Charged Higgs Day, Sept. 1, 2018

Charged Higgs boson in the Georgi-Machacek Model

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References

- C.W. Chiang, S. Kanemura, K.Yaguy, PRD90,115025
  Novel constraint on the parameter space of the Georgi-Machacek model

- C.W. Chiang, S. Kanemura, K.Yaguy, JHEP 01(2013)026.
  Testing the custodial symmetry in the Higgs sector of the Georgi-Machacek model

- C.W. Chiang, S. Kanemura, K.Yaguy, PRD93,055002
  Phenomenology of the Georgi-Machacek model at future electron-positron colliders

Georgi-Machacek model

- Georgi and Machacek (GM) in mid-80s.
- it can provide tiny mass to neutrinos, dubbed the Type-II Seesaw
- the Higgs potential in this model can be constructed to maintain a custodial $SU(2)_V$ symmetry at the tree level
- Physical Higgs bosons
  1. 5-plet Higgs bosons $H_5 (= H_5^{\pm\pm}, H_5^{\pm}, H_5^0)$
  2. 3-plet Higgs bosons $H_3 (= H_3^{\pm}, H_3^0)$
  3. singlet Higgs boson H_1^0

Higgs sector

- a isospin doublet field ϕ with $Y = 1/2$
- a complex triple field χ with $Y = 1$
- a real triplet field ξ with $Y = 0$.

$$Q = T_3 + Y$$

- Expressing them in the $SU(2)_L \times SU(2)_R$ covariant form

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^{+} \\ -(\phi^{+})^{*} & \phi^{0} \end{pmatrix} \qquad \Delta = \begin{pmatrix} \chi^{0*} & \xi^{+} & \chi^{++} \\ -(\chi^{+})^{*} & \xi^{0} & \chi^{+} \\ (\chi^{++})^{*} & -(\xi^{+})^{*} & \chi^{0} \end{pmatrix}$$

Neutral components and Lagrangian

$$\phi^0 = \frac{1}{\sqrt{2}}(\phi_r + v_\phi + i\phi_i), \quad \chi^0 = \frac{1}{\sqrt{2}}(\chi_r + i\chi_i) + v_\chi, \quad \xi^0 = \xi_r + v_\xi,$$

- When $v_\chi = v_\xi \equiv v_\Delta$, the $SU(2)_L \times sU(2)_R$ is reduced to the custodial symmetry.

$$\mathcal{L}_{\rm GM} = \mathcal{L}_{\rm kin} + \mathcal{L}_Y + \mathcal{L}_\nu - V_H,$$

$$
\begin{aligned}
V_H = {} & m_1^2 \mathrm{tr}(\Phi^\dagger \Phi) + m_2^2 \mathrm{tr}(\Delta^\dagger \Delta) + \lambda_1 \mathrm{tr}(\Phi^\dagger \Phi)^2 + \lambda_2 [\mathrm{tr}(\Delta^\dagger \Delta)]^2 + \lambda_3 \mathrm{tr}[(\Delta^\dagger \Delta)^2] \\
& + \lambda_4 \mathrm{tr}(\Phi^\dagger \Phi) \mathrm{tr}(\Delta^\dagger \Delta) + \lambda_5 \mathrm{tr}\left(\Phi^\dagger \frac{\tau^a}{2} \Phi \frac{\tau^b}{2}\right) \mathrm{tr}(\Delta^\dagger t^a \Delta t^b) \\
& + \mu_1 \mathrm{tr}\left(\Phi^\dagger \frac{\tau^a}{2} \Phi \frac{\tau^b}{2}\right) (P^\dagger \Delta P)^{ab} + \mu_2 \mathrm{tr}\left(\Delta^\dagger t^a \Delta t^b\right) (P^\dagger \Delta P)^{ab},
\end{aligned}
$$

t^a are the 3×3 matrix representation of the $SU(2)$ generators

$$t_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \quad t_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & -i & 0 \\ i & 0 & -i \\ 0 & i & 0 \end{pmatrix}, \quad t_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

$$P = \begin{pmatrix} -1/\sqrt{2} & i/\sqrt{2} & 0 \\ 0 & 0 & 1 \\ 1/\sqrt{2} & i/\sqrt{2} & 0 \end{pmatrix}$$

- Physical Higgs bosons
  1. 5-plet Higgs bosons $H_5(= H_5^{\pm\pm}, H_5^{\pm}, H_5^0)$
  2. 3-plet Higgs bosons $H_3(= H_3^{\pm}, H_3^0)$
  3. singlet Higgs boson H_1^0

CP-even

$$H_5^{\pm\pm} = \chi^{\pm\pm}, \quad H_5^{\pm} = \frac{1}{\sqrt{2}}(\chi^{\pm} - \xi^{\pm}), \quad H_5^0 = \frac{1}{\sqrt{3}}(\chi_r - \sqrt{2}\xi_r),$$

CP-odd

$$\tilde{H}_3^{\pm} = \frac{1}{\sqrt{2}}(\chi^{\pm} + \xi^{\pm}), \quad \tilde{H}_3^0 = \chi_i,$$

$$\tilde{H}_1^0 = \frac{1}{\sqrt{3}}(\xi_r + \sqrt{2}\chi_r).$$

CP-even

- fields with tildes: not mass eigenstates

Tadpole conditions

$$\left.\frac{\partial V_H}{\partial \phi_r}\right|_0 = 0, \quad \left.\frac{\partial V_H}{\partial \xi_r}\right|_0 = 0, \quad \left.\frac{\partial V_H}{\partial \chi_r}\right|_0 = 0,$$

- the parameters m_1^2 and m_2^2 can be eliminated as

$$m_1^2 = -v^2\left(2c_H^2\lambda_1 + \frac{3}{8}s_H^2\lambda_4 + \frac{3}{16}s_H^2\lambda_5\right) + \frac{3}{8}s_H^2 M_1^2,$$

$$m_2^2 = -v^2\left(\frac{3}{4}s_H^2\lambda_2 + \frac{1}{4}s_H^2\lambda_3 + c_H^2\lambda_4 + \frac{1}{2}c_H^2\lambda_5\right) + \frac{1}{2}c_H^2 M_1^2 + \frac{1}{4}M_2^2,$$

where $v^2 = v_\phi^2 + 8v_\Delta^2 = 1/(\sqrt{2}G_F)$ and $\boxed{\tan\theta_H = 2\sqrt{2}v_\Delta/v_\phi}$

$$M_1^2 = -\frac{v}{\sqrt{2}s_H}\mu_1, \quad M_2^2 = -3\sqrt{2}s_H v\mu_2.$$

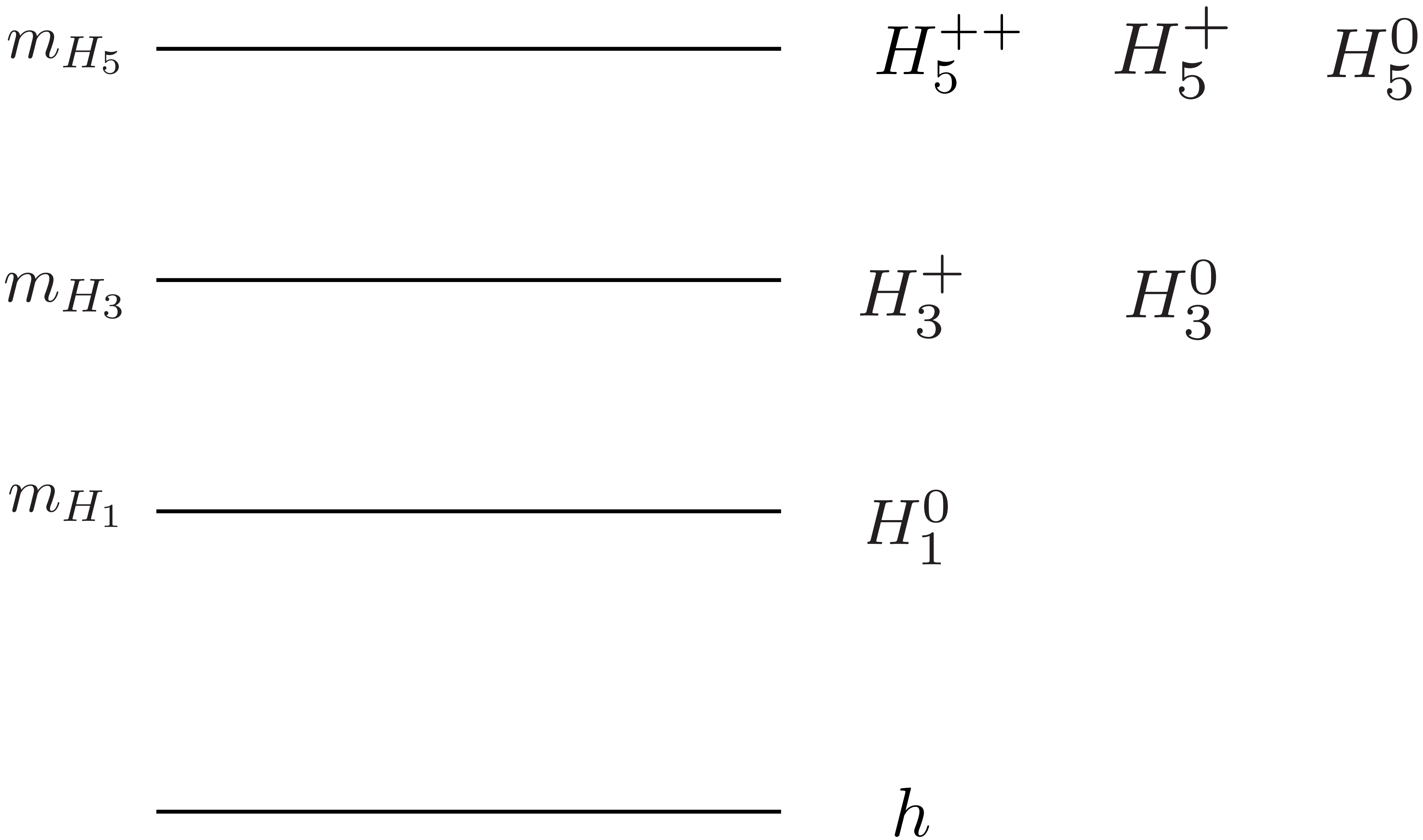
Mass eigenstates

$$\begin{pmatrix} \phi_i \\ \tilde{H}_3^0 \end{pmatrix} = U_{\text{CP-odd}} \begin{pmatrix} G^0 \\ H_3^0 \end{pmatrix}, \quad \begin{pmatrix} \phi^\pm \\ \tilde{H}_3^\pm \\ H_5^\pm \end{pmatrix} = U_\pm \begin{pmatrix} G^\pm \\ H_3^\pm \\ H_5^\pm \end{pmatrix}, \quad \begin{pmatrix} \phi_r \\ \tilde{H}_1^0 \\ H_5^0 \end{pmatrix} = U_{\text{CP-even}} \begin{pmatrix} h \\ H_1^0 \\ H_5^0 \end{pmatrix}$$

$$U_{\text{CP-odd}} = \begin{pmatrix} c_H & -s_H \\ s_H & c_H \end{pmatrix}, \quad U_\pm = \begin{pmatrix} \begin{matrix} & U_{\text{CP-odd}} & \end{matrix} & \begin{matrix} 0 \\ \\ 0 \end{matrix} \\ \begin{matrix} & 0 & & 0 \end{matrix} & 1 \end{pmatrix}, \quad U_{\text{CP-even}} = \begin{pmatrix} c_\alpha & -s_\alpha & 0 \\ s_\alpha & c_\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Two mixing angles $\alpha, \ \theta_H$

Three new mass scales



Parameters

- Five parameters

$$m_{H_1}, \quad m_{H_3}, \quad m_{H_5}, \quad \alpha$$

$$\lambda_1 = \frac{1}{8v^2 c_H^2}(m_h^2 c_\alpha^2 + m_{H_1}^2 s_\alpha^2),$$

$$\lambda_2 = \frac{1}{6v^2 s_H^2}\left[2m_{H_1}^2 c_\alpha^2 + 2m_h^2 s_\alpha^2 + 3M_2^2 - 2m_{H_5}^2 + 6c_H^2(m_{H_3}^2 - M_1^2)\right],$$

$$\lambda_3 = \frac{1}{v^2 s_H^2}\left[c_H^2(2M_1^2 - 3m_{H_3}^2) + m_{H_5}^2 - M_2^2\right],$$

$$\lambda_4 = \frac{1}{6v^2 s_H c_H}\left[\frac{\sqrt{6}}{2} s_{2\alpha}(m_h^2 - m_{H_1}^2) + 3 s_H c_H (2m_{H_3}^2 - M_1^2)\right],$$

$$\lambda_5 = \frac{2}{v^2}(M_1^2 - m_{H_3}^2).$$

$$M_1^2 = -\frac{v}{\sqrt{2} s_H}\mu_1, \quad M_2^2 = -3\sqrt{2} s_H v \mu_2.$$

Decoupling limit: $s_H \to 0$

- Equivalently $v_\Delta \to 0$

$$\begin{pmatrix} \phi_i \\ \tilde{H}_3^0 \end{pmatrix} = U_{\text{CP-odd}} \begin{pmatrix} G^0 \\ H_3^0 \end{pmatrix}, \quad \begin{pmatrix} \phi^\pm \\ \tilde{H}_3^\pm \\ H_5^\pm \end{pmatrix} = U_\pm \begin{pmatrix} G^\pm \\ H_3^\pm \\ H_5^\pm \end{pmatrix}, \quad \begin{pmatrix} \phi_r \\ \tilde{H}_1^0 \\ H_5^0 \end{pmatrix} = U_{\text{CP-even}} \begin{pmatrix} h \\ H_1^0 \\ H_5^0 \end{pmatrix}$$

$$U_{\text{CP-odd}} = \begin{pmatrix} c_H & -s_H \\ s_H & c_H \end{pmatrix}, \quad U_\pm = \begin{pmatrix} \begin{array}{cc|c} \multicolumn{2}{c}{\multirow{2}{*}{$U_{\text{CP-odd}}$}} & 0 \\ & & 0 \\ 0 & 0 & 1 \end{array} \end{pmatrix}, \quad U_{\text{CP-even}} = \begin{pmatrix} c_\alpha & -s_\alpha & 0 \\ s_\alpha & c_\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Decoupling limit: $s_H \to 0$

0

$$M_1^2 = -\frac{v}{\sqrt{2}s_H}\mu_1, \quad M_2^2 = -3\sqrt{2}s_H v\mu_2.$$

- finite if $\mu_1 \to 0$ in the same rate as s_H.

Yukawa couplings for leptons

Reparametrization

$$\chi = \begin{pmatrix} \frac{\chi^+}{\sqrt{2}} & -\chi^{++} \\ \chi^0 & -\frac{\chi^+}{\sqrt{2}} \end{pmatrix}$$

$$\mathcal{L}_\nu = h_{ij} \overline{L_L^{ic}} i\tau_2 \chi L_L^j + \text{h.c.}$$

$$\mathcal{L}_\nu = \frac{2\sqrt{2} m_\nu}{s_H v} H_5^{++} \overline{e_i^c} P_L e_i - \frac{2\sqrt{2} m_\nu}{s_H v} \left(H_5^+ + c_H H_3^+ + s_H G^+ \right) \overline{\nu_i^c} P_L e_i \Big]$$
$$+ \frac{2 m_\nu}{s_H v} \left[\frac{1}{\sqrt{3}} (H_5^0 + \sqrt{2} s_\alpha h + c_\alpha H_1^0) + i(G^0 s_H + H_3^0 c_H) \right] \overline{\nu_i^c} P_L \nu_i + \text{h.c.}$$

Yukawa couplings

$$\mathcal{L}_Y = - \sum_{f=u,d,e} \frac{m_f}{v} \left[\frac{c_\alpha}{c_H} \bar{f} f h - \frac{s_\alpha}{c_H} \bar{f} f H_1^0 + i \mathrm{Sign}(f) \tan\theta_H \bar{f} \gamma_5 f H_3^0 \right]$$
$$- \frac{\sqrt{2} V_{ud}}{v} \left[\tan\theta_H \bar{u} (m_u P_L - m_d P_R) d H_3^+ \right] + \frac{\sqrt{2} m_e}{v} \tan\theta_H \bar{\nu} P_R e H_3^+ + \mathrm{h.c.},$$

Gauge couplings

$$\boxed{\mathcal{L}_{\rm kin} = \frac{1}{2}{\rm tr}(D_\mu\Phi)^\dagger(D^\mu\Phi) + \frac{1}{2}{\rm tr}(D_\mu\Delta)^\dagger(D^\mu\Delta),}$$

$$D_\mu\Phi = \partial_\mu\Phi + ig\frac{\tau^a}{2}W_\mu^a\Phi - ig'B_\mu\Phi\frac{\tau^3}{2},$$
$$D_\mu\Delta = \partial_\mu\Delta + igt^aW_\mu^a\Delta - ig'B_\mu\Delta t^3.$$

$$\boxed{m_W^2 = \frac{g^2}{4}v^2, \quad m_Z^2 = \frac{g^2}{4\cos^2\theta_W}v^2.}$$

$\rho = m_W^2/(m_Z^2\cos^2\theta_W)$ is unity at the tree level.

