Type-II seesaw Scalar Triplet Model at a 100TeV pp collider

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AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS
Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts Amherst

Outline

- Motivations for the complex triplet model
- Model key features
- Model discovery
- Higgs portal parameter determination
- Summary

Motivations

- **Neutrino oscillation**

  Neutrinos are massive, masses are generated through a type-II seesaw mechanism. (P.F. Perez, T. Han, G. Huang, T. Li, K. Wang, 2008)

- **Baryon asymmetry of the Universe**

  Electroweak baryogenesis from the Higgs portal.

- **Roadmap for future colliders**

  CEPC (China), ILC (Japan), FCC (Europe)

Model key features

$\Delta(1,3,2)$

$$V(\Phi,\Delta) = -m^2\Phi^\dagger\Phi + M^2\mathrm{Tr}(\Delta^\dagger\Delta) + \left[\mu\Phi^{\mathrm{T}}\mathrm{i}\tau_2\Delta^\dagger\Phi + \mathrm{h.c.}\right] + \lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2\left[\mathrm{Tr}(\Delta^\dagger\Delta)\right]^2 + \lambda_3\mathrm{Tr}[\Delta^\dagger\Delta\Delta^\dagger\Delta] + \lambda_4(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_5\Phi^\dagger\Delta\Delta^\dagger\Phi$$

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$$\rho \equiv \frac{m_W^2}{m_Z^2\cos^2\theta_W} = \frac{1+\frac{2v_\Delta^2}{v_\Phi^2}}{1+\frac{4v_\Delta^2}{v_\Phi^2}}$$

$$\rho = 1.0006 \pm 0.0009$$

PDG, 2016

$$0 \le v_\Delta \lesssim 3.0\ \ \mathrm{GeV}$$

$$v_\Delta \ll v_\Phi \simeq v$$

$$v = \sqrt{v_\Delta^2 + v_\Phi^2} = 246\,\mathrm{GeV}$$

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$$\sin\beta_\pm \sim \sin\beta_0 \sim \sin\alpha \sim \frac{v_\Delta}{v_\Phi} \sim 0$$

Model key features

$$m_h^2 \simeq 2v_\Phi^2\lambda_1 \simeq 2v^2\lambda_1, \quad m_H \simeq m_\Delta \simeq m_A, \quad m_{H^\pm}^2 \simeq m_\Delta^2 - \frac{\lambda_5}{4}v_\Phi^2, \quad m_{H^{\pm\pm}}^2 \simeq m_\Delta^2 - \frac{\lambda_5}{2}v_\Phi^2$$

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Fixed by SM Higgs mass

$$\lambda_1 \simeq 0.129$$

Model key features

$$\Delta m = |m_{H^{\pm\pm}} - m_{H^{\pm}}| \approx |m_{H^{\pm}} - m_{H,A}| \approx \frac{|\lambda_5| v_\Phi^2}{8 m_\Delta} \approx \frac{|\lambda_5| v^2}{8 m_\Delta}$$

Determined by mass splitting

$$m_h^2 \simeq 2 v_\Phi^2 \lambda_1 \simeq 2 v^2 \lambda_1, \quad m_H \simeq m_\Delta \simeq m_A, \quad m_{H^\pm}^2 \simeq m_\Delta^2 - \frac{\lambda_5}{4} v_\Phi^2, \quad m_{H^{\pm\pm}}^2 \simeq m_\Delta^2 - \frac{\lambda_5}{2} v_\Phi^2$$

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Fixed by SM Higgs mass

$\lambda_1 \simeq 0.129$

Basically the mass scale of the triplet

Model key features

$$m_h^2 \simeq 2v_\Phi^2\lambda_1 \simeq 2v^2\lambda_1, \quad m_H \simeq m_\Delta \simeq m_A, \quad m_{H^\pm}^2 \simeq m_\Delta^2 - \frac{\lambda_5}{4}v_\Phi^2, \quad m_{H^{\pm\pm}}^2 \simeq m_\Delta^2 - \frac{\lambda_5}{2}v_\Phi^2$$

