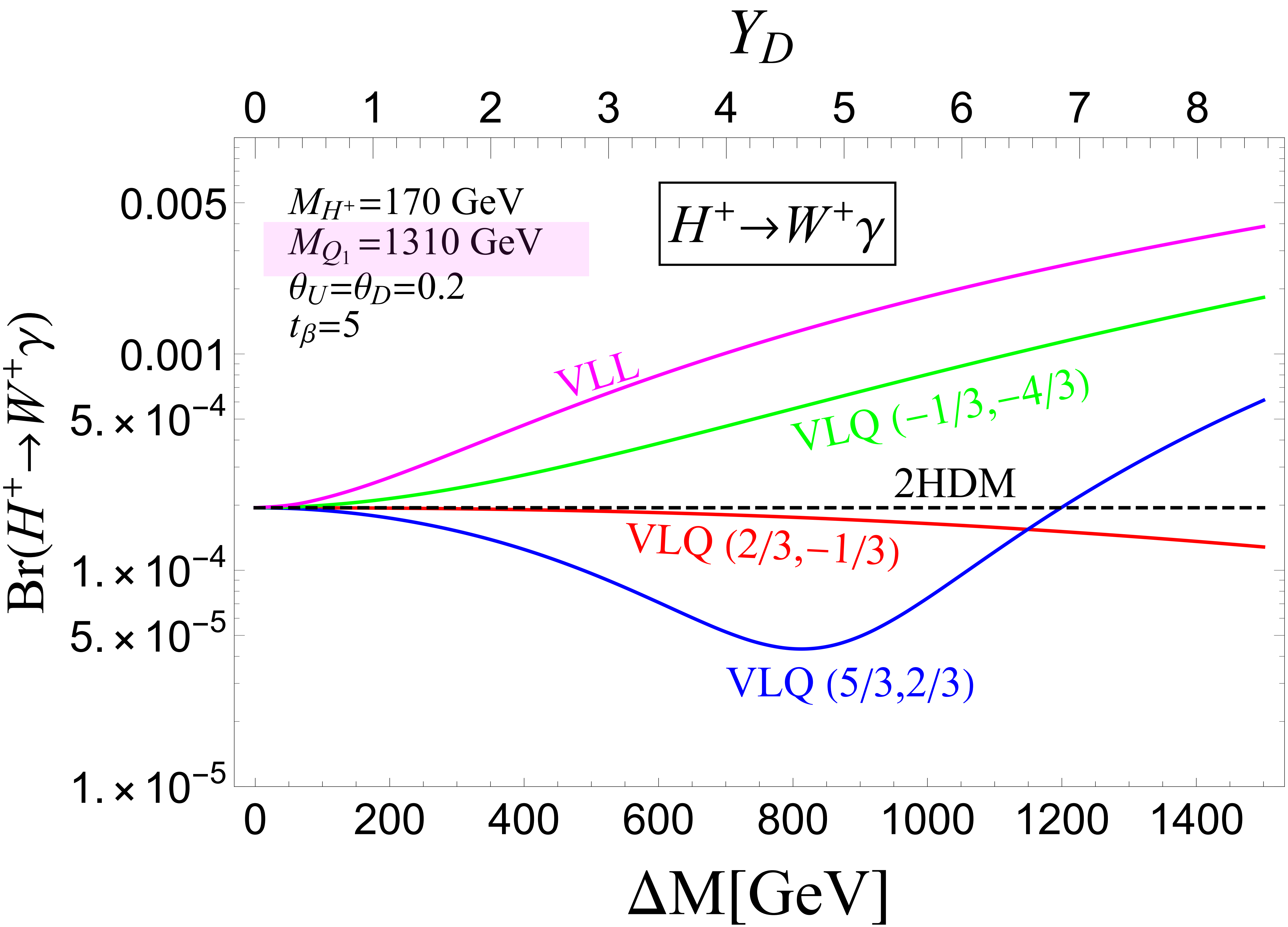
Low mass of the VLFs



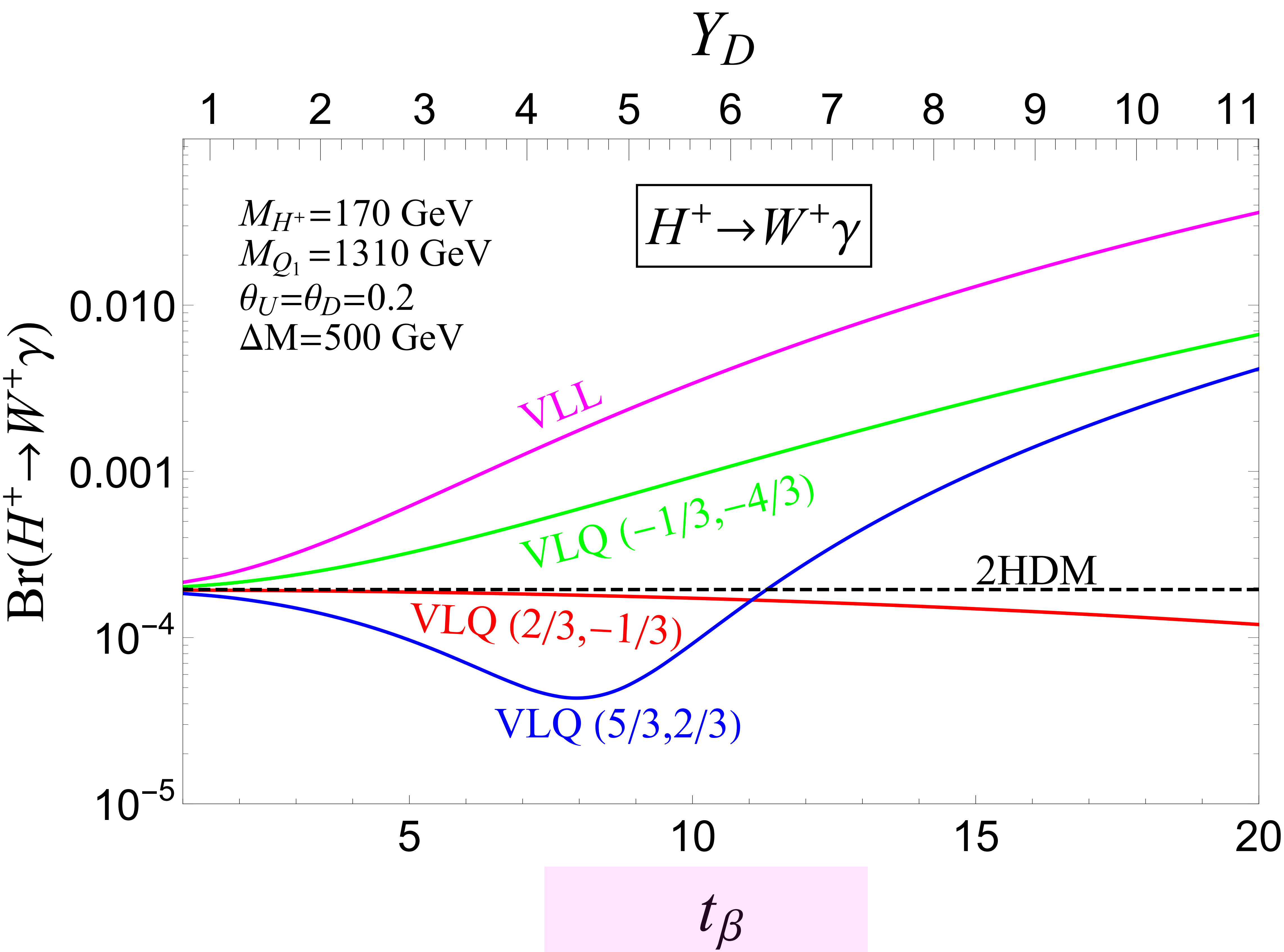
Low mass of the VLFs