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 ($\mathrm{U}(1)_\mathrm{Q}$–c)	1–loop

GM gauge-gauge-scalar vertices

Vertex	Coefficient	Vertex	Coefficient
$H_5^{\pm\pm} W_\mu^{\mp} W_\nu^{\mp}$	$\frac{g^2}{2\sqrt{2}} s_H v g_{\mu\nu}$	$H_1^0 Z_\mu Z_\nu$	$-\frac{g_Z^2}{12}(3 s_\alpha c_H - 2\sqrt{6} c_\alpha s_H) v g_{\mu\nu}$
$H_5^{\pm} W_\mu^{\mp} Z_\nu$	$\mp \frac{g g_Z}{2} s_H v g_{\mu\nu}$	$h W_\mu^+ W_\nu^-$	$\frac{g^2}{6}(3 c_\alpha c_H + 2\sqrt{6} s_\alpha s_H) v g_{\mu\nu}$
$H_5^0 W_\mu^+ W_\nu^-$	$-\frac{g^2}{2\sqrt{3}} s_H v g_{\mu\nu}$	$h Z_\mu Z_\nu$	$\frac{g_Z^2}{12}(3 c_\alpha c_H + 2\sqrt{6} s_\alpha s_H) v g_{\mu\nu}$
$H_5^0 Z_\mu Z_\nu$	$\frac{g_Z^2}{2\sqrt{3}} s_H v g_{\mu\nu}$	$G^{\pm} W_\mu^{\mp} A_\nu$	$\pm e m_W g_{\mu\nu}$
$H_1^0 W_\mu^+ W_\nu^-$	$-\frac{g^2}{6}(3 s_\alpha c_H - 2\sqrt{6} c_\alpha s_H) v g_{\mu\nu}$	$G^{\pm} W_\mu^{\mp} Z_\nu$	$\mp e s_W m_Z g_{\mu\nu}$

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
$h : c_{\beta-\alpha}$ $\quad H : s_{\beta-\alpha}$	$\boxed{H_iA_jZ}$	YES	–
	$H^+H^-Z(\gamma)$	YES	–
$s_{\beta-\alpha}(1)$	$\boxed{H^+W^-H_i(A_i)}$	YES	–

GM gauge-scalar-scalar vertices

Vertex	Coefficient	Vertex	Coefficient
$H_5^{++}H_5^{--}A_\mu$	$2e(p_1-p_2)_\mu$	$H_5^{\pm\pm}H_5^{\mp}W_\mu^{\mp}$	$-\frac{g}{\sqrt{2}}(p_1-p_2)_\mu$
$H_5^{+}H_5^{-}A_\mu$	$-e(p_1-p_2)_\mu$	$H_5^{\pm}H_5^{0}W_\mu^{\mp}$	$\frac{\sqrt{3}}{2}g(p_1-p_2)_\mu$
$H_3^{+}H_3^{-}A_\mu$	$-e(p_1-p_2)_\mu$	$H_5^{\pm\pm}H_3^{\mp}W_\mu^{\mp}$	$-\frac{g}{\sqrt{2}}\boxed{c_H}(p_1-p_2)_\mu$
$G^{+}G^{-}A_\mu$	$-e(p_1-p_2)_\mu$	$H_5^{\pm}H_3^{0}W_\mu^{\mp}$	$\mp i\frac{g}{2}\boxed{c_H}(p_1-p_2)_\mu$
$H_5^{++}H_5^{--}Z_\mu$	$\frac{g}{c_W}(1-2s_W^2)(p_1-p_2)_\mu$	$H_3^{\pm}H_5^{0}W_\mu^{\mp}$	$-\frac{\sqrt{3}}{6}g\boxed{c_H}(p_1-p_2)_\mu$
$H_5^{+}H_5^{-}Z_\mu$	$-\frac{g}{2c_W}(1-2s_W^2)(p_1-p_2)_\mu$	$H_3^{\pm}H_3^{0}W_\mu^{\mp}$	$\mp i\frac{g}{2}(p_1-p_2)_\mu$

$H_3^+ H_3^- Z_\mu$	$-\frac{g}{2c_W}(1-2s_W^2)(p_1-p_2)_\mu$	$H_3^{\pm} H_1^0 W_\mu^{\mp}$	$\frac{g}{6}(2\sqrt{6}c_H c_\alpha + 3 s_H s_\alpha)(p_1-p_2)_\mu$
$H_5^{\pm} H_3^{\mp} Z_\mu$	$\pm\frac{g_Z}{2} c_H (p_1-p_2)_\mu$	$\boxed{H_3^{\pm} h W_\mu^{\mp}}$	$\frac{g}{6}(2\sqrt{6}\boxed{c_H s_\alpha} - 3 s_H c_\alpha)(p_1-p_2)_\mu$
$H_5^0 H_3^0 Z_\mu$	$i\frac{g_Z}{\sqrt{3}} c_H (p_1-p_2)_\mu$	$G^{\pm} h W^{\mp}$	$\frac{g}{6}(3c_\alpha c_H + 2\sqrt{6} s_\alpha s_H)$
$H_3^0 H_1^0 Z_\mu$	$-i\frac{g_Z}{6}(2\sqrt{6}c_H c_\alpha + 3 s_H s_\alpha)(p_1-p_2)_\mu$	$H_3^0 h Z_\mu$	$-i\frac{g_Z}{6}(2\sqrt{6}c_H s_\alpha - 3 s_H c_\alpha)(p_1-p_2)_\mu$

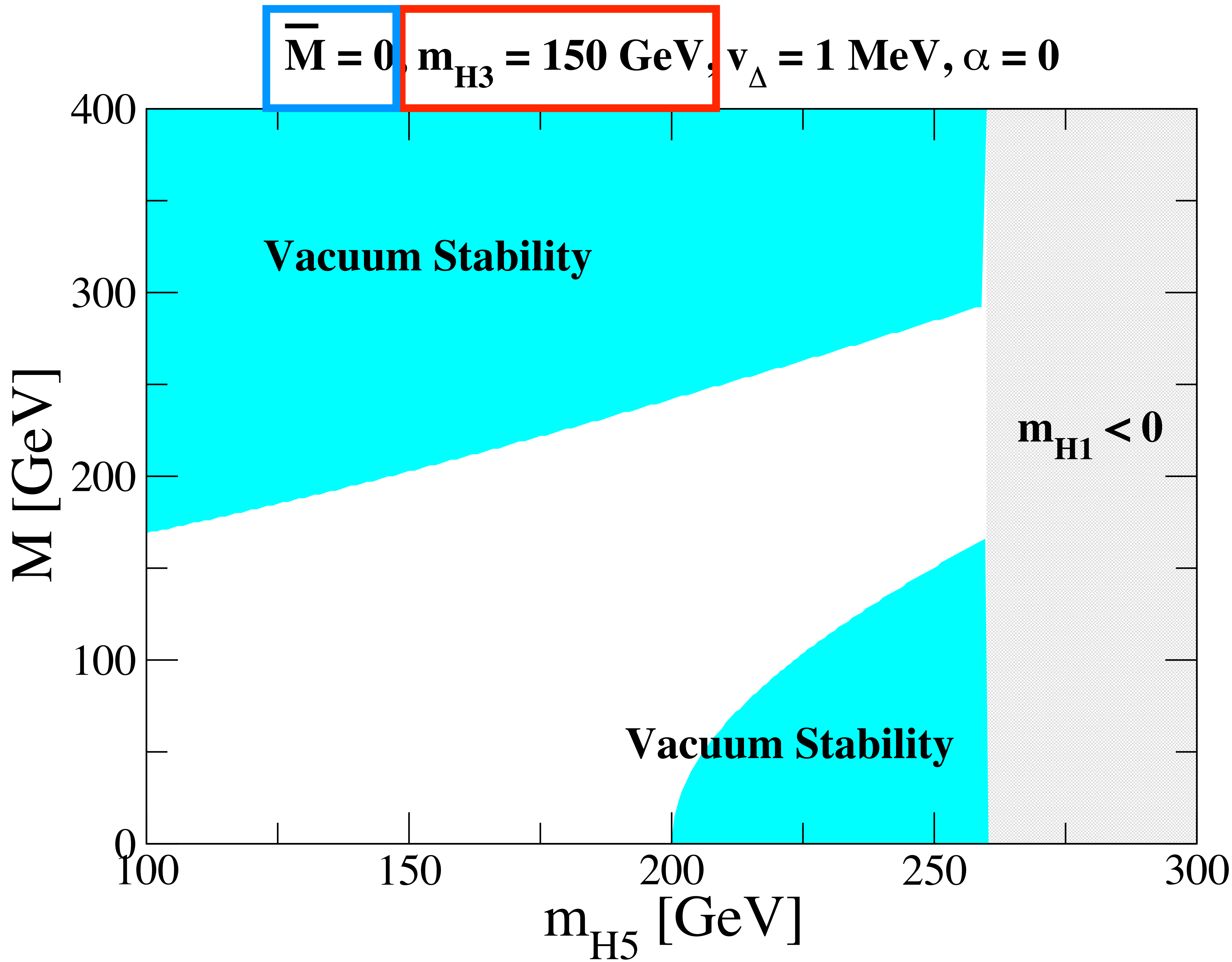
Constraints

- Perturbative unitarity and vacuum stability bounds
- Zbb data
- Higgs decay

Perturbative unitarity and vacuum stability bounds

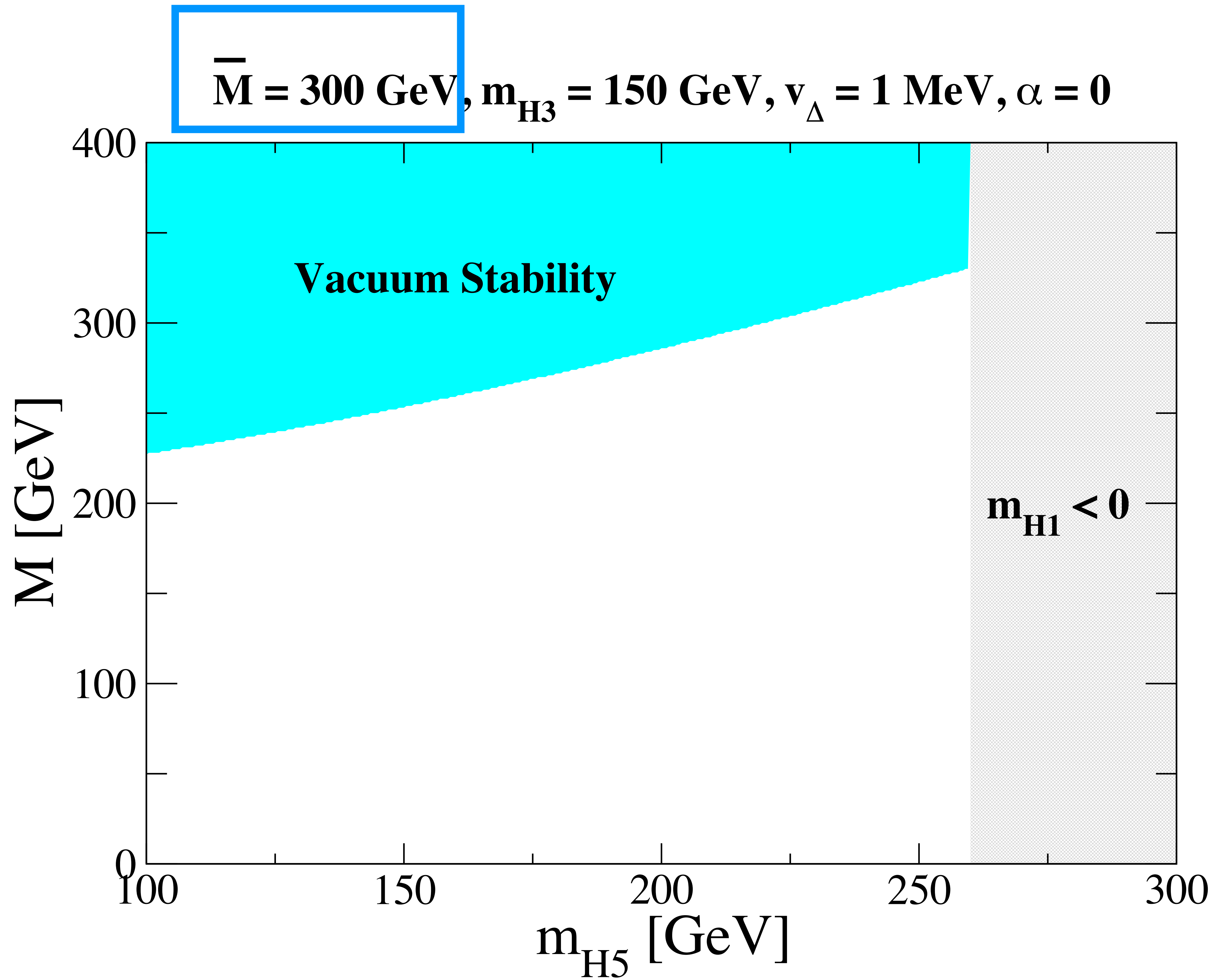
Reparametrization

$$m_{H_1}^2 = \frac{1}{2}\left(3m_{H_3}^2 - m_{H_5}^2 + 3s_H^2\bar{M}^2\right), \quad M_1^2 = \frac{1}{2}\left(3m_{H_3}^2 - m_{H_5}^2 + M^2\right), \quad M_2^2 = M^2$$

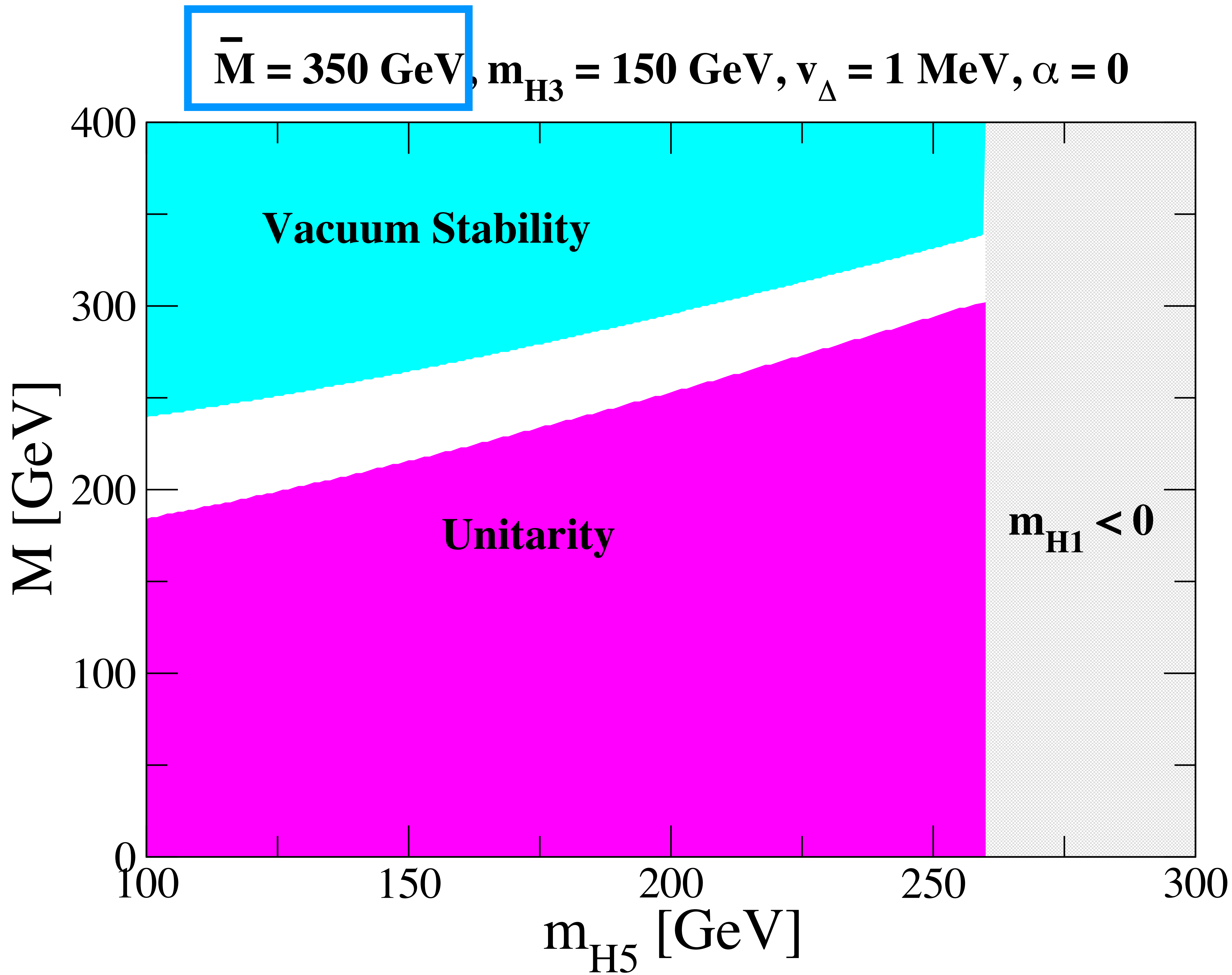


Degenerate

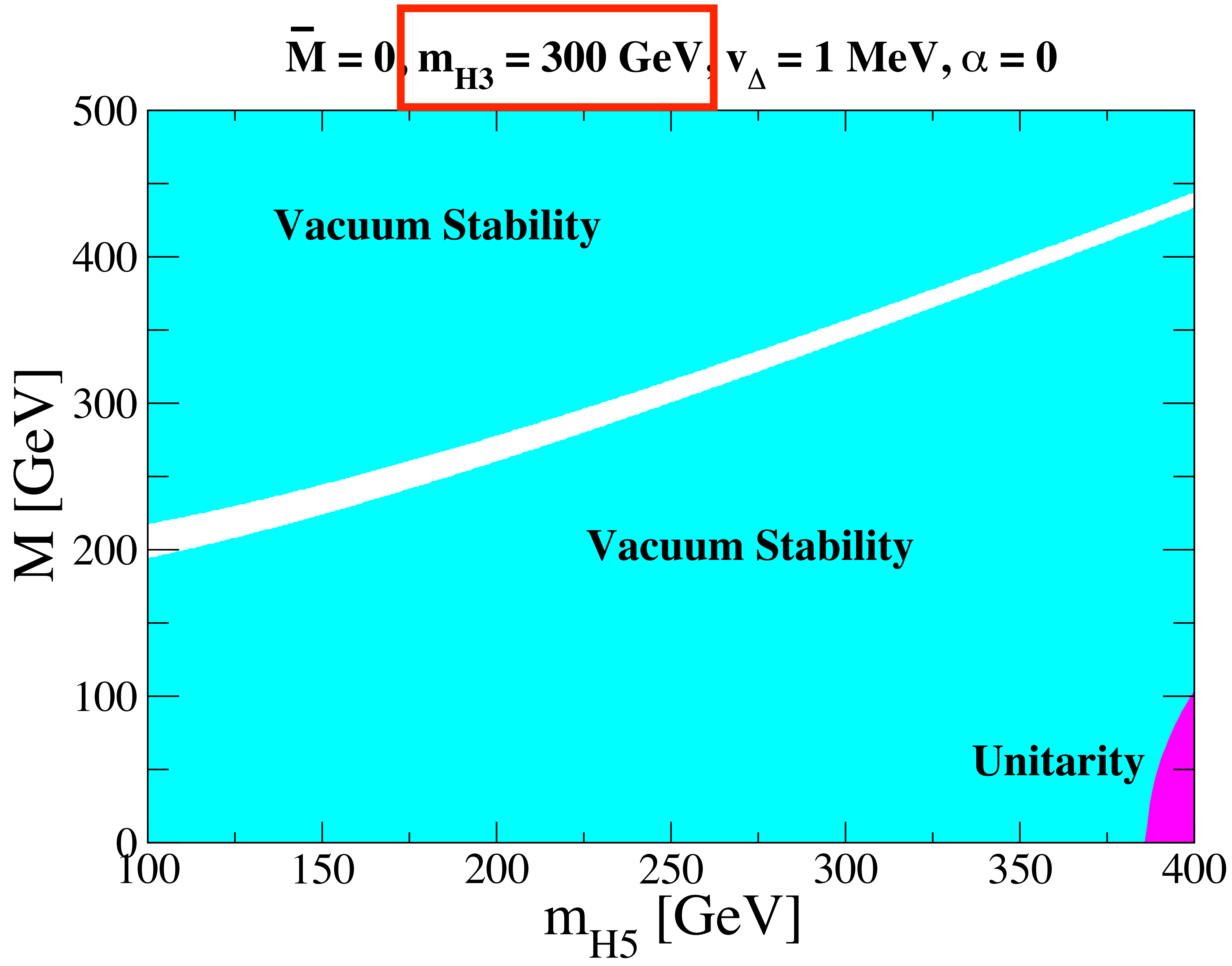
$$m_{H_1}^2 = \frac{1}{2}\left(3m_{H_3}^2 \boxed{- m_{H_5}^2} + 3s_H^2\bar{M}^2\right)$$