Also determines the mass hierarchy

$$\lambda_5 \leq 0: \; m_h < m_H \simeq m_A \leq m_{H^\pm} \leq m_{H^{\pm\pm}}$$

Model key features

$$V(\Phi,\Delta) = -m^2\Phi^\dagger\Phi + M^2\mathrm{Tr}(\Delta^\dagger\Delta) + \left[\mu\Phi^{\mathrm{T}}\mathrm{i}\tau_2\Delta^\dagger\Phi + \mathrm{h.c.}\right] + \lambda_1(\Phi^\dagger\Phi)^2$$
$$+ \lambda_2\left[\mathrm{Tr}(\Delta^\dagger\Delta)\right]^2 + \lambda_3\mathrm{Tr}[\Delta^\dagger\Delta\Delta^\dagger\Delta] + \lambda_4(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_5\Phi^\dagger\Delta\Delta^\dagger\Phi$$

How determine?

Model key features

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How determine?

$$\mathrm{Br}(\mathrm{A}\to\mathrm{hZ},\mathrm{H}\to\mathrm{ZZ},\mathrm{H}\to\mathrm{W^+W^-},\mathrm{H^\pm}\to\mathrm{hW^\mp}) = \mathrm{F}(\lambda_4,\lambda_5,\ldots)$$

Model key features

Brief summary

Fixed by SM Higgs mass

$$V(\Phi,\Delta) = -m^2\Phi^\dagger\Phi + M^2\mathrm{Tr}(\Delta^\dagger\Delta) + \left[\mu\Phi^\mathrm{T}\mathrm{i}\tau_2\Delta^\dagger\Phi + \mathrm{h.c.}\right] + \lambda_1(\Phi^\dagger\Phi)^2$$
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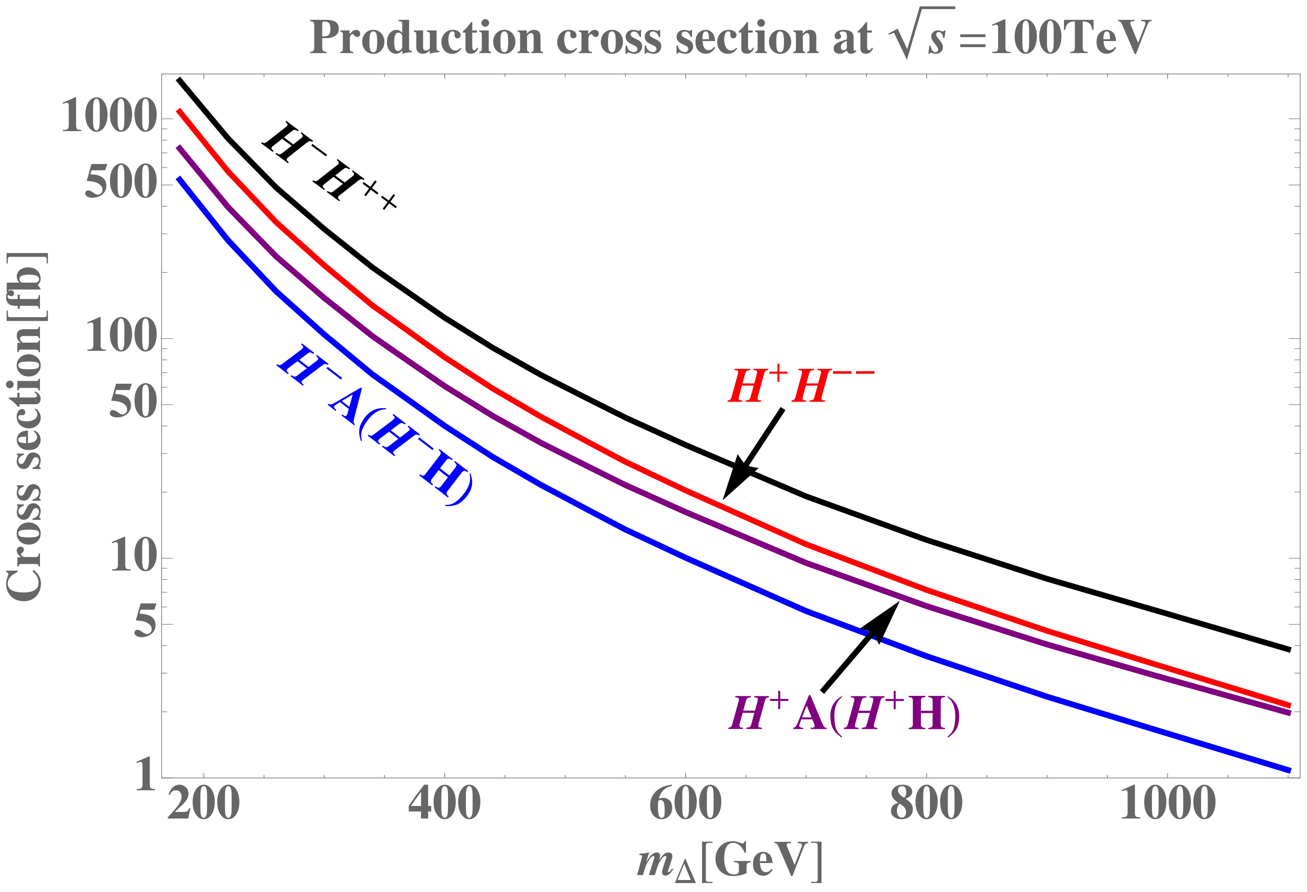
Remain unknown