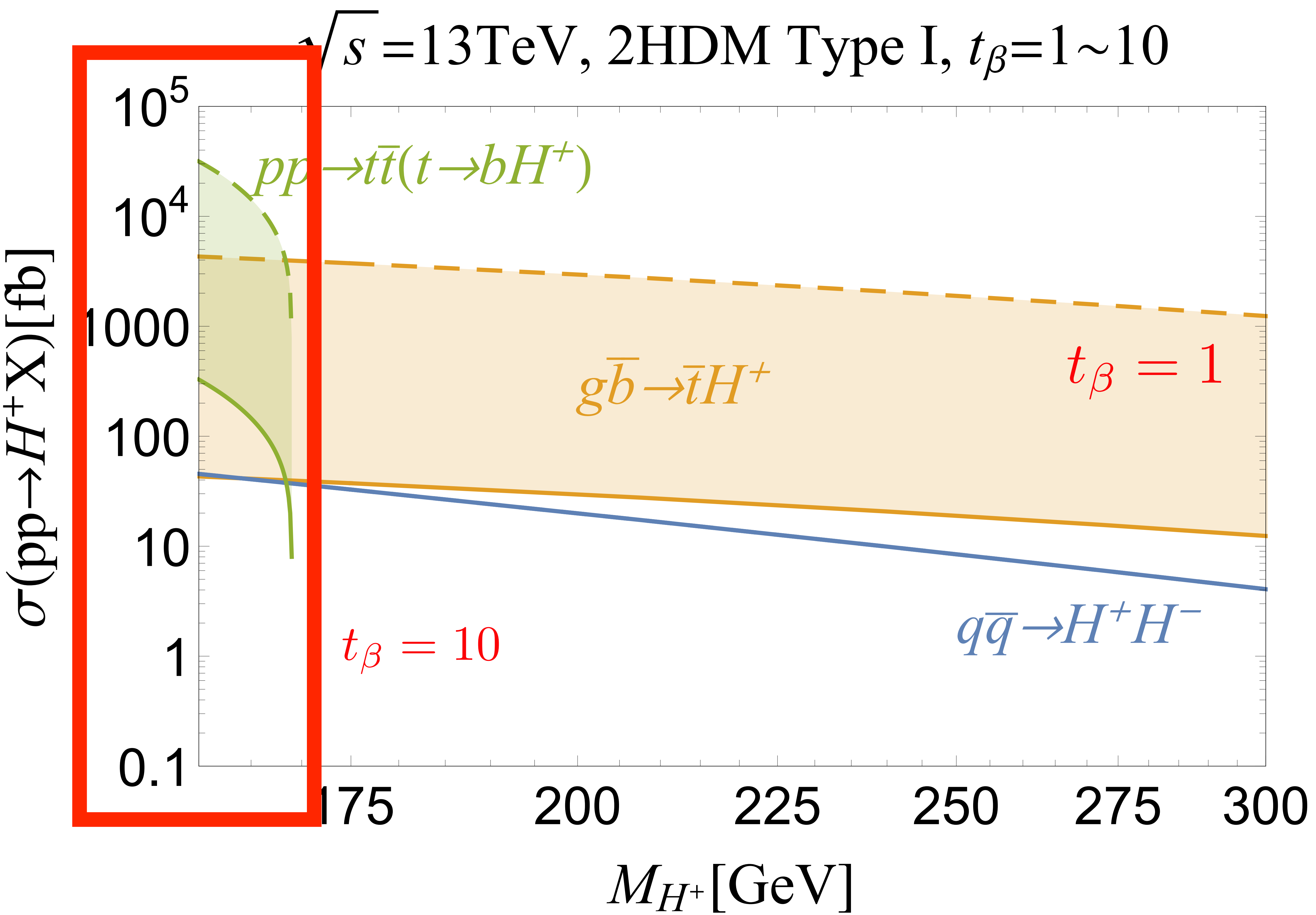
High mass of the VLFs



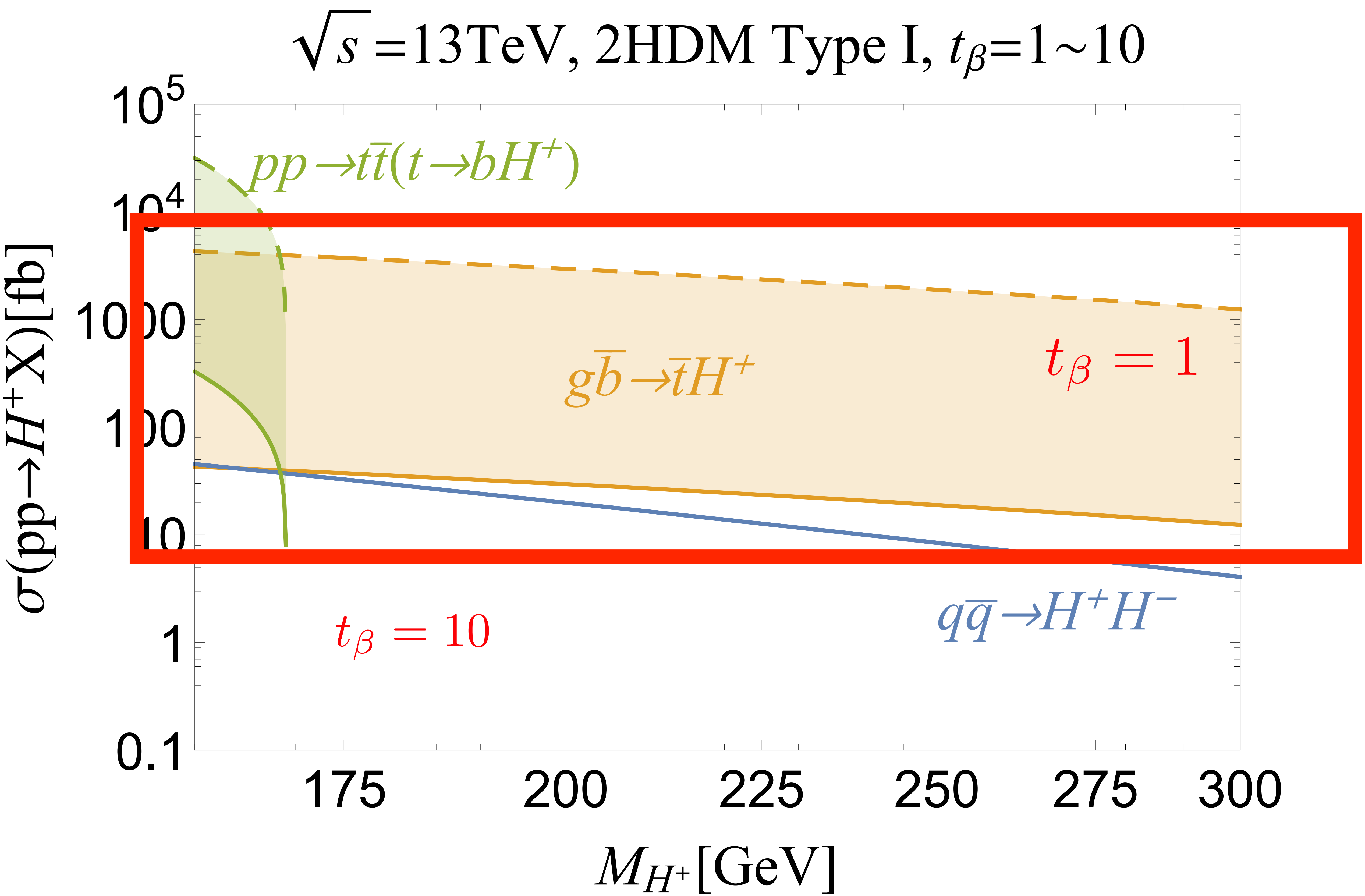
High mass of the VLFs



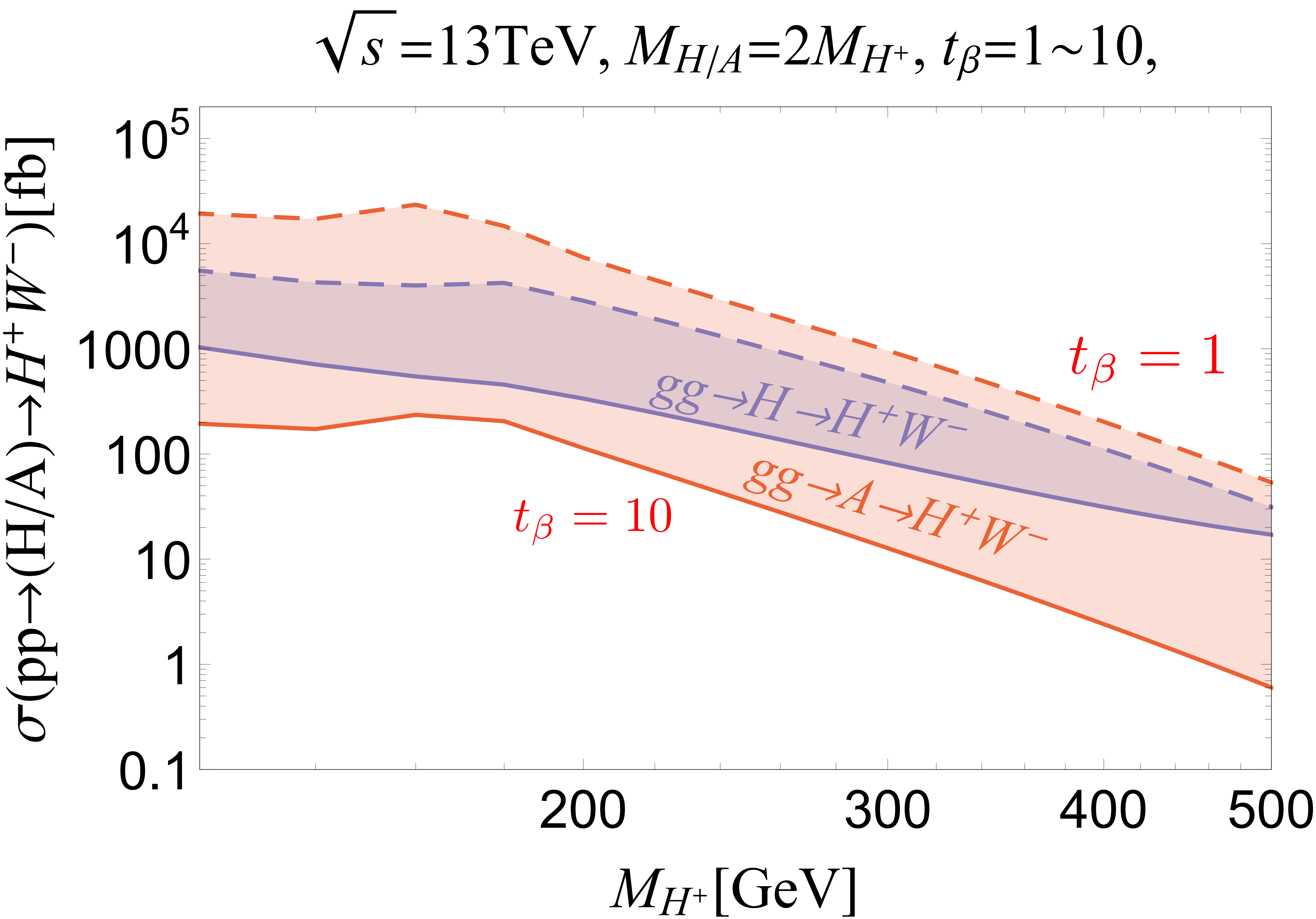