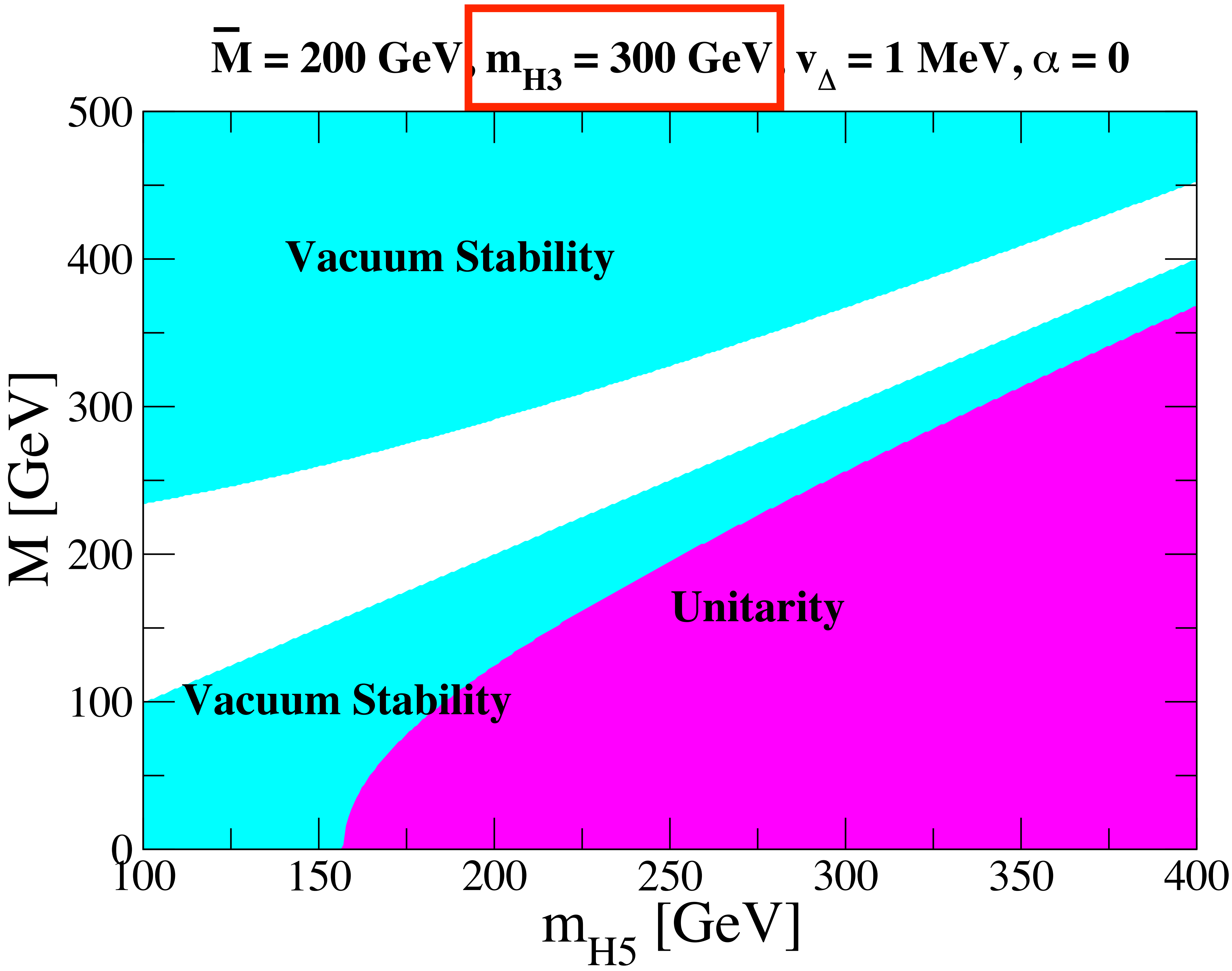
$\bar{M}$ = 300 GeV, m_{H3} = 150 GeV, v_Δ = 1 MeV, α = 0
Vacuum Stability
$m_{H1} < 0$
M [GeV]
m_{H5} [GeV]
0
100
200
300
400
100
150
200
250
300



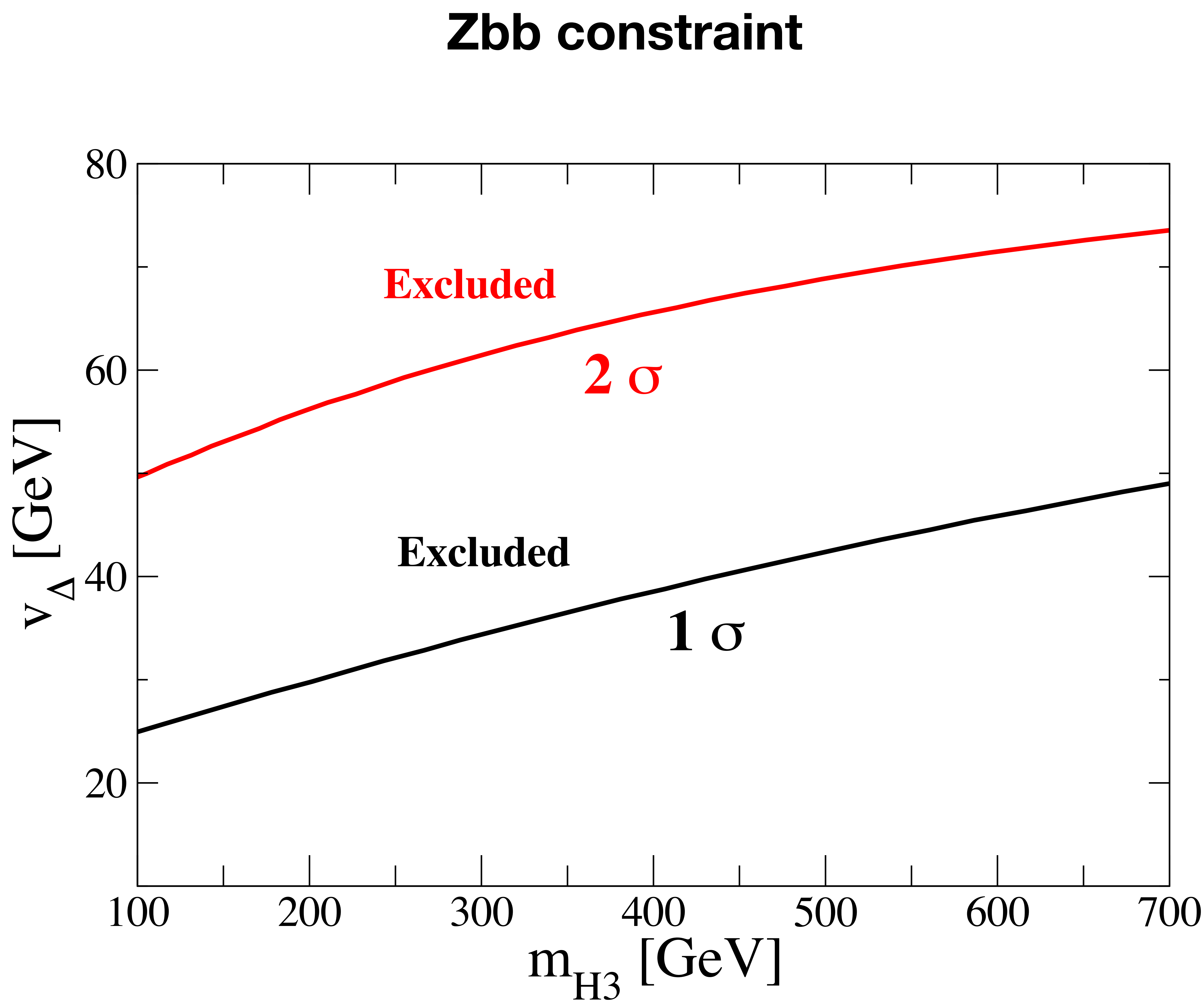
$\bar{M}$ = 350 GeV, m_{H3} = 150 GeV, v_Δ = 1 MeV, α = 0
Vacuum Stability
Unitarity
$m_{H1} < 0$
M [GeV]
m_{H5} [GeV]
0
100
200
300
400
150
250



$\bar{M} = 0$, $m_{H3} = 300$ GeV, $v_\Delta = 1$ MeV, $\alpha = 0$
Vacuum Stability
Vacuum Stability
Unitarity
M [GeV]
m_{H5} [GeV]
0
100
200
300
400
500
100
150
200
250
300
350
400



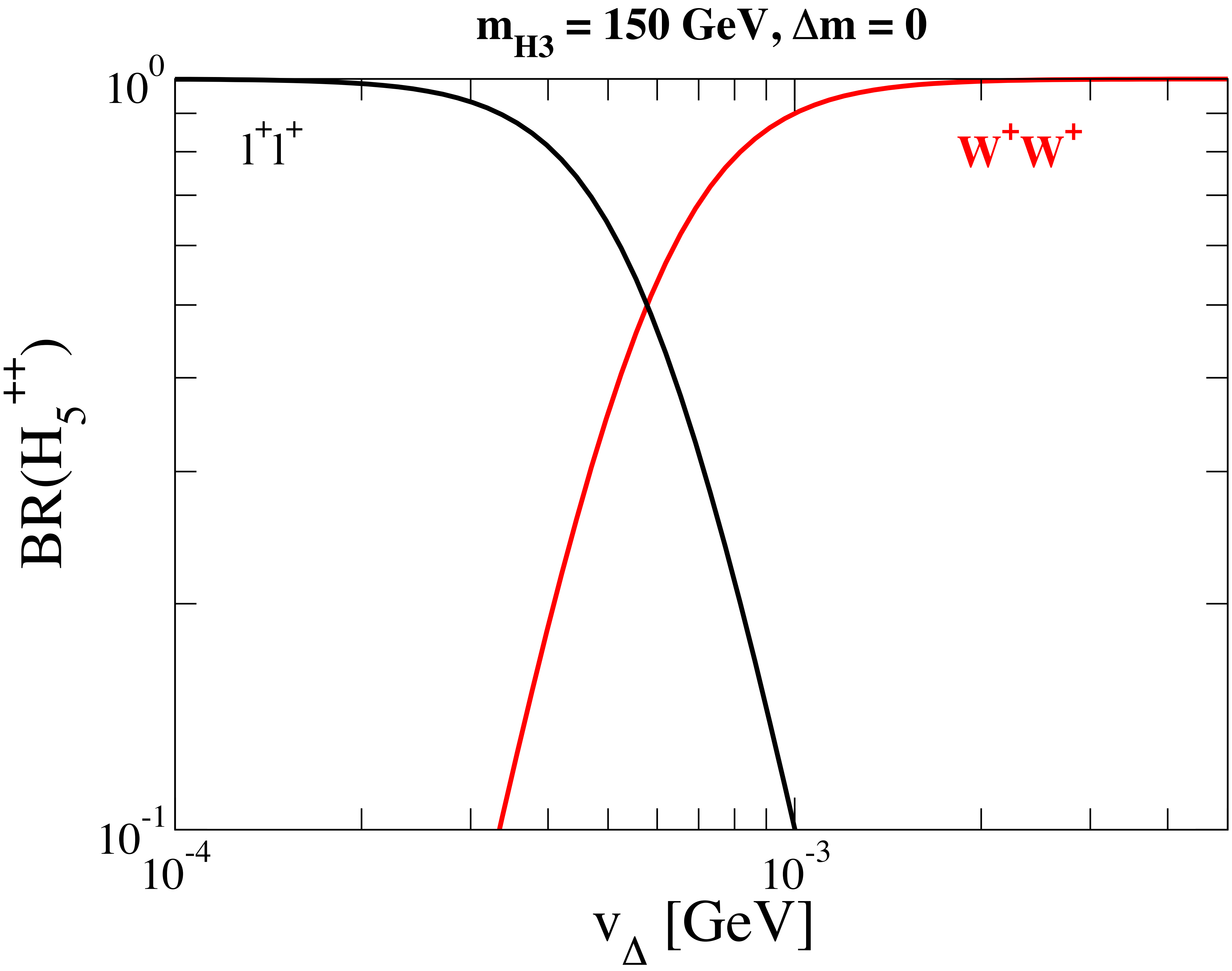
$\bar{M}$ = 200 GeV, m_{H3} = 300 GeV, v_Δ = 1 MeV, α = 0
Vacuum Stability
Unitarity
Vacuum Stability
M [GeV]
m_{H5} [GeV]
0
100
200
300
400
500
100
150
200
250
300
350
400

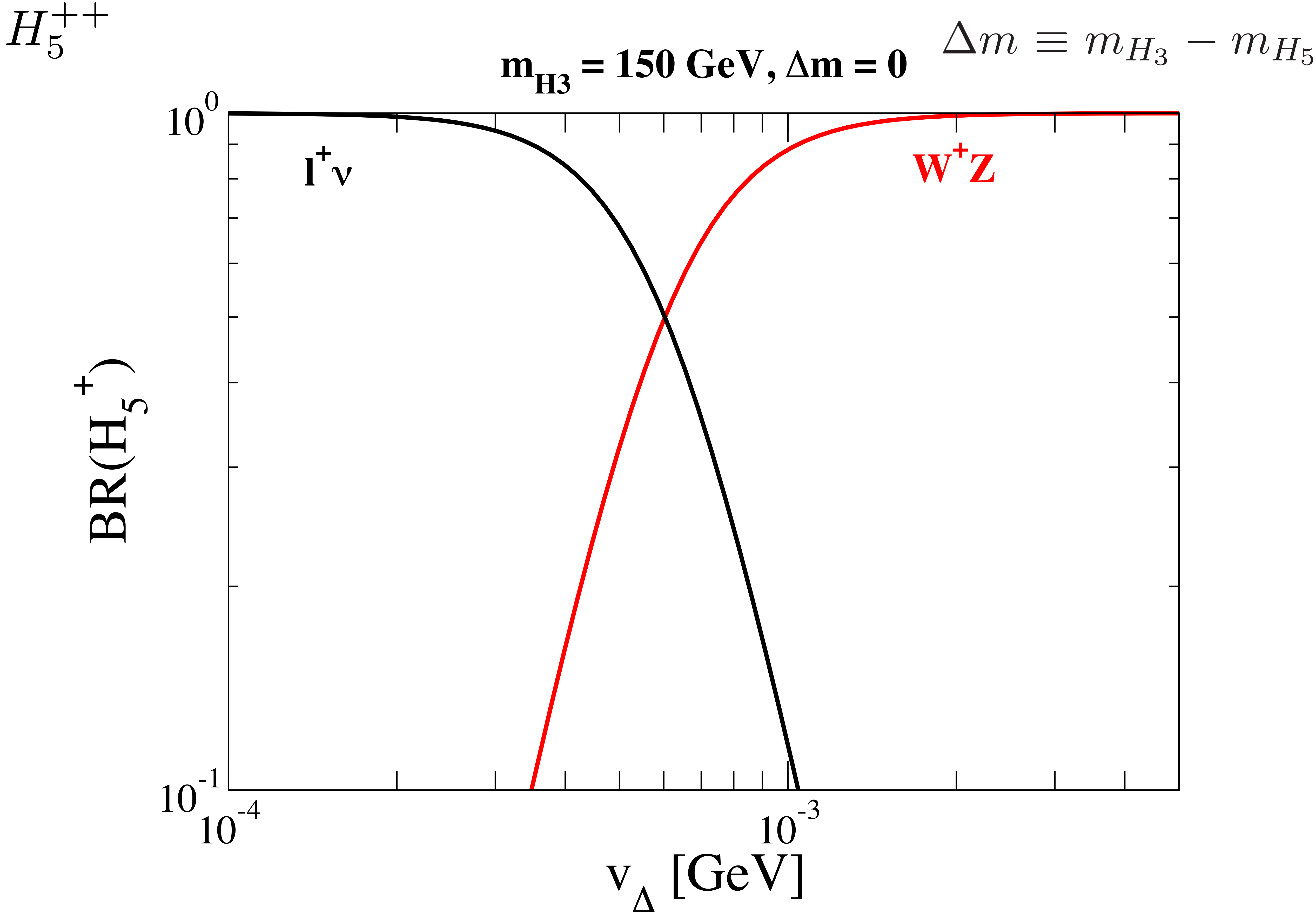

Zbb constraint
Excluded
2 σ
Excluded
1 σ
80
60
40
20
100
200
300
400
500
600
700
v_Δ [GeV]
m_{H3} [GeV]