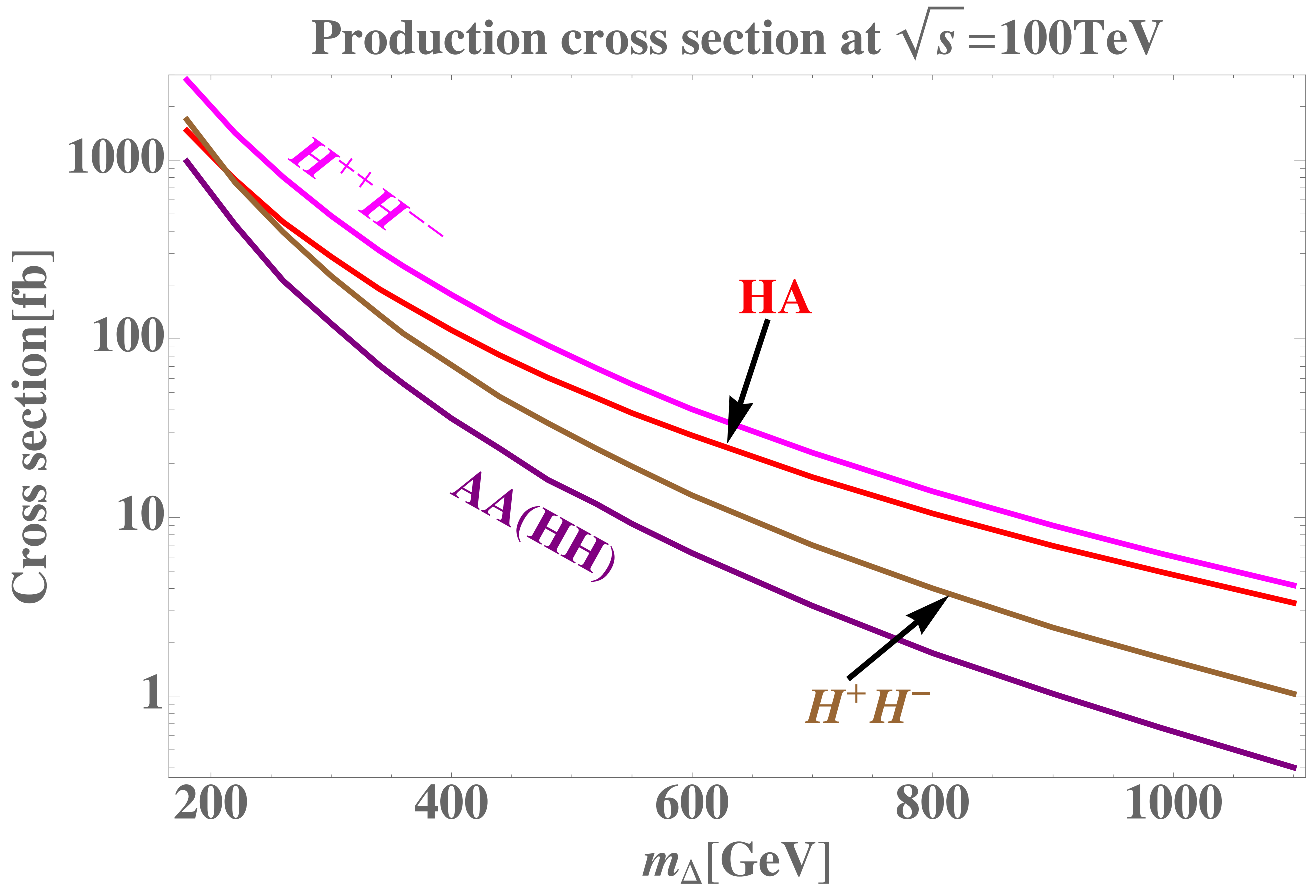
From the BRs

Determined by mass splitting

Model discovery

$$\lambda_1 = 0.129, \lambda_2 = 0.2, \lambda_3 = 0, \lambda_4 = 0, \lambda_5 = -0.1$$