Production of the charged Higgs boson



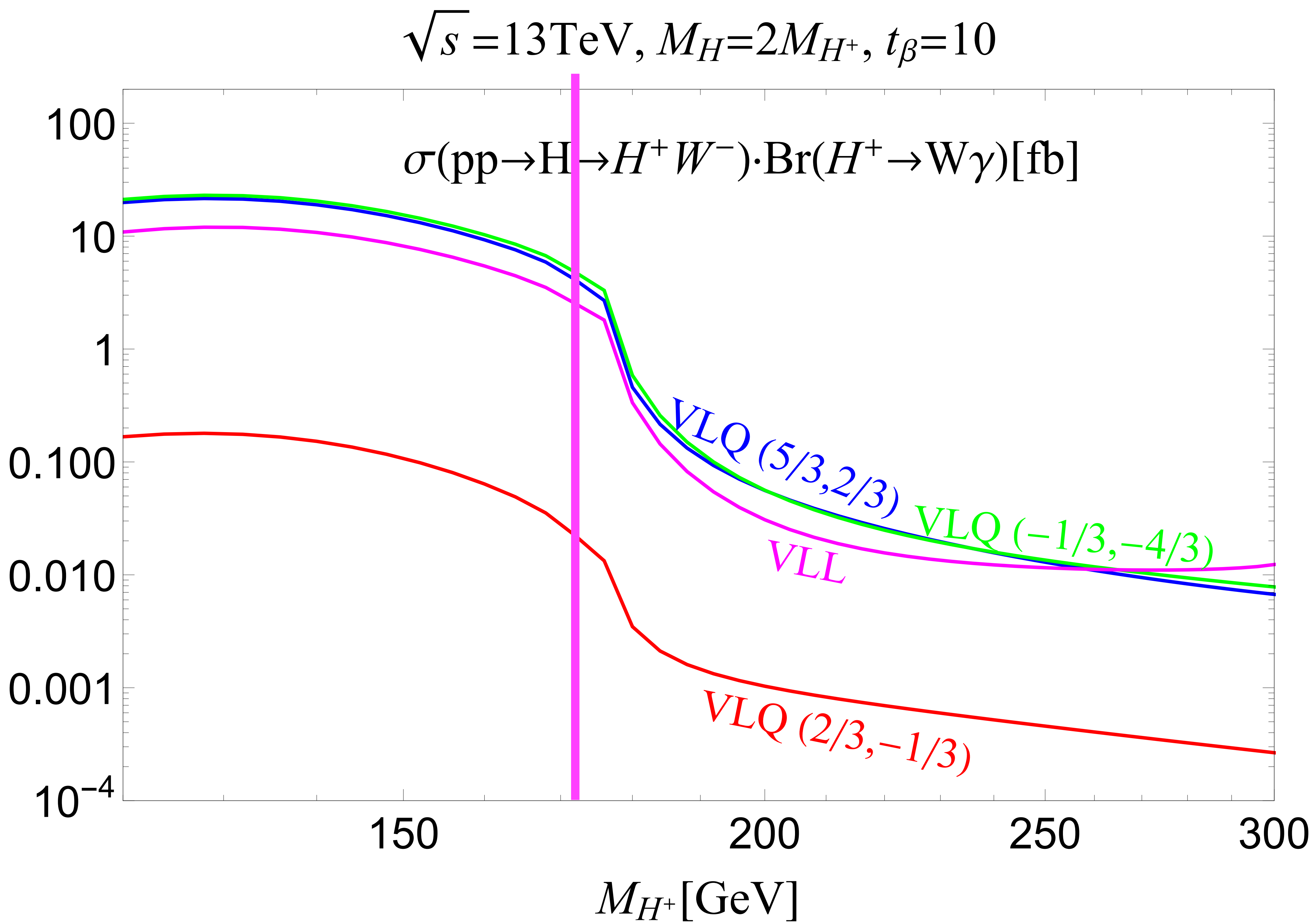
$\sqrt{s}$ =13TeV, 2HDM Type I, t_β=1~10
10^5
10^4
1000
100
10
1
0.1
175
200
225
250
275
300
σ(pp→H^+X)[fb]
M_{H^+}[GeV]
$pp \to t\bar{t}(t \to bH^+)$
$g\bar{b} \to \bar{t}H^+$
$t_\beta = 1$
$t_\beta = 10$
$q\bar{q} \to H^+H^-$



$\sqrt{s}$=13TeV, 2HDM Type I, t_β=1~10
10^5
10^4
1000
100
10
1
0.1
$\sigma(\mathrm{pp}\to H^+\mathrm{X})$[fb]
$pp\to t\bar{t}(t\to bH^+)$
$g\bar{b}\to\bar{t}H^+$
$t_\beta=1$
$t_\beta=10$
$q\bar{q}\to H^+H^-$
175
200
225
250
275
300
M_{H^+}[GeV]