Decays of heavy Higgs

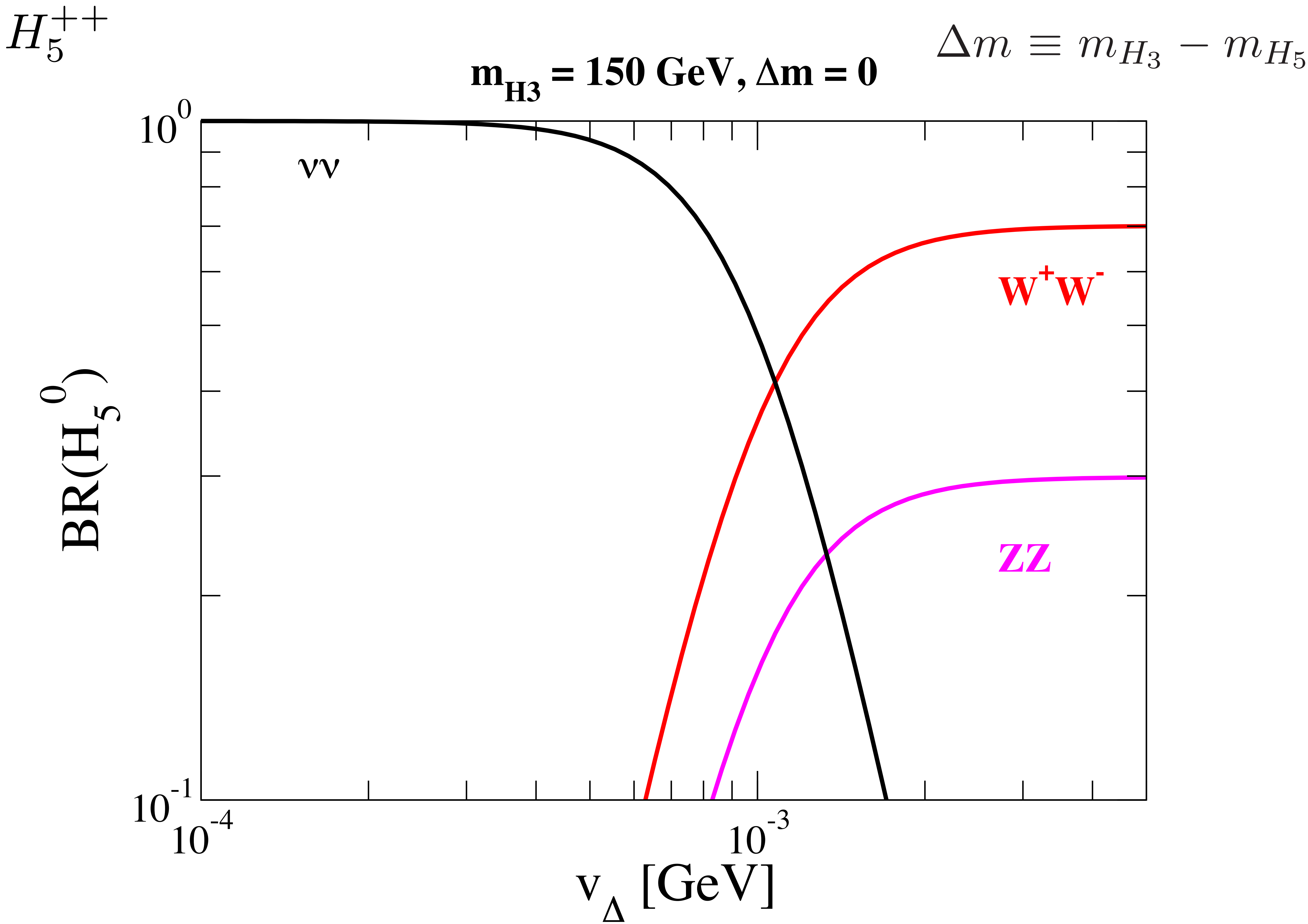
H_5^{++}

$\Delta m \equiv m_{H_3} - m_{H_5}$



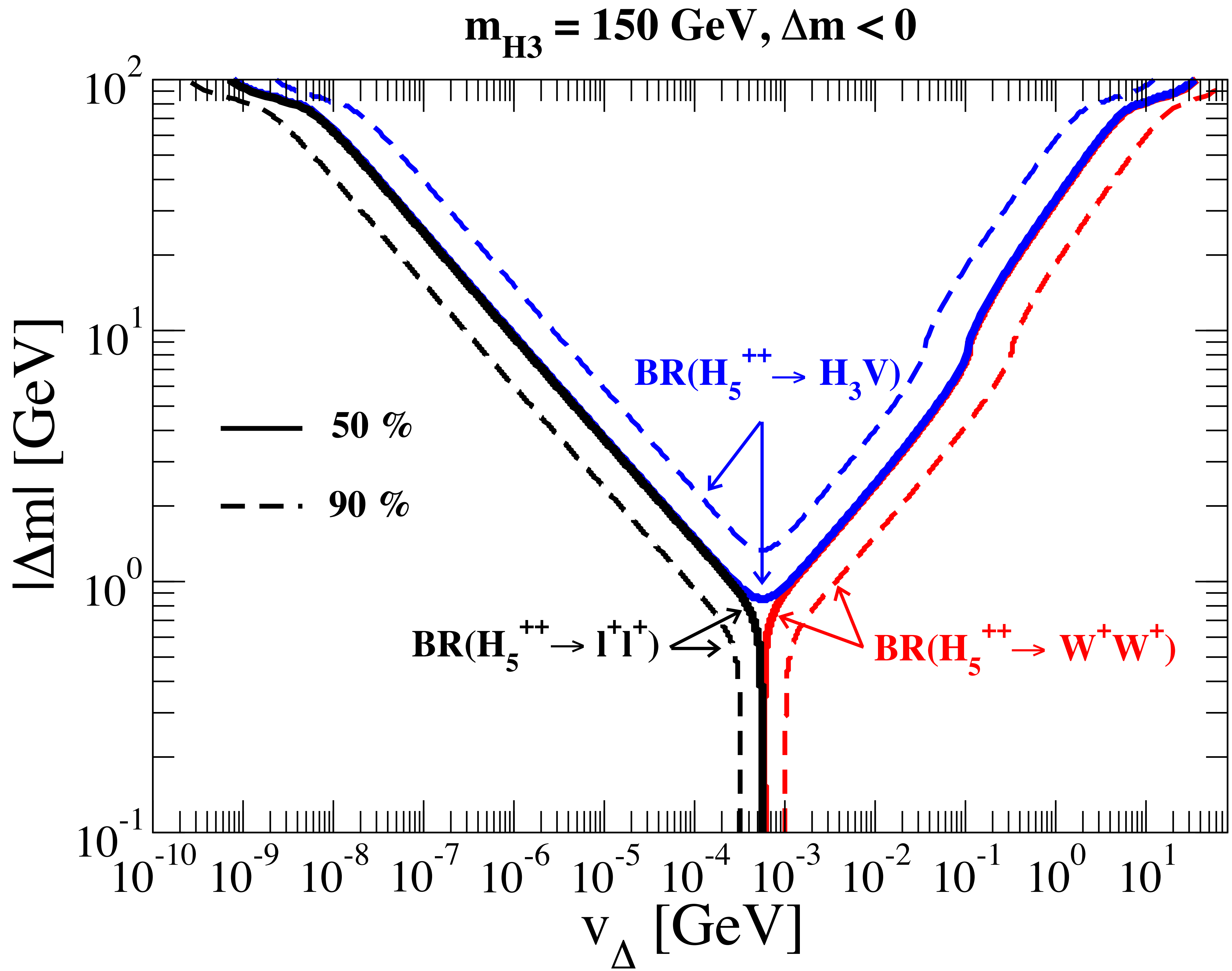


H_5^{++}
$\Delta m \equiv m_{H_3} - m_{H_5}$
m_{H3} = 150 GeV, Δm = 0
$l^+\nu$
W^+Z
$BR(H_5^+)$
10^0
10^{-1}
10^{-4}
10^{-3}
v_Δ [GeV]

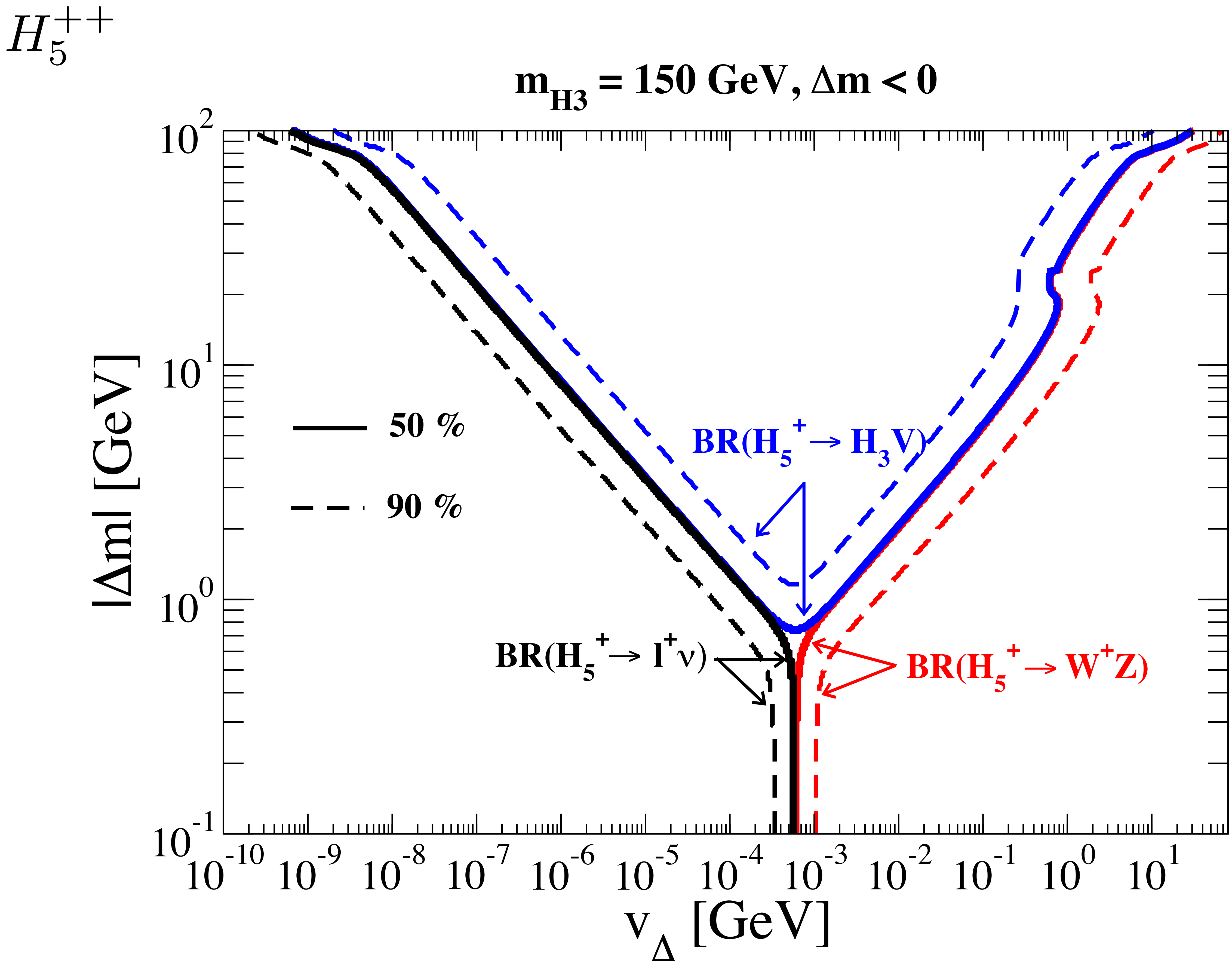


H_5^{++}
$\Delta m \equiv m_{H_3} - m_{H_5}$
m_{H3} = 150 GeV, Δm = 0
10^0
10^{-1}
10^{-4}
10^{-3}
$BR(H_5^0)$
v_Δ [GeV]
νν
W^+W^-
ZZ

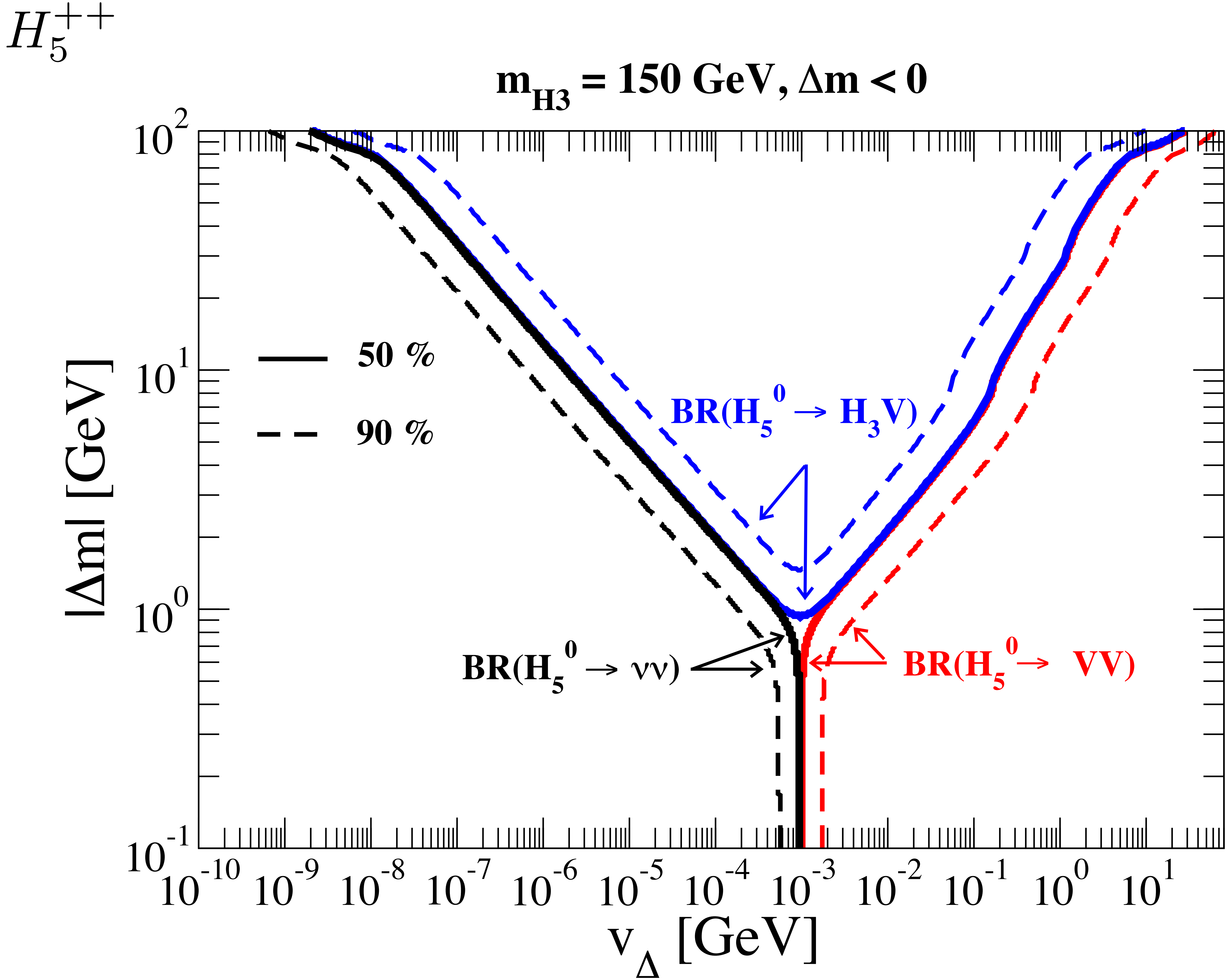
H_5^{++}



m_H3 = 150 GeV, Δm < 0
BR(H_5^++ → H_3V)
50 %
90 %
BR(H_5^++ → l^+l^+)
BR(H_5^++ → W^+W^+)
|Δm| [GeV]
v_Δ [GeV]
10^2
10^1
10^0
10^-1
10^-10
10^-9
10^-8
10^-7
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
10^0
10^1

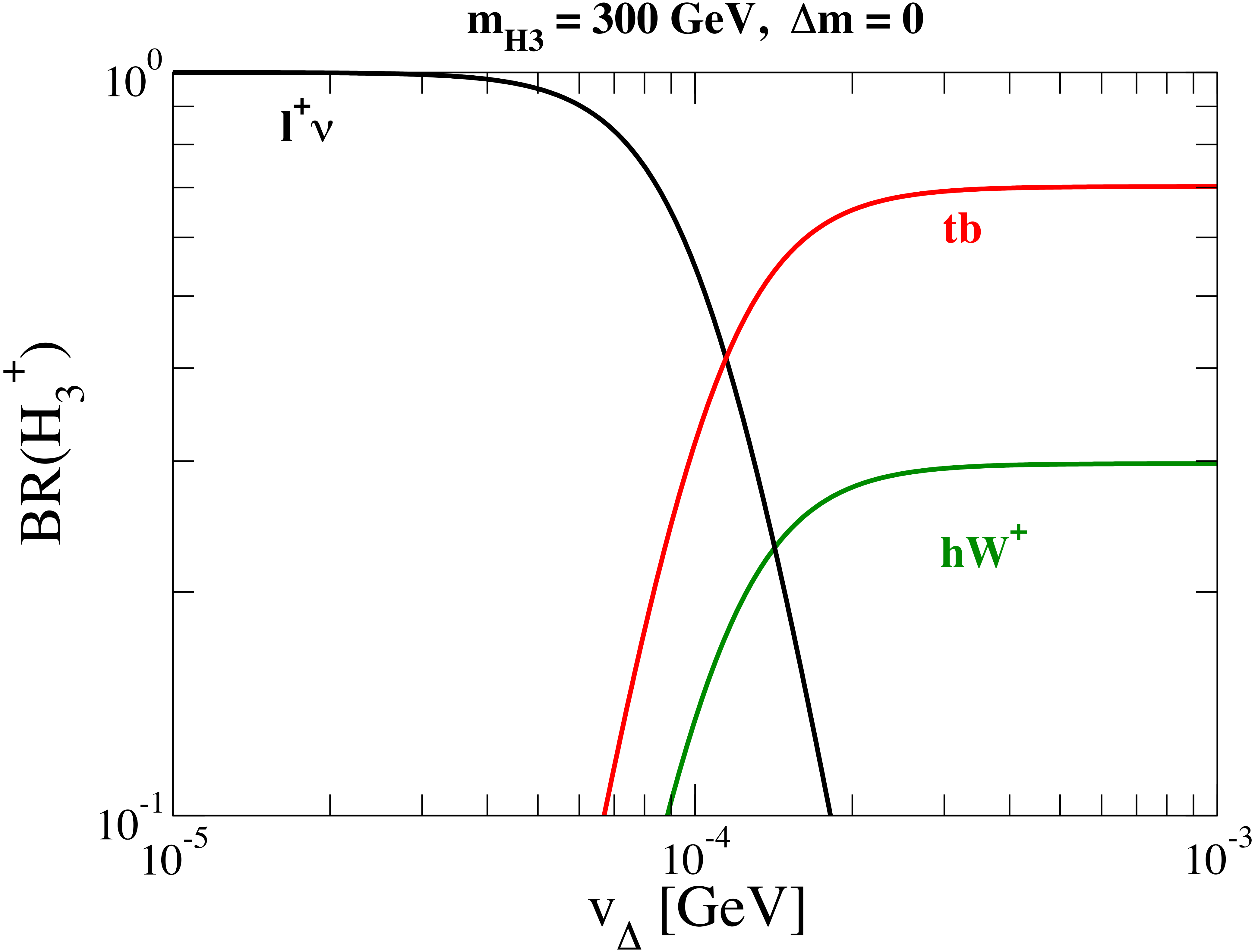


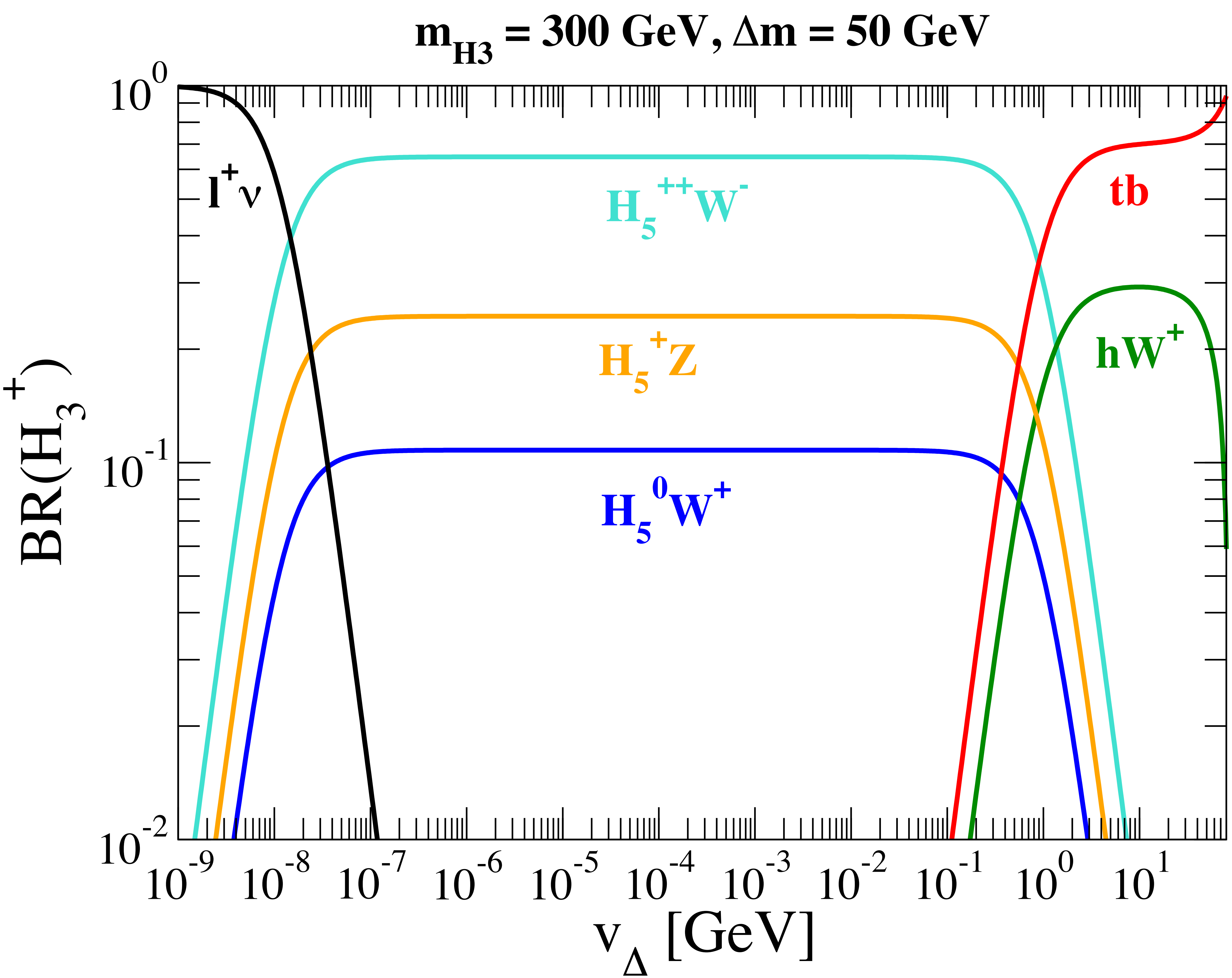
H_5^{++}
m_{H3} = 150 GeV, Δm < 0
|Δm| [GeV]
v_Δ [GeV]
50 %
90 %
BR($H_5^+ \to H_3 V$)
BR($H_5^+ \to l^+ \nu$)
BR($H_5^+ \to W^+ Z$)