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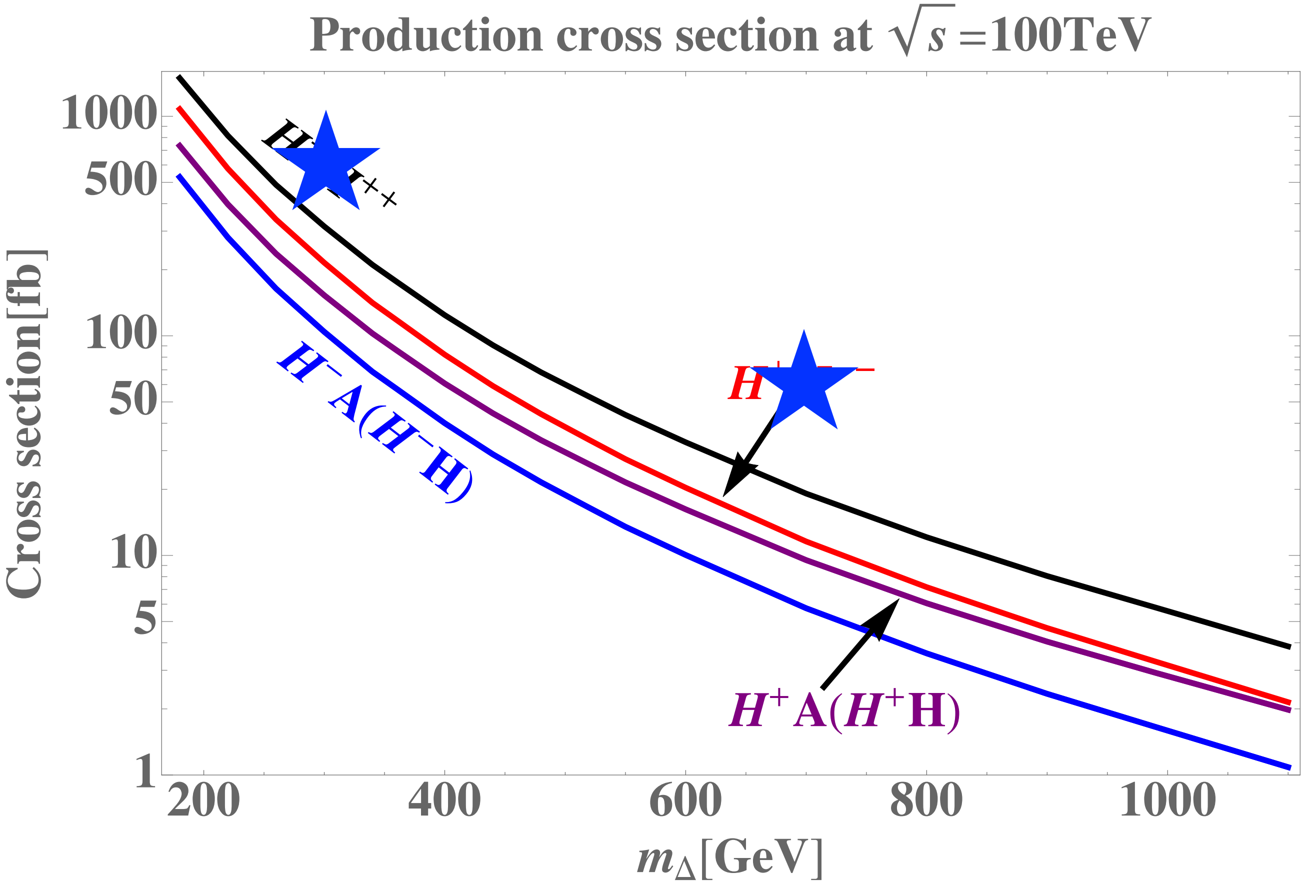