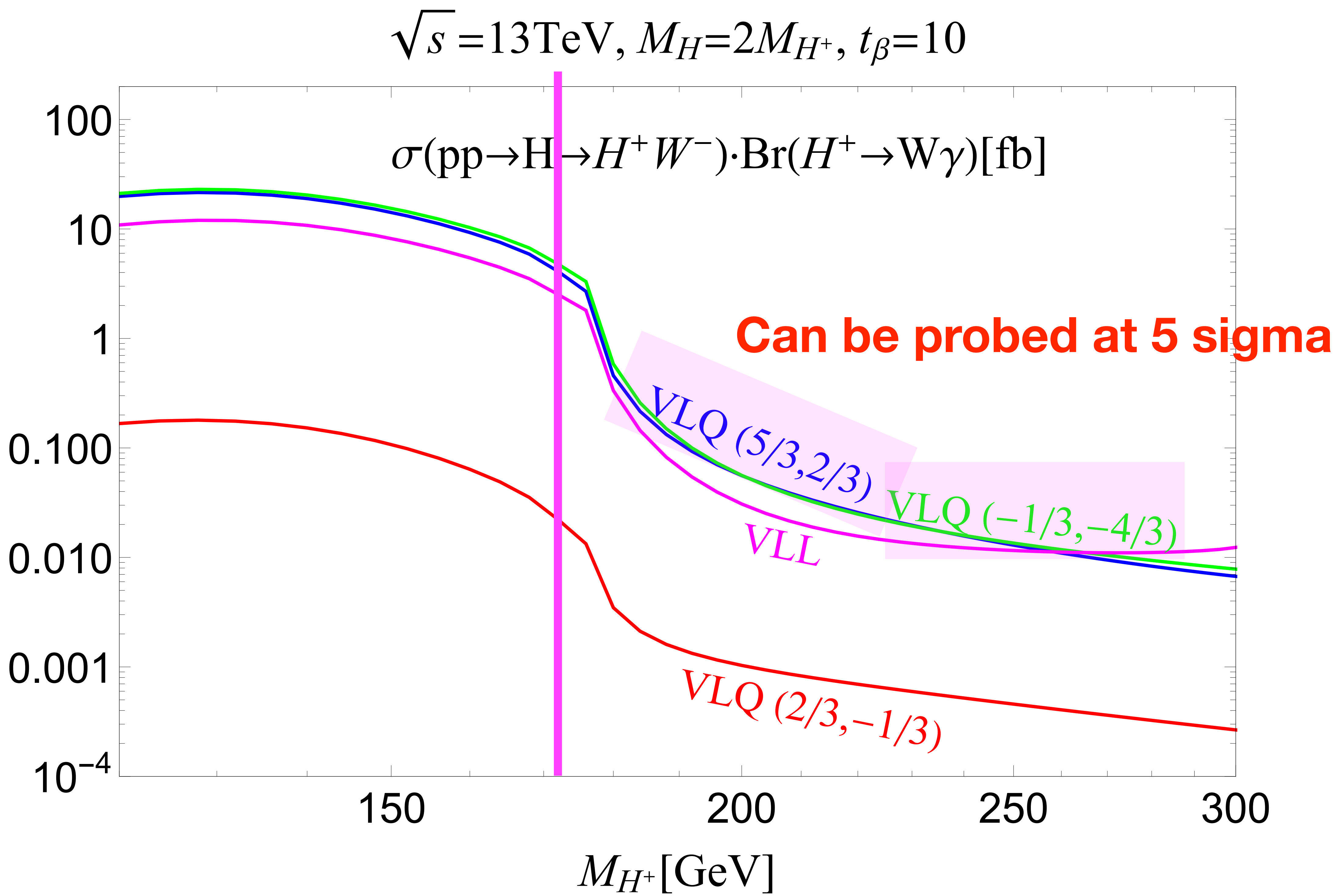


NOTE: Negligible VLQ contributions



$\sigma_{\rm SM}(pp \to W^+W^-\gamma) = 14\,{\rm fb}$ with $\left|M_{W^+\gamma}\right| < (170 \pm 10)$ GeV

NOTE: No VLQ contributions to gg->A



$\sigma_{\rm SM}(pp \to W^+W^-\gamma) = 14\,{\rm fb}$ with $|M_{W^+\gamma}| < (170 \pm 10)$ GeV

Conclusions

- The charged Higgs boson with $M_{H^\pm} \sim m_t$ is tricky to probe at the LHC.
- $H^\pm \to W^\pm\gamma$ can serve as a complementary channel.
- The branching ratio can be enhanced in a 2HDM with the VLFs.