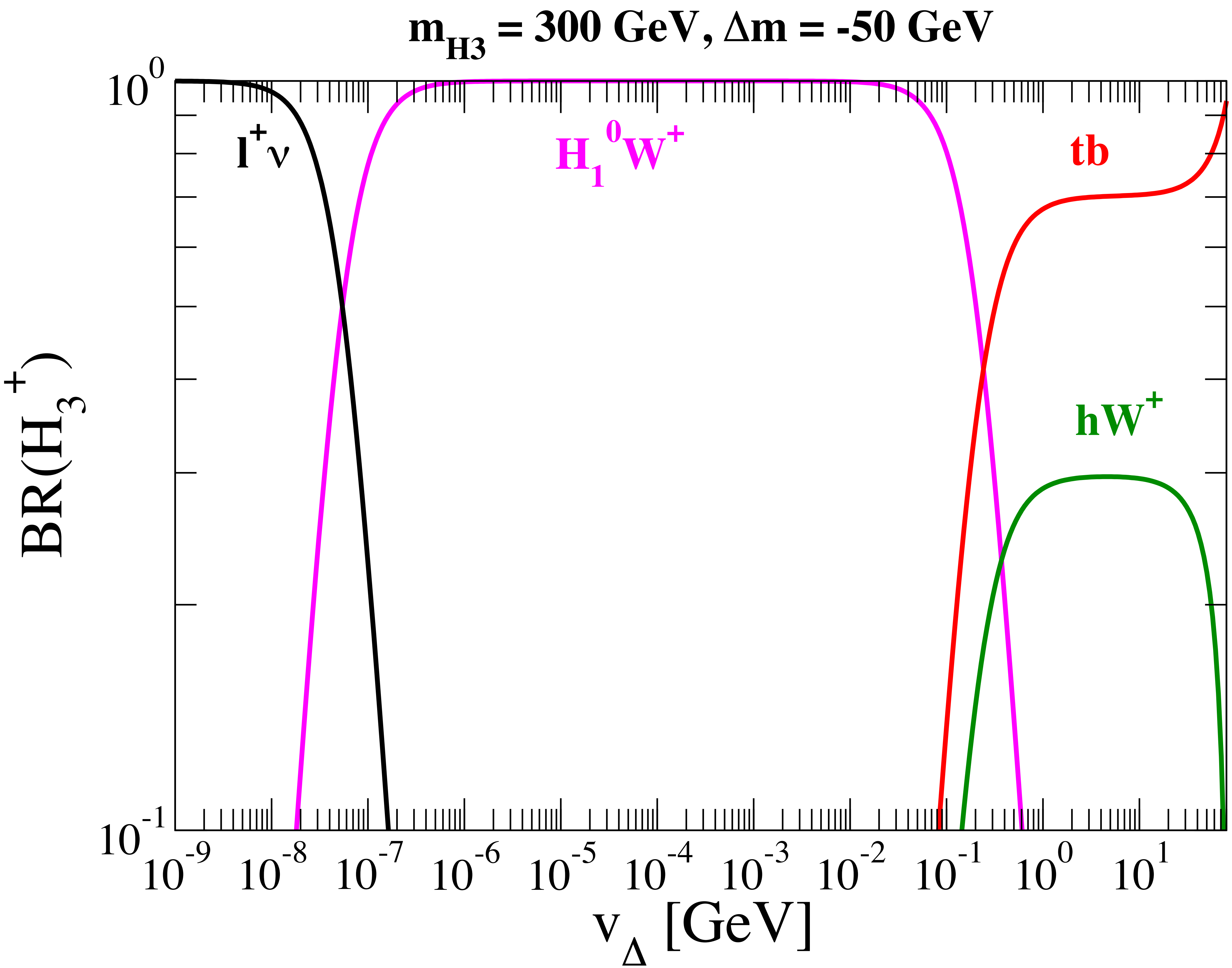
H_5^{++}
m_{H3} = 150 GeV, Δm < 0
50 %
90 %
BR($H_5^0 \to H_3V$)
BR($H_5^0 \to \nu\nu$)
BR($H_5^0 \to VV$)
|Δm| [GeV]
v_Δ [GeV]
10^2
10^1
10^0
10^{-1}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1

H_3^+

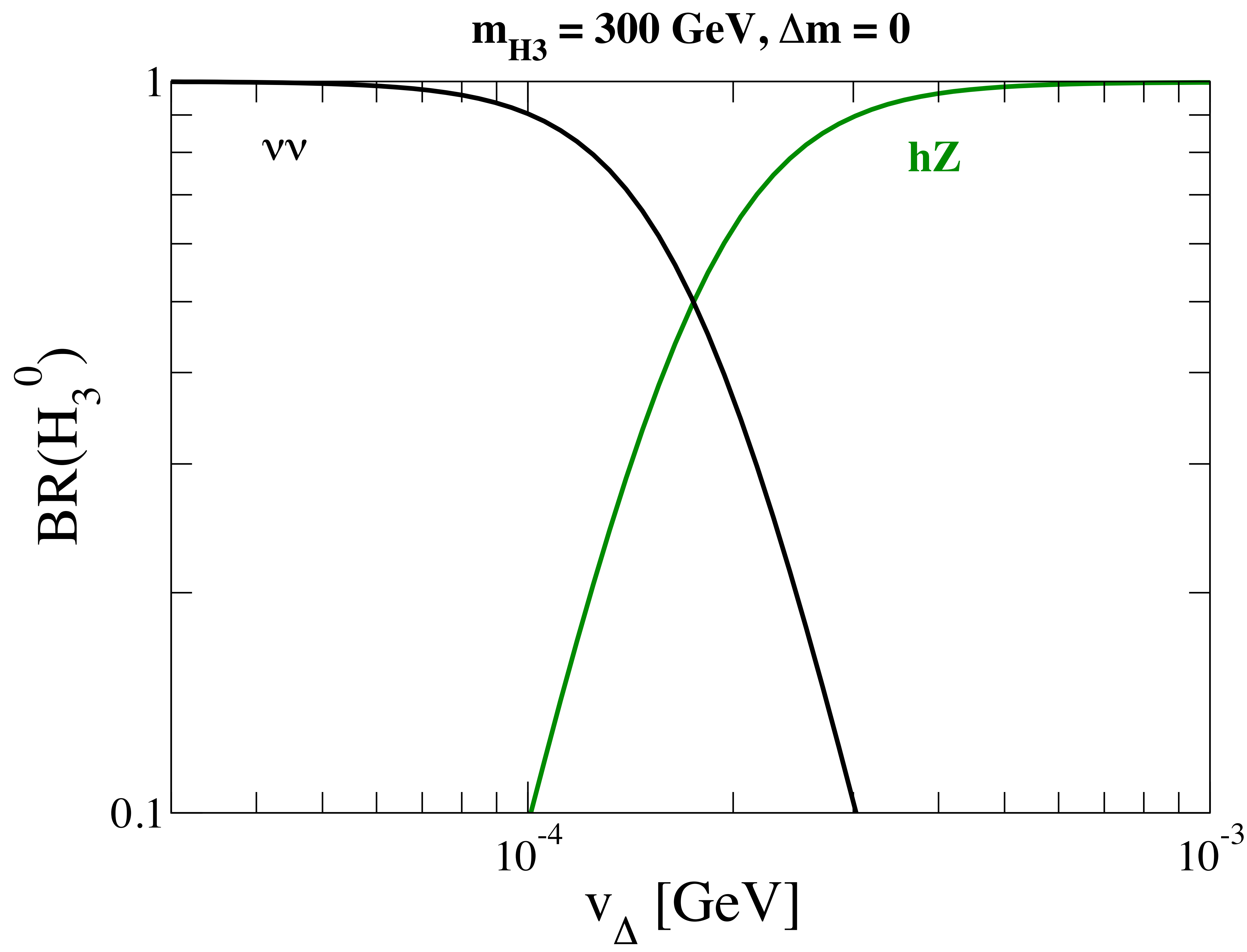




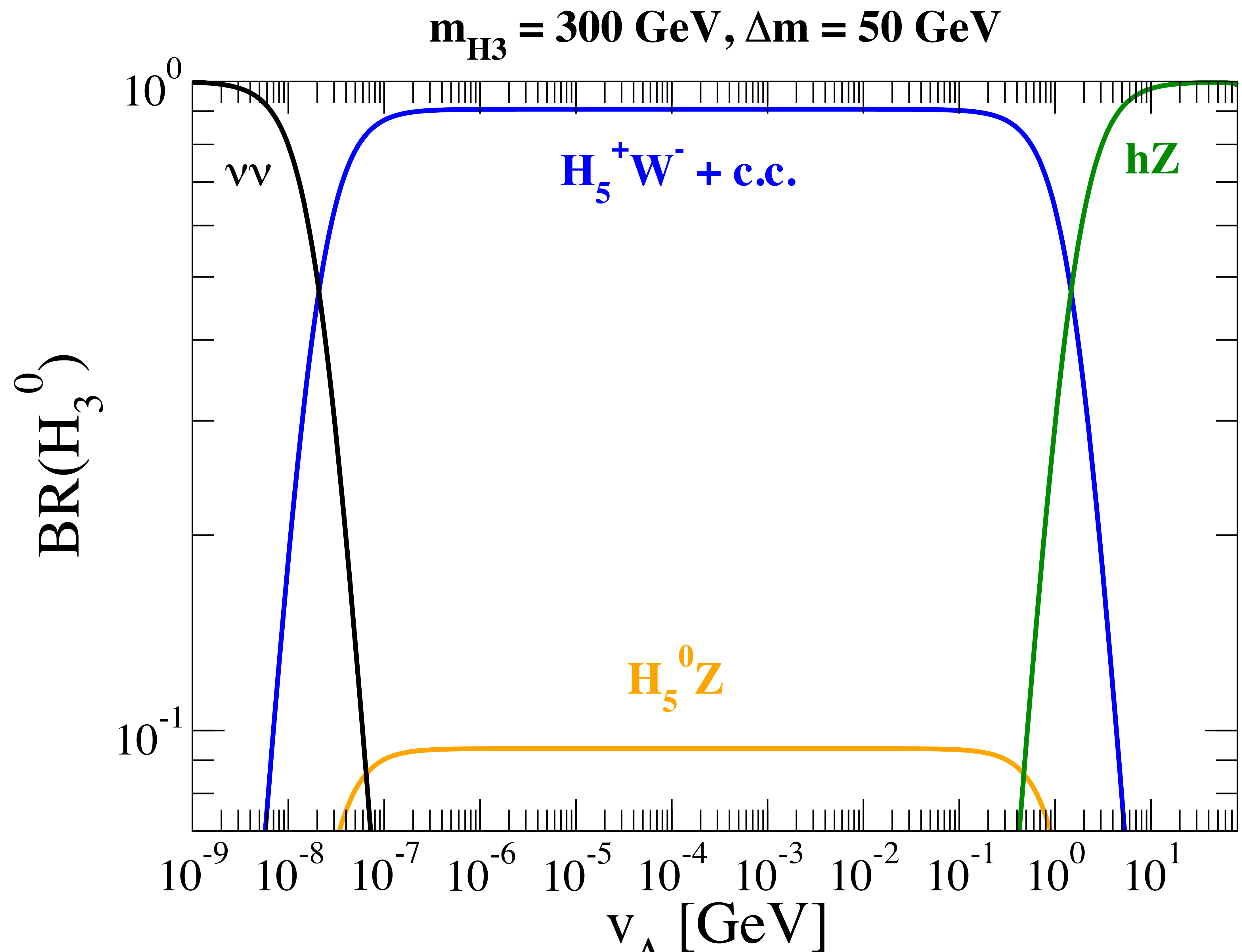
m_{H3} = 300 GeV, Δm = 50 GeV
$l^+\nu$
$H_5^{++}W^-$
H_5^+Z
$H_5^0W^+$
tb
hW^+
$BR(H_3^+)$
v_Δ [GeV]
10^0
10^{-1}
10^{-2}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1



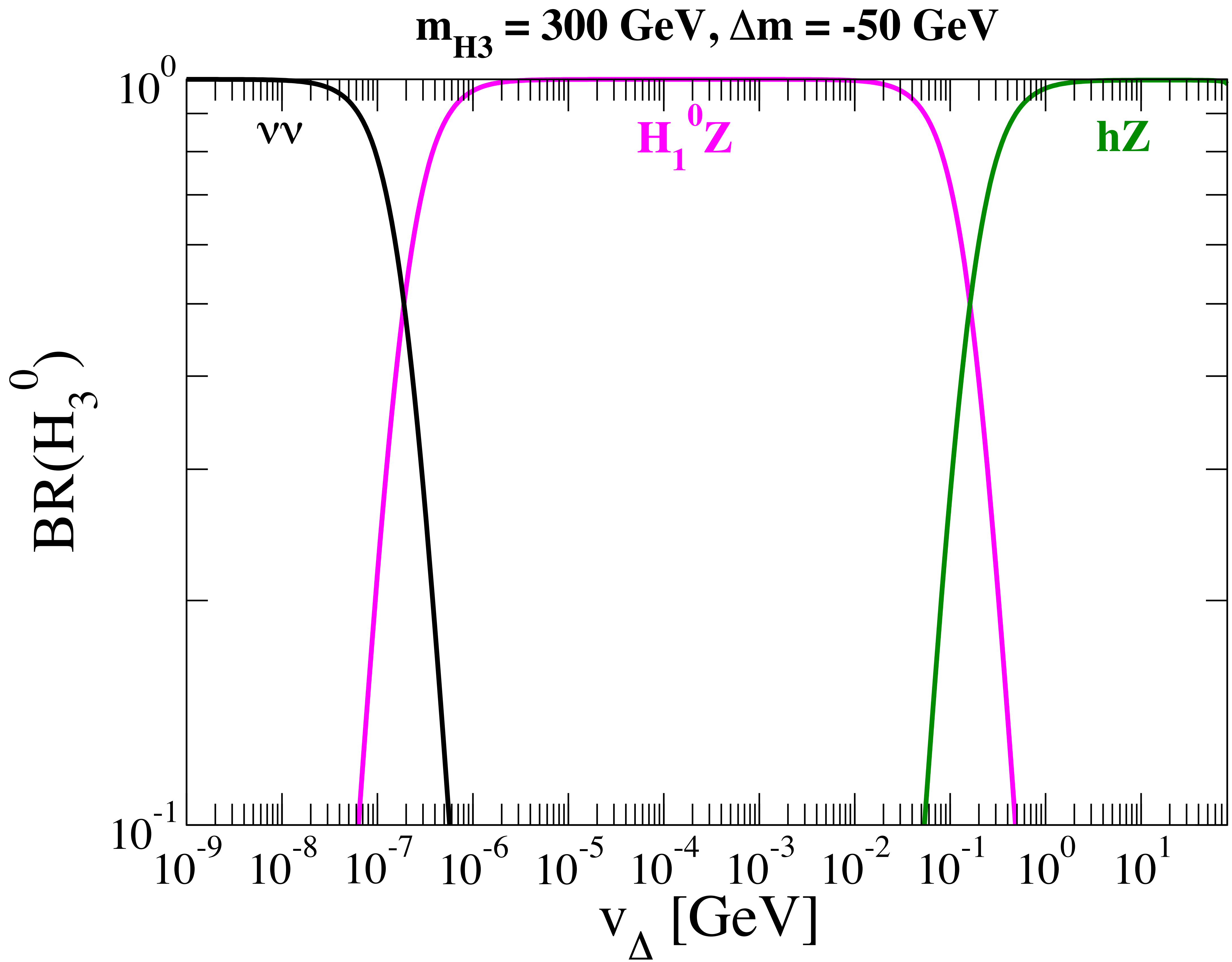
m_{H3} = 300 GeV, Δm = -50 GeV
10^0
10^{-1}
$l^+\nu$
$H_1^0W^+$
tb
hW^+
$BR(H_3^+)$
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^0 10^1
v_Δ [GeV]



m_{H3} = 300 GeV, Δm = 0
1
0.1
$\nu\nu$
hZ
$BR(H_3^0)$
10^{-4}
10^{-3}
v_Δ [GeV]