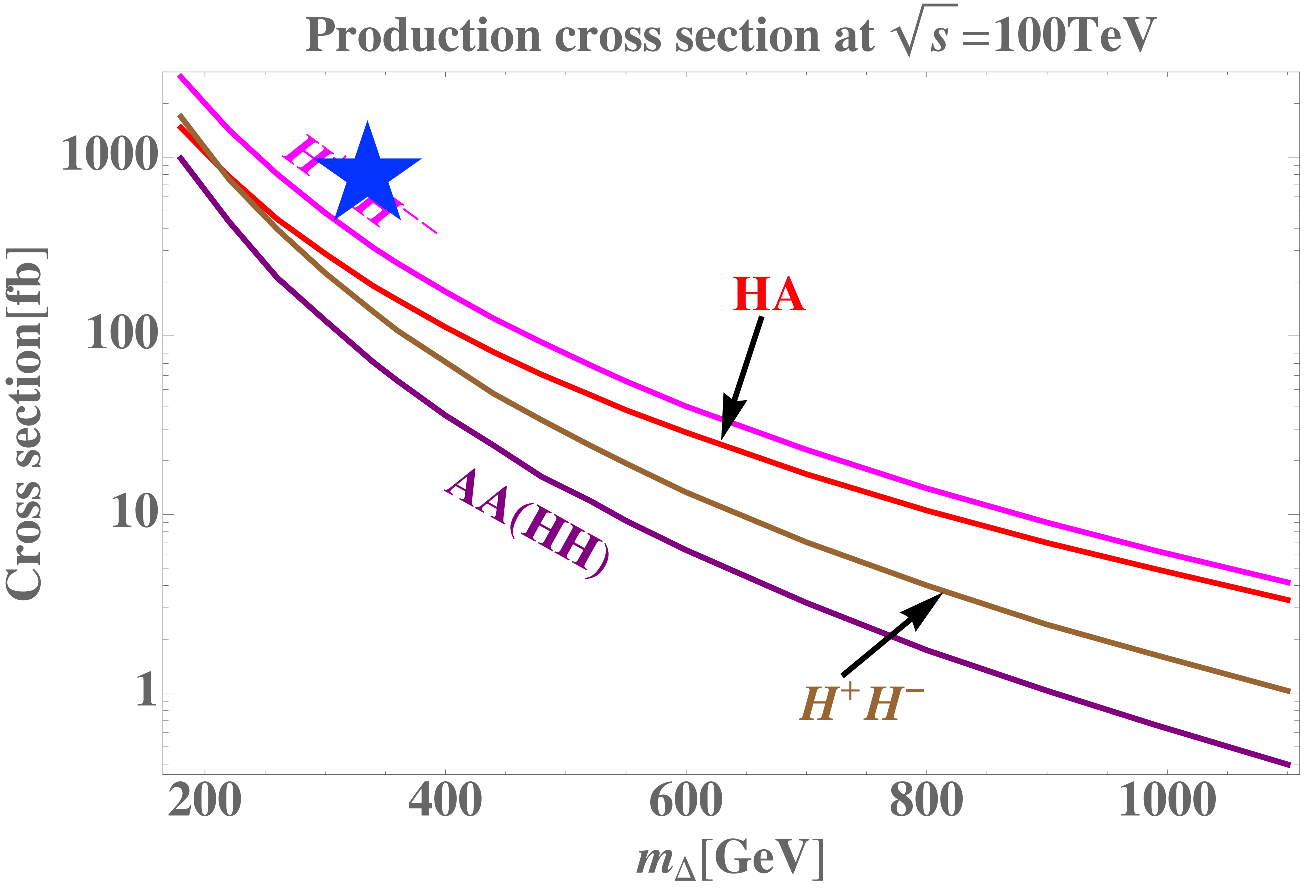
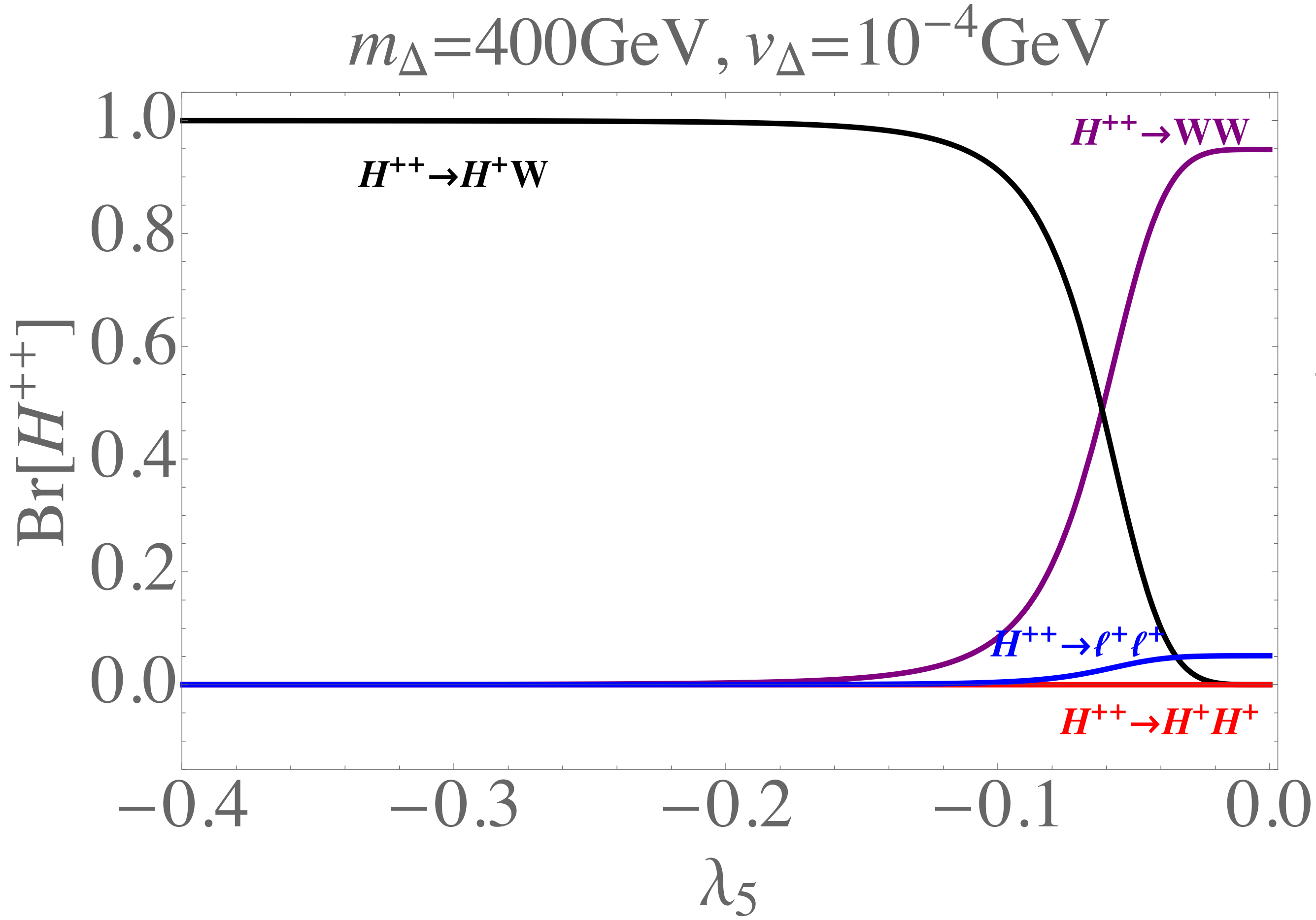
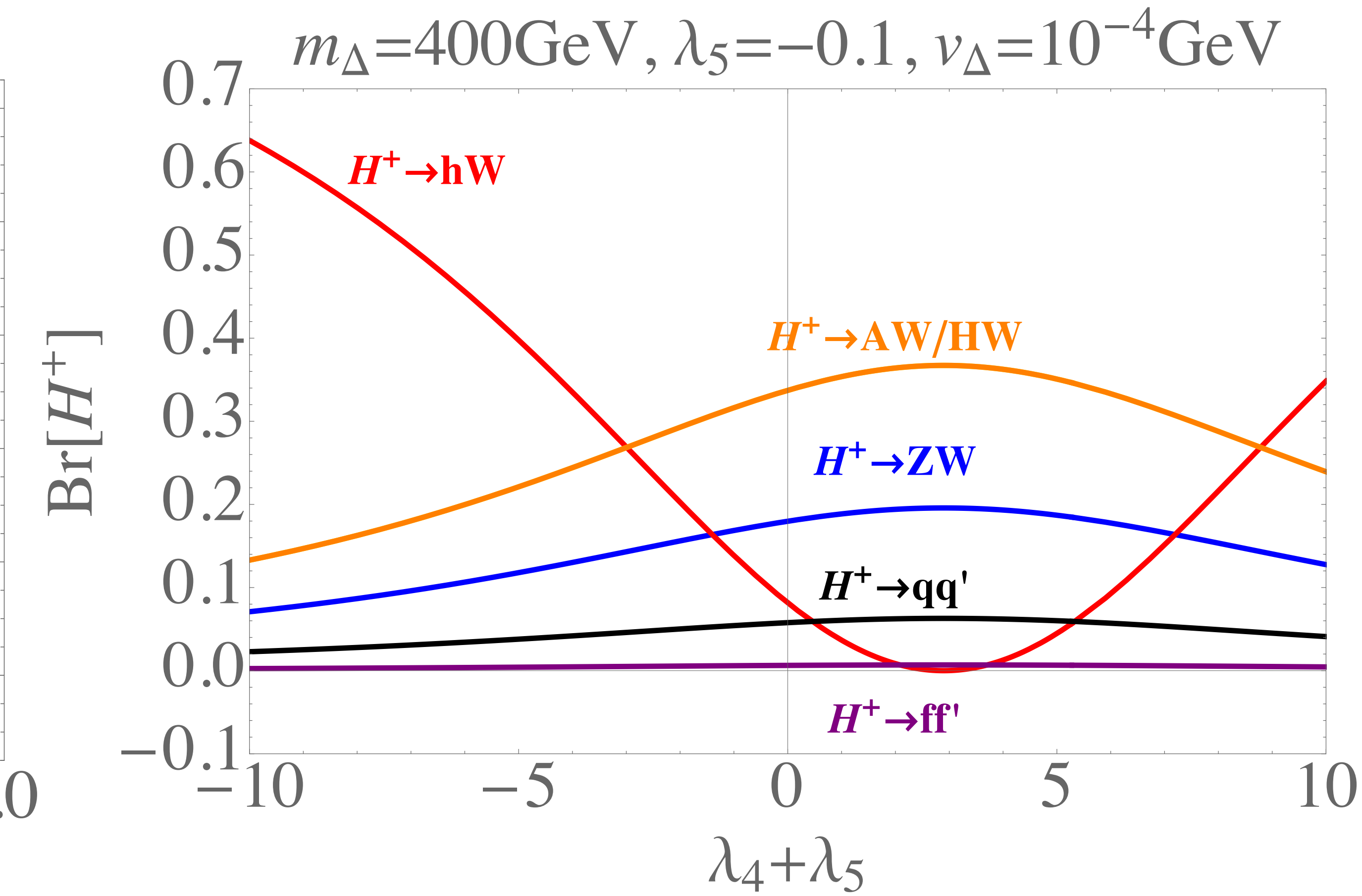