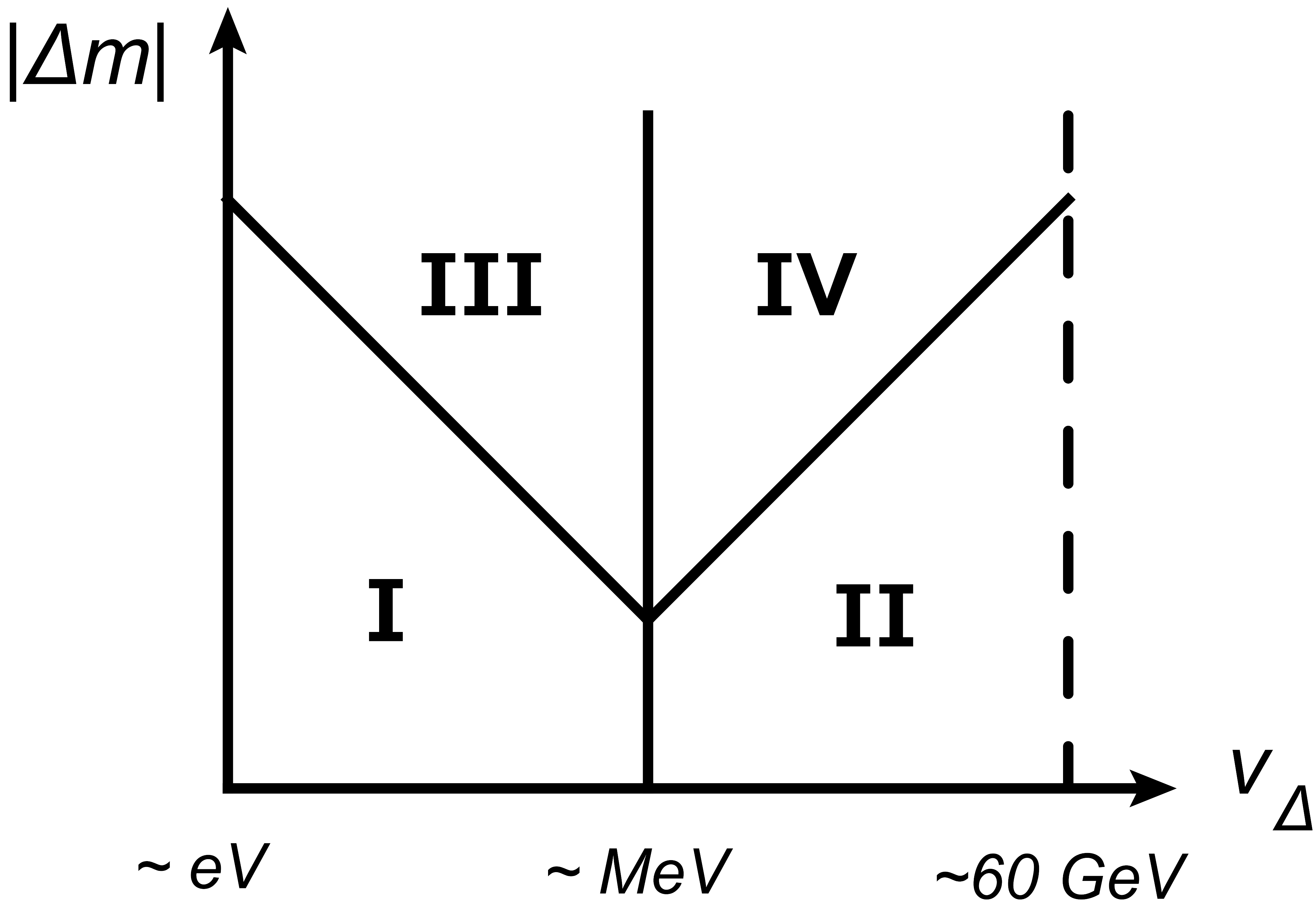


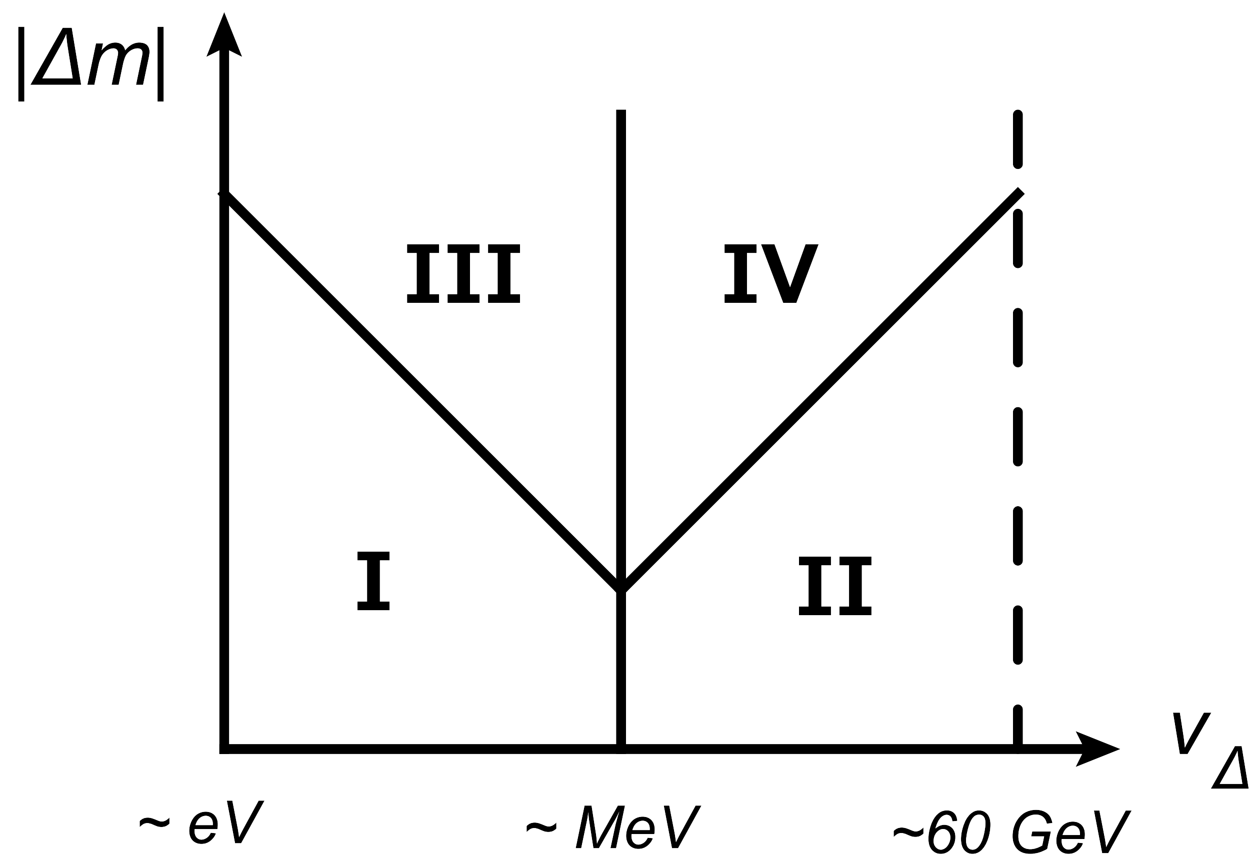
m_{H3} = 300 GeV, Δm = 50 GeV
$BR(H_3^0)$
v_Δ [GeV]
$\nu\nu$
$H_5^+W^-$ + c.c.
hZ
H_5^0Z
10^0
10^{-1}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1



m_H3 = 300 GeV, Δm = -50 GeV
νν
H_1^0Z
hZ
BR(H_3^0)
v_Δ [GeV]
10^0
10^-1
10^-9
10^-8
10^-7
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
10^0
10^1

$$\Delta m \equiv m_{H_3} - m_{H_5}$$

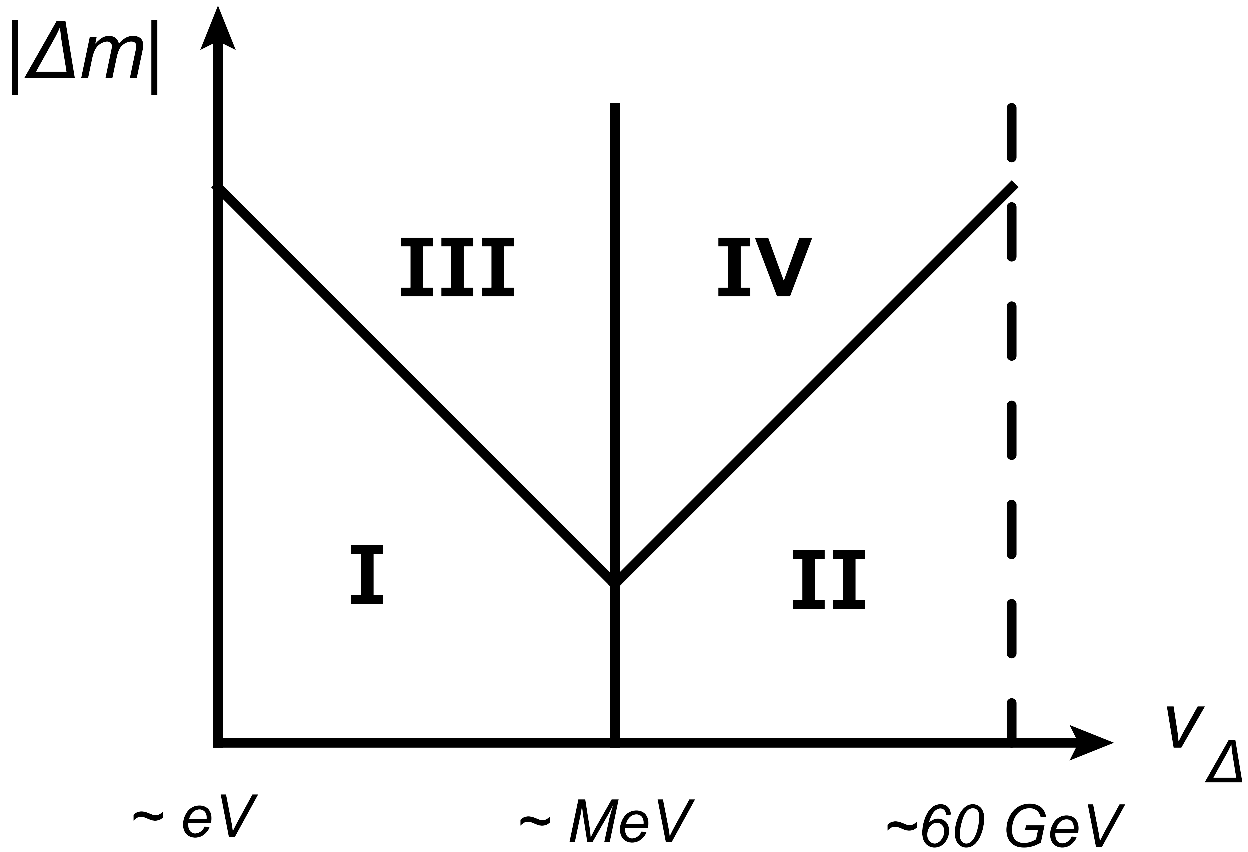




In Region I

$$H_5^{++} \to \ell^+\ell^+, \quad H_5^{+} \to \ell^+\nu, \quad H_5^{0} \to \nu\nu,$$

$$H_3^{+} \to \ell^+\nu, \quad H_3^{0} \to \nu\nu.$$



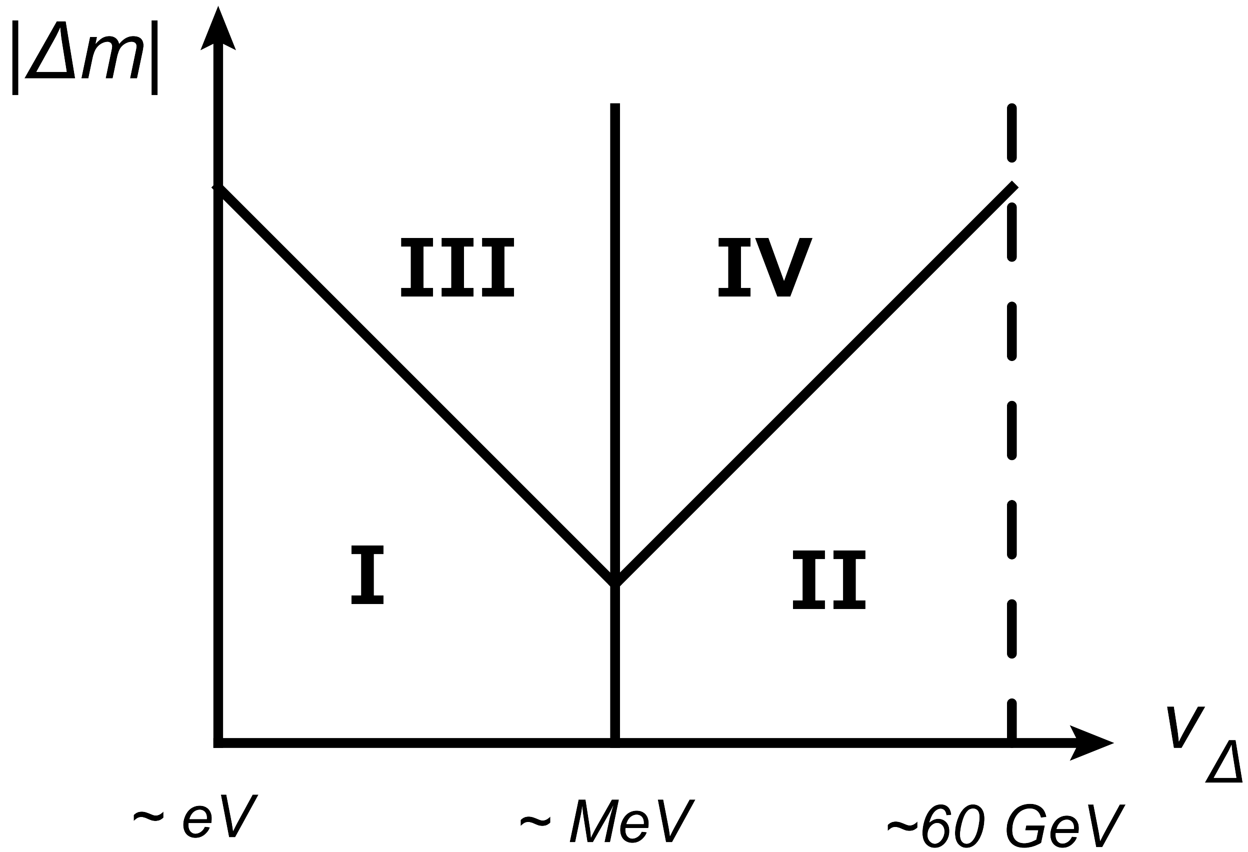
Region II

$$H_5^{++} \to W^+W^+, \quad H_5^+ \to W^+Z, \quad H_5^0 \to W^+W^-/ZZ,$$

$$H_3^+ \to \tau^+\nu/c\bar{s}, \quad H_3^0 \to b\bar{b}.$$

$m_3 > m_5$

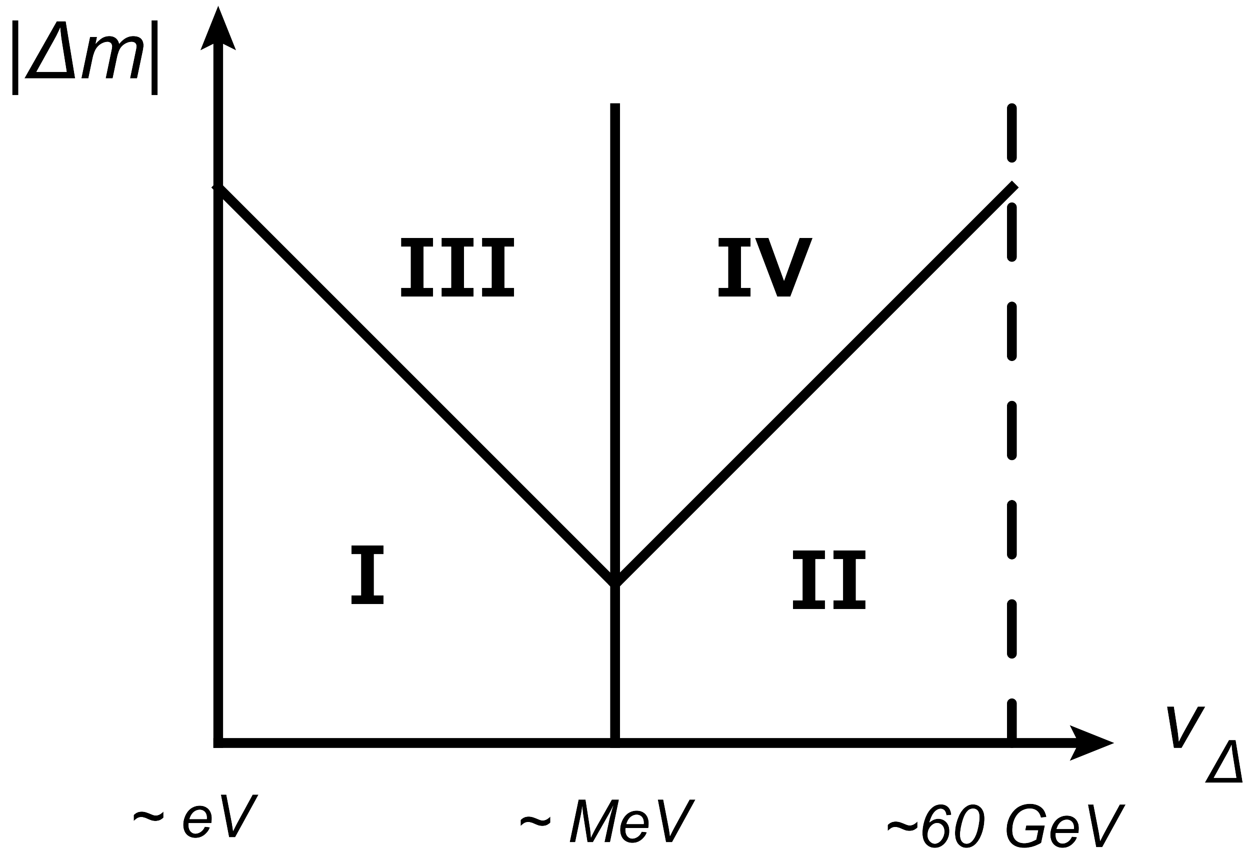
In the case of $\Delta m > 0$



Region III (Region IV)

$$H_5^{++} \to \ell^+\ell^+ \; (W^+W^+), \quad H_5^+ \to \ell^+\nu \; (W^+Z), \quad H_5^0 \to \nu\nu \; (W^+W^-/ZZ),$$

$$H_3^+ \to H_5^{++}W^-/H_5^+Z/H_5^0W^+, \quad H_3^0 \to H_5^\pm W^\mp/H_5^0Z.$$



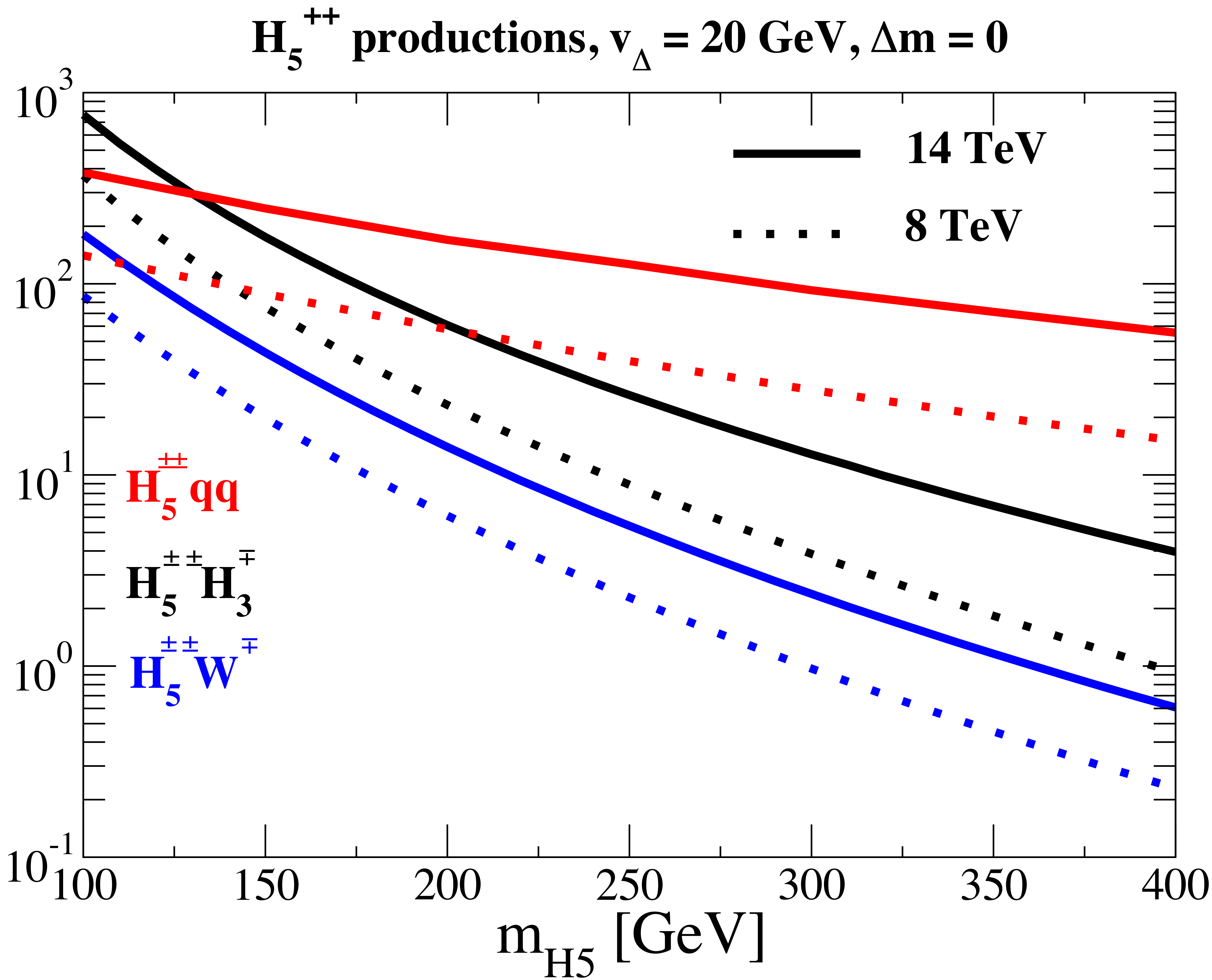
In the case of $\Delta m < 0$,

Region III (Region IV)

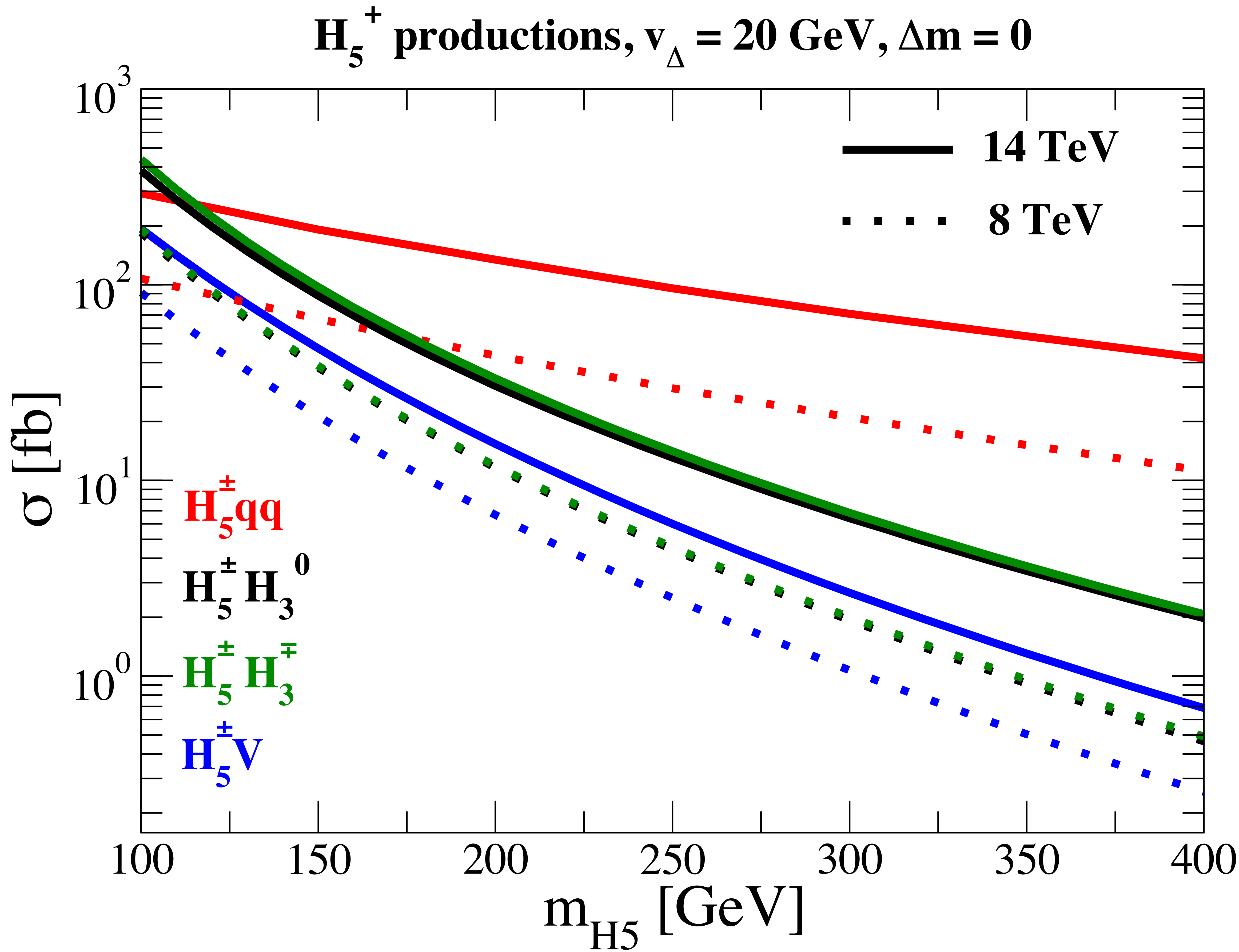
$$H_5^{++} \to H_3^+ W^+, \quad H_5^+ \to H_3^+ Z / H_3^0 W^+, \quad H_5^0 \to H_3^\pm W^\mp / H_3^0 Z$$

$$H_3^+ \to H_1^0 W^+, \quad H_3^0 \to H_1^0 Z.$$

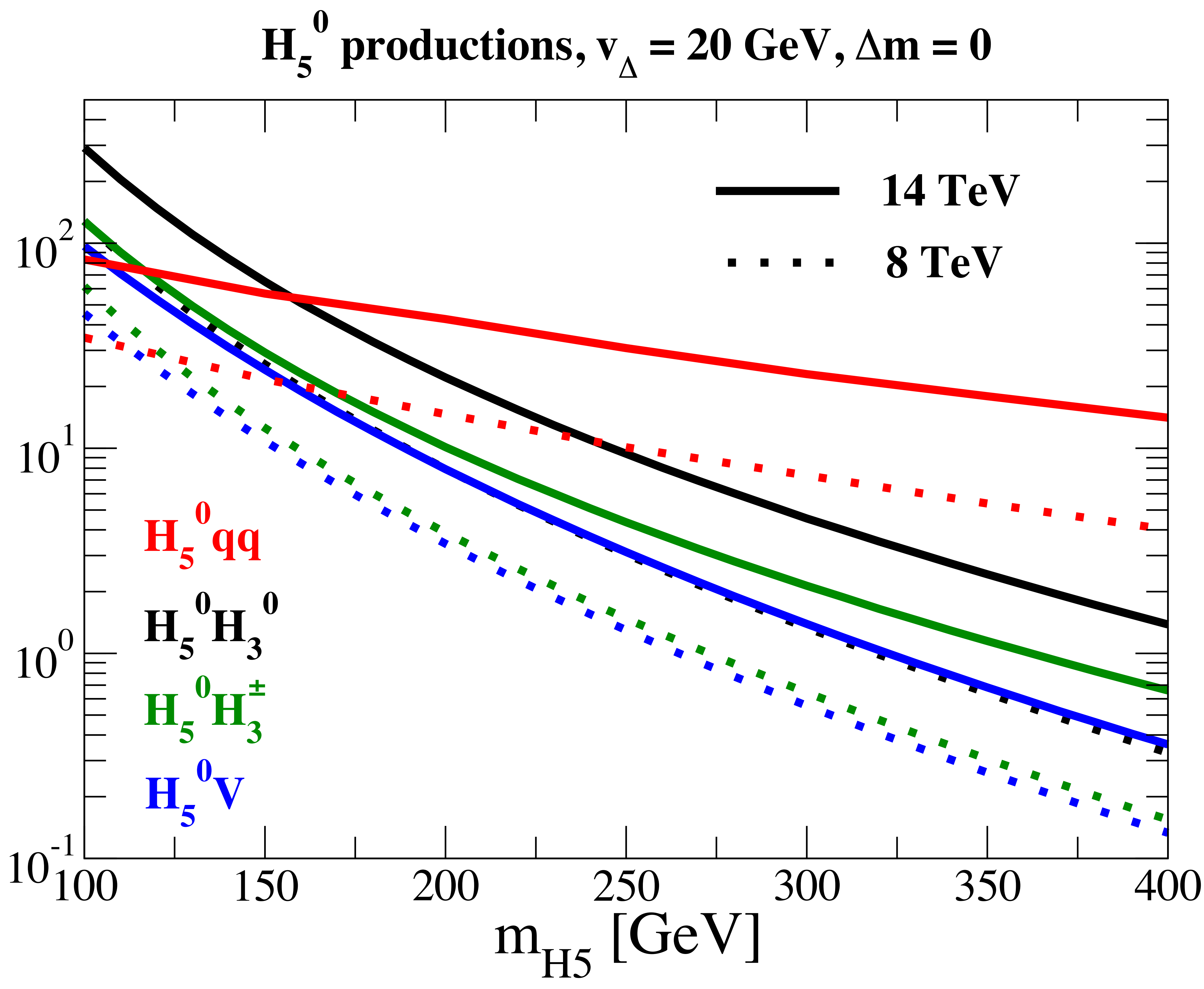
Production at the LHC



H5++ productions, vΔ = 20 GeV, Δm = 0
14 TeV
8 TeV
σ [fb]
H5±± qq
H5±± H3∓
H5±± W∓
m_H5 [GeV]
10^3
10^2
10^1
10^0
10^-1
100
150
200
250
300
350
400



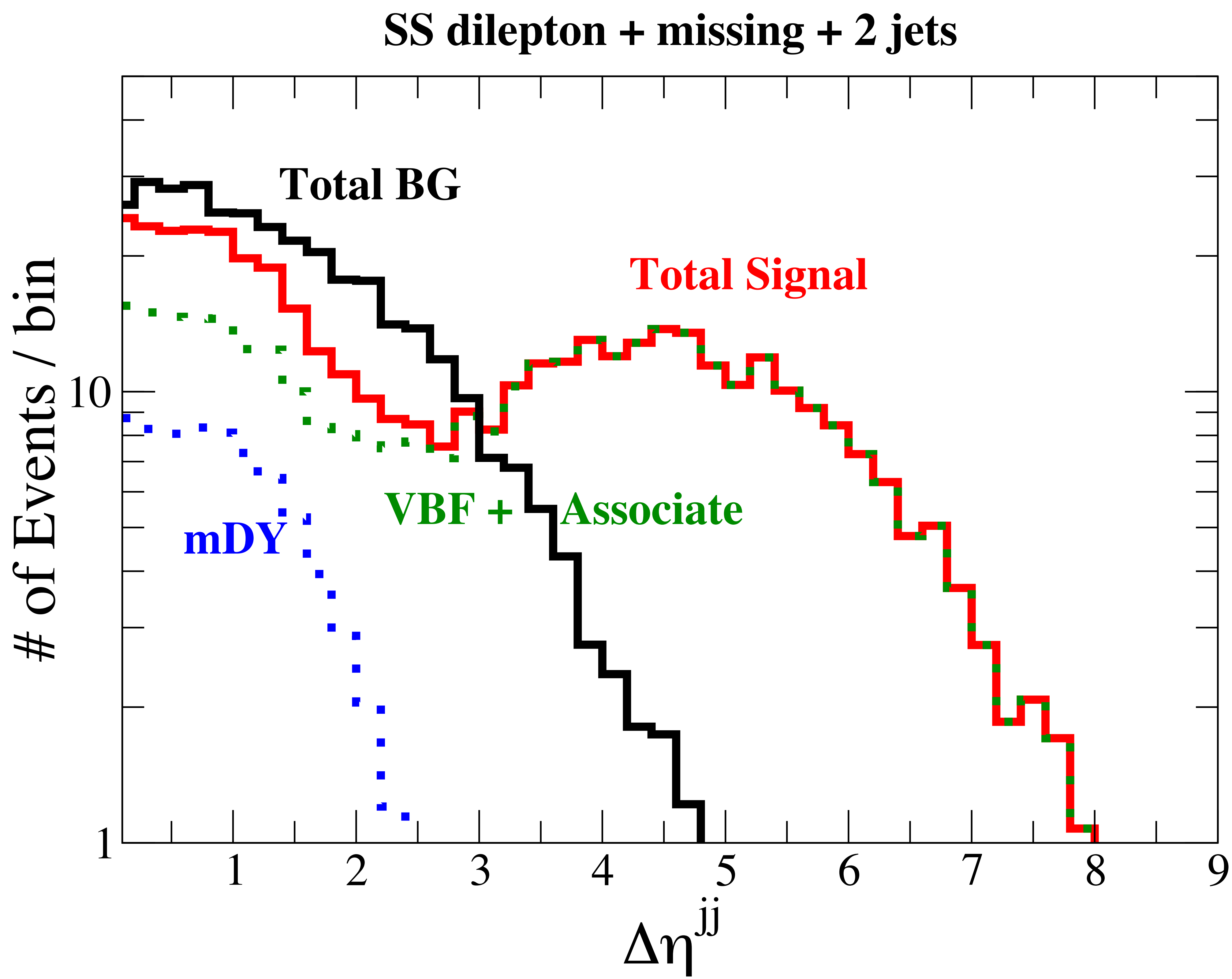
H_5^+ productions, v_Δ = 20 GeV, Δm = 0
14 TeV
8 TeV
$H_5^\pm qq$
$H_5^\pm H_3^0$
$H_5^\pm H_3^\mp$
$H_5^\pm V$
σ [fb]
m_{H5} [GeV]
10^3
10^2
10^1
10^0
100
150
200
250
300
350
400



H_5^0 productions, v_Δ = 20 GeV, Δm = 0
14 TeV
8 TeV
$H_5^0 qq$
$H_5^0 H_3^0$
$H_5^0 H_3^\pm$
$H_5^0 V$
σ [fb]
10^{-1}
10^{0}
10^{1}
10^{2}
100
150
200
250
300
350
400
m_{H5} [GeV]

$$q\bar{q}' \to H_5^{\pm\pm}W^{\mp} \to W^{\pm}W^{\pm}jj$$

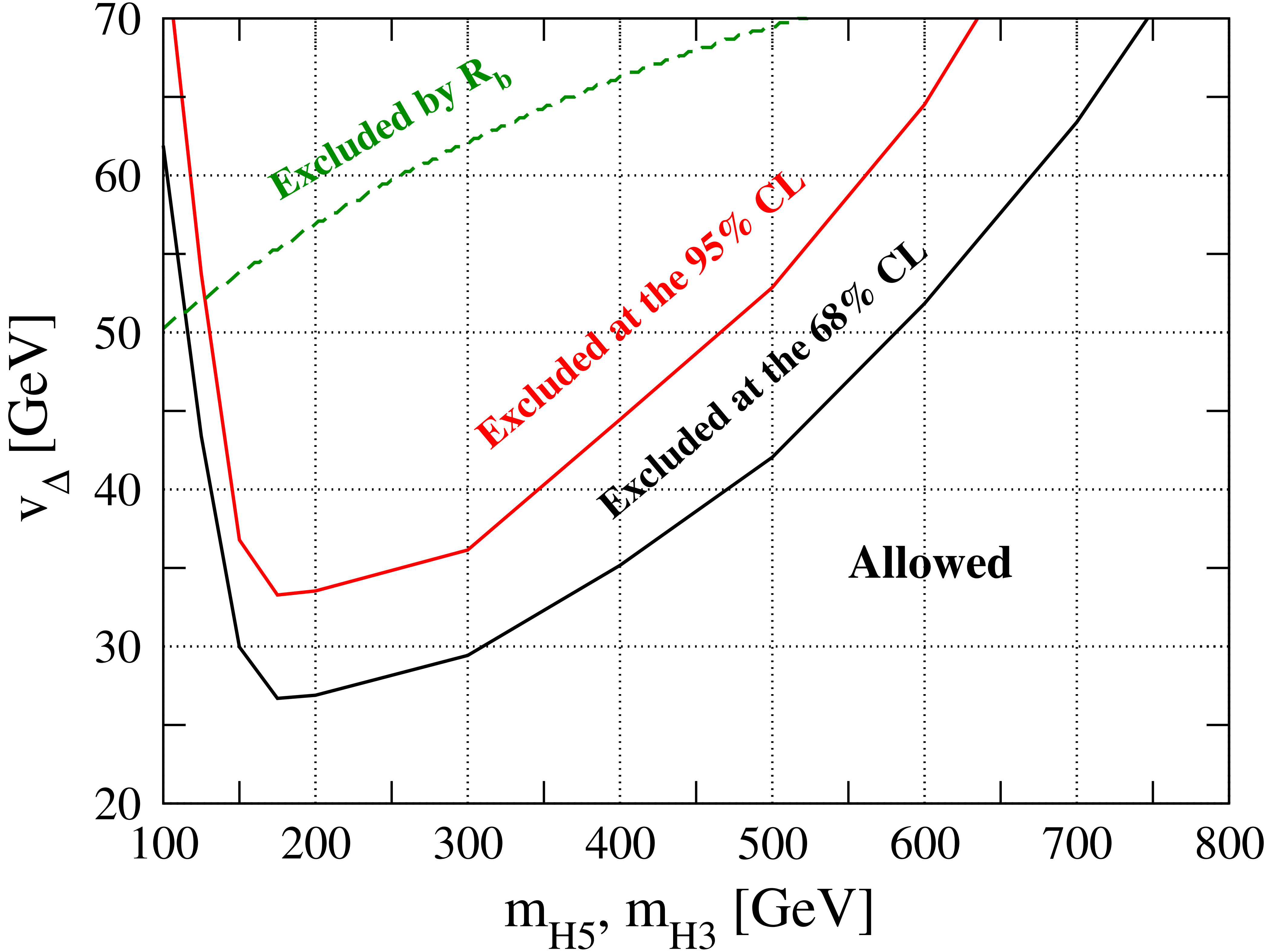
	$\ell^{\pm}\ell^{\pm}jj\not{E}_T$		
Cuts	$H_5^{\pm\pm}jj$	$W^{\pm}W^{\pm}jj$	$\mathcal{S}$
Basic	3.71 (8.72)	3.48 (8.13)	13.8 (21.2)
$\Delta\eta^{jj}$	1.82 (5.68)	0.20 (0.65)	12.8 (22.6)
M_T	1.80 (5.58)	0.05 (0.12)	13.2 (23.4)



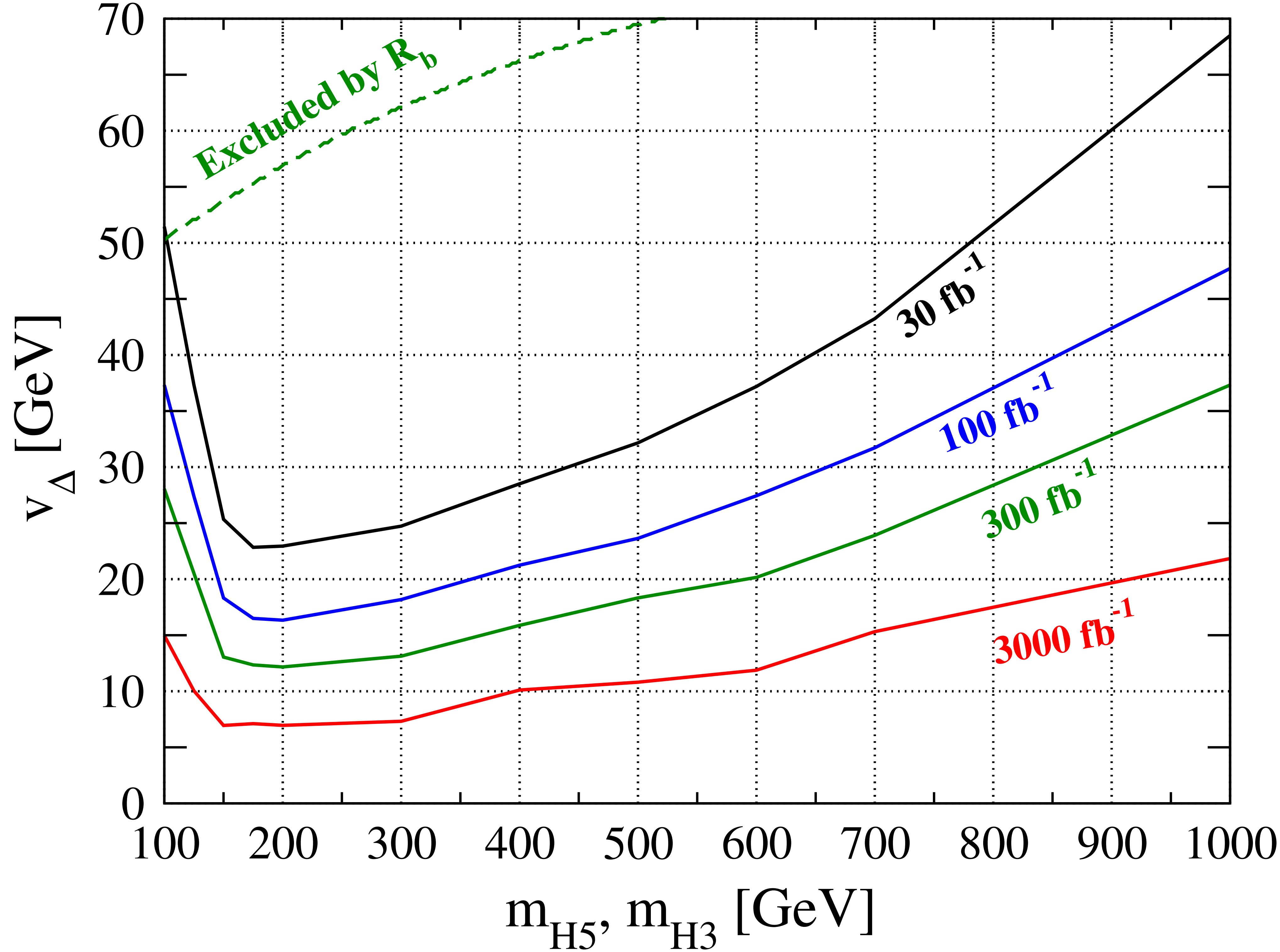
SS dilepton + missing + 2 jets
Total BG
Total Signal
VBF + Associate
mDY
# of Events / bin
10
1
1
2
3
4
5
6
7
8
9
$\Delta\eta^{jj}$