Model discovery





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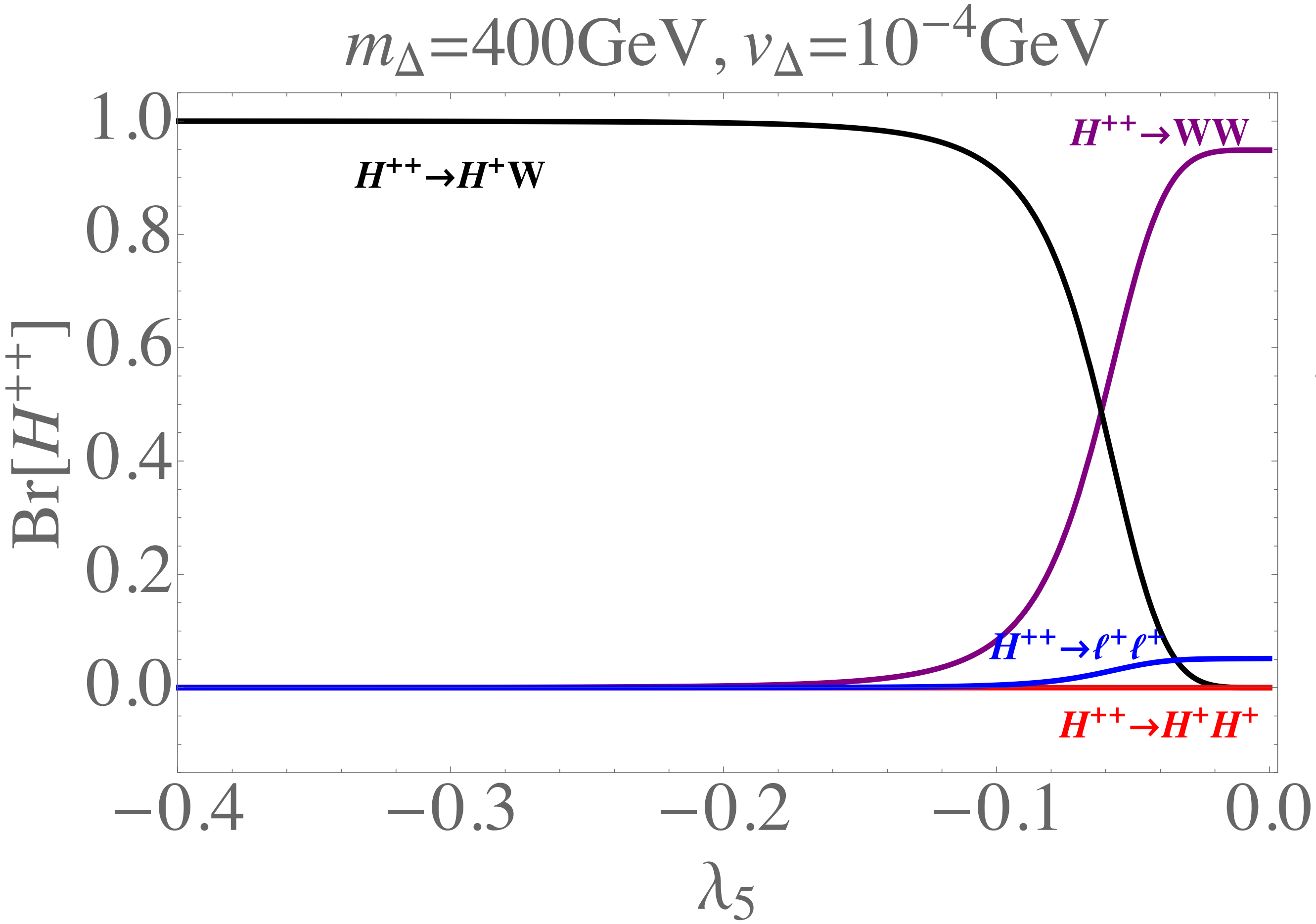