- PRD90,115025

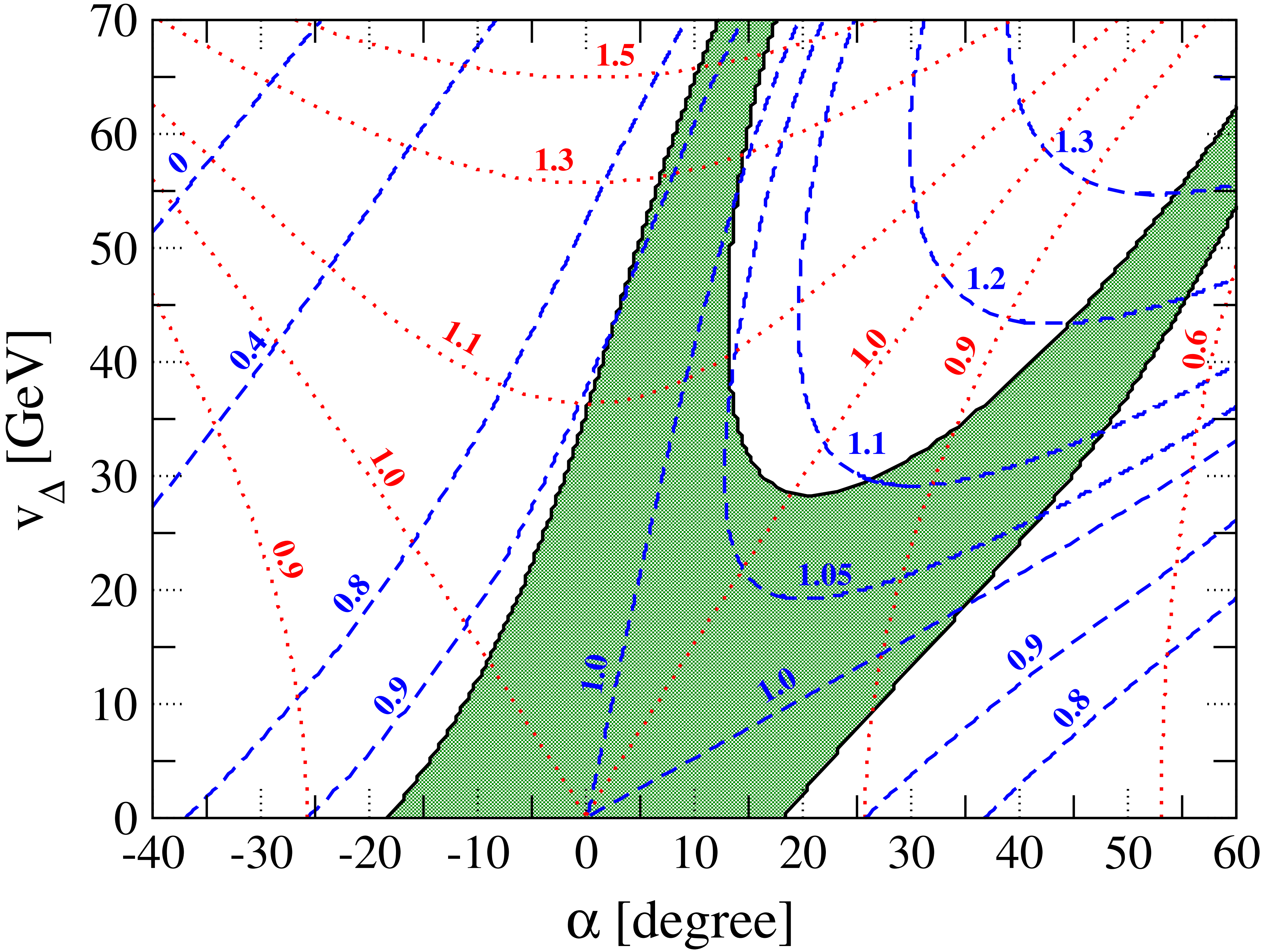
ATLAS-CONF-2014- 013: by the 8-TeV LHC data



at the 14-TeV LHC



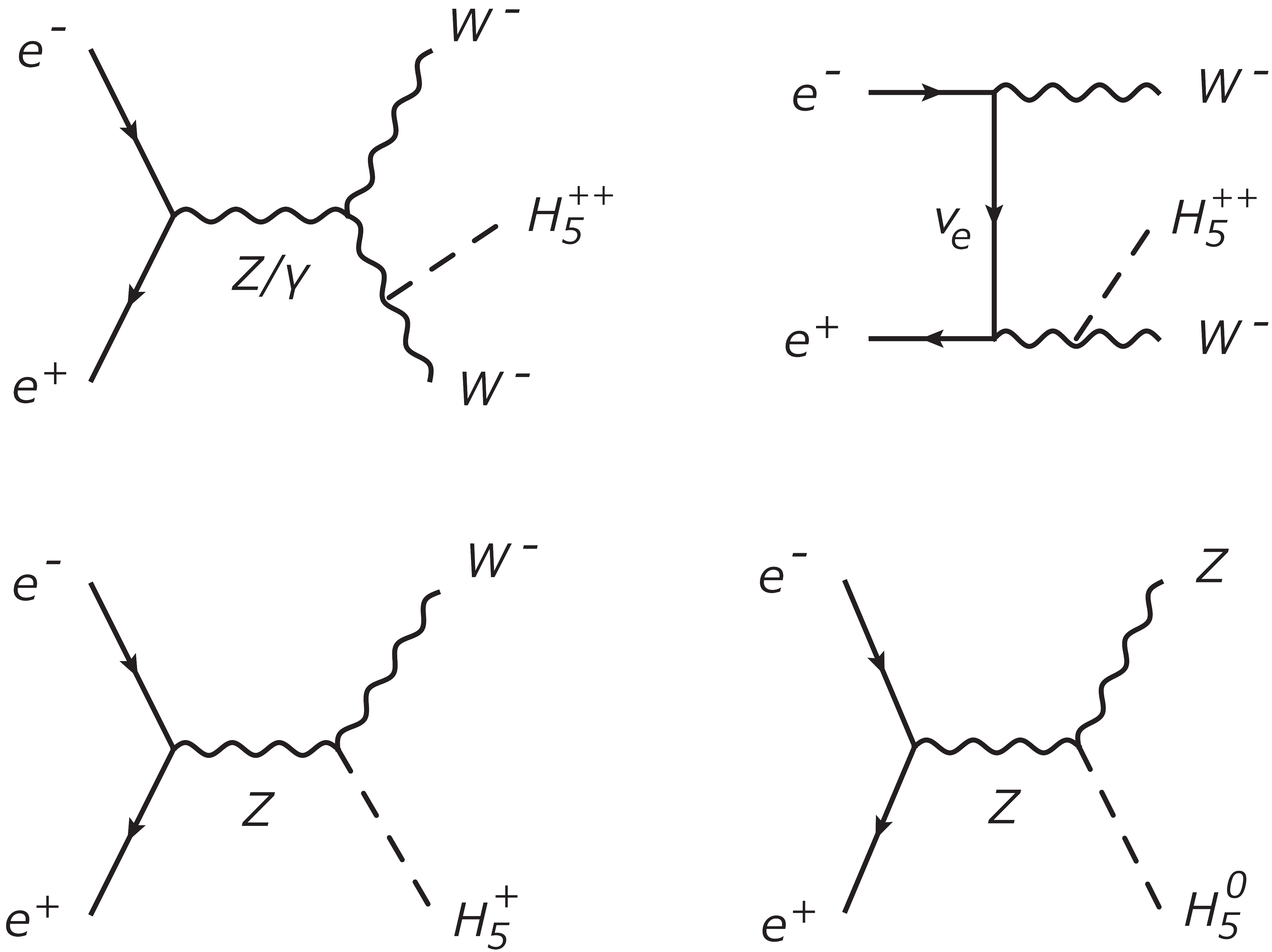
Higgs precision



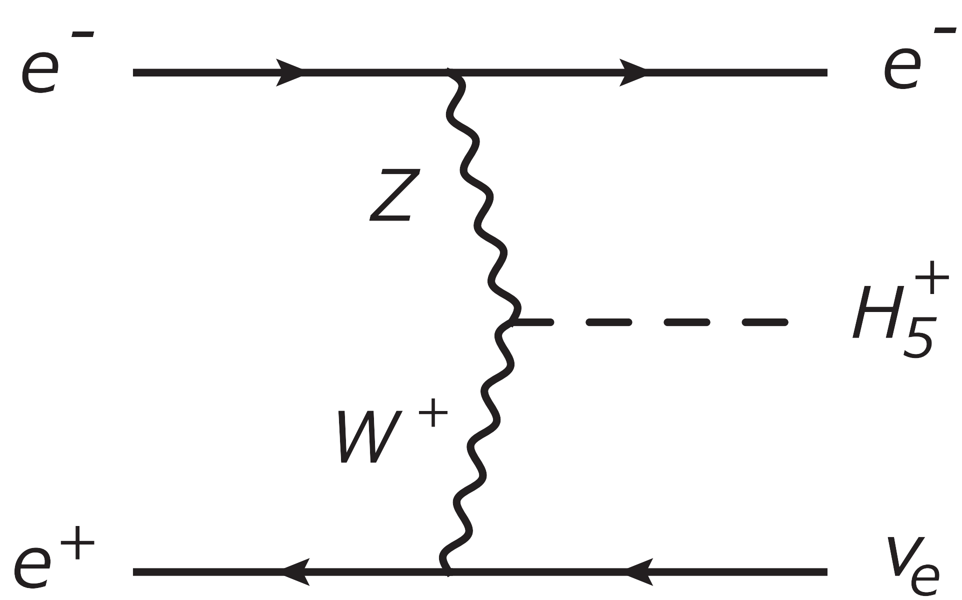
Green: $\mu_V \in 1 \pm 0.1$

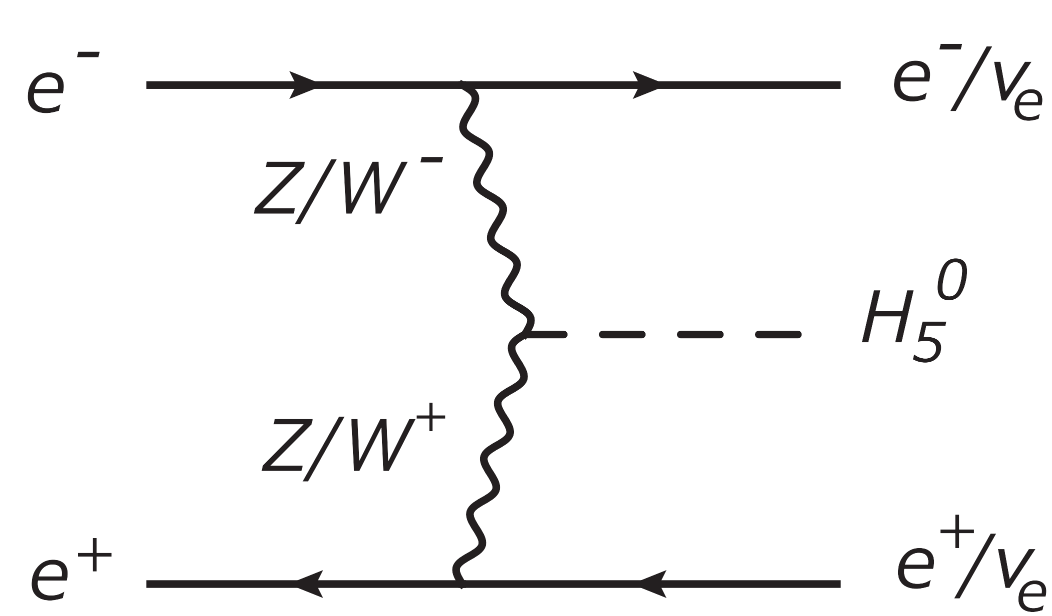
at future electron-positron colliders

- PRD93,055002

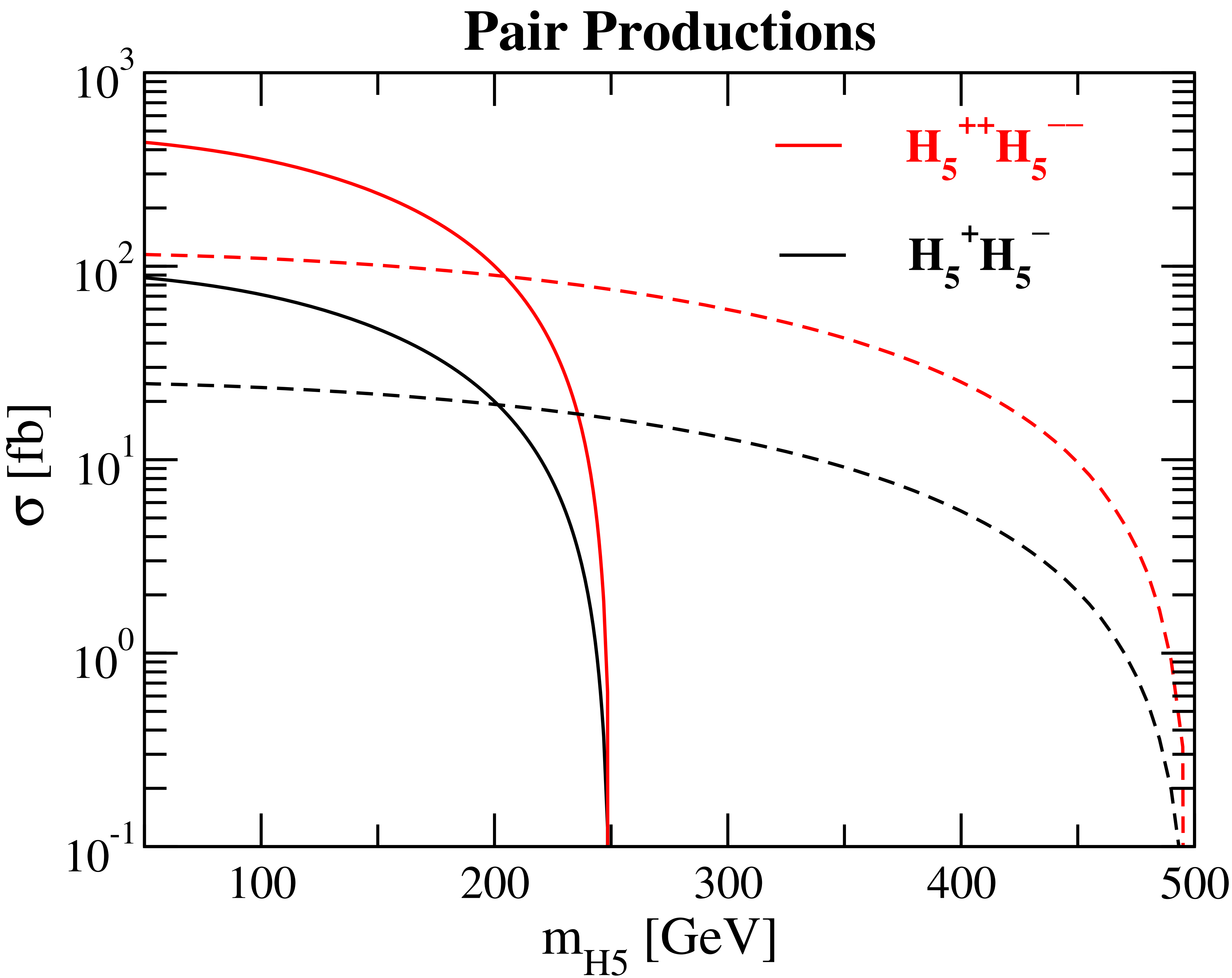


e-
e+
Z/γ
W-
H5++
W-
e-
e+
νe
W-
H5++
W-
e-
e+
Z
W-
H5+
e-
e+
Z
Z
H50

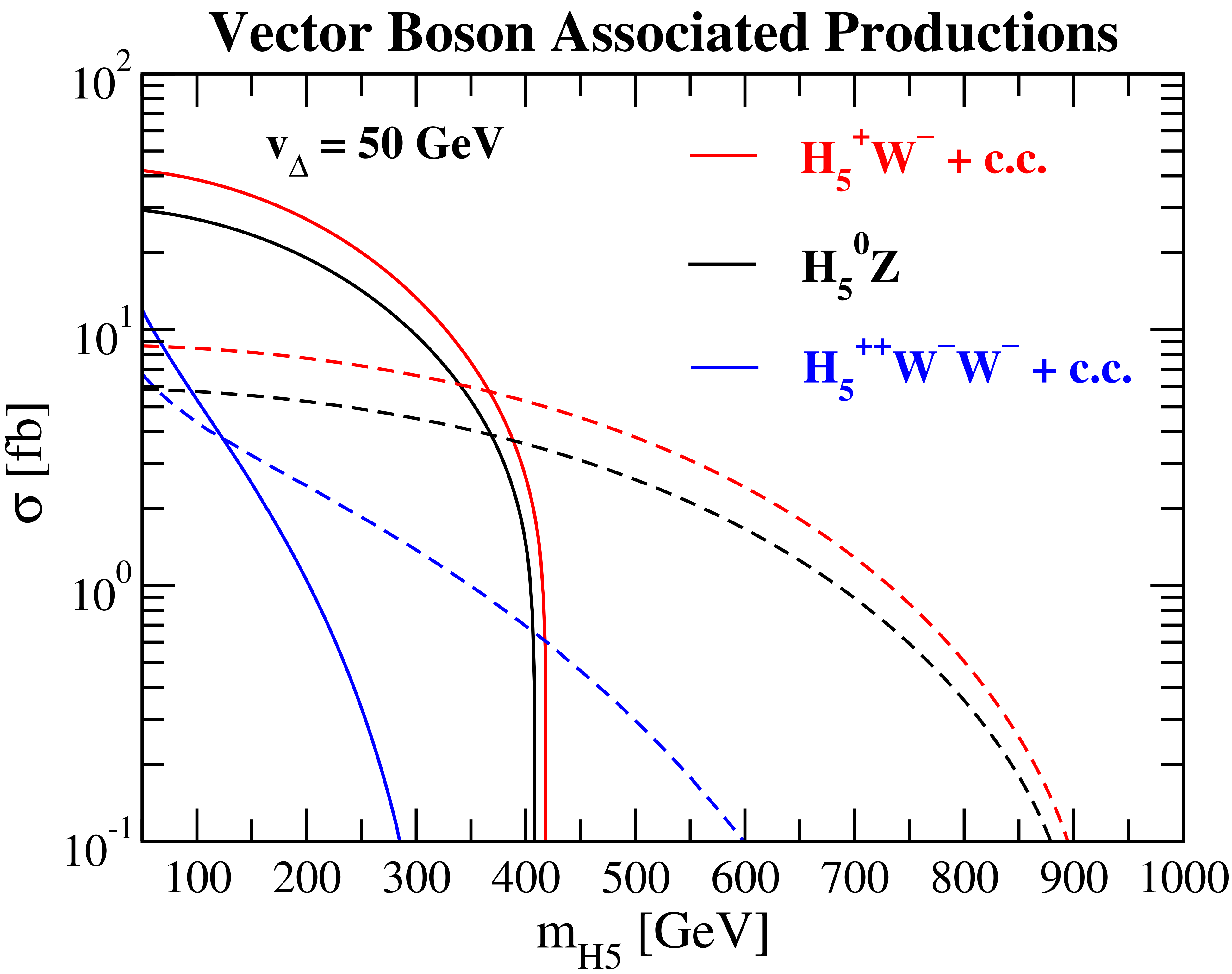

e-
e-
Z
H5+
W +
e+
νe


e-
e-/νe
Z/W-
H50
Z/W+
e+
e+/νe

Collider energy: 500 GeV (solid curves) and 1 TeV (dashed curves).



Collider energy: 500 GeV (solid curves) and 1 TeV (dashed curves).



Collider energy: 500 GeV (solid curves) and 1 TeV (dashed curves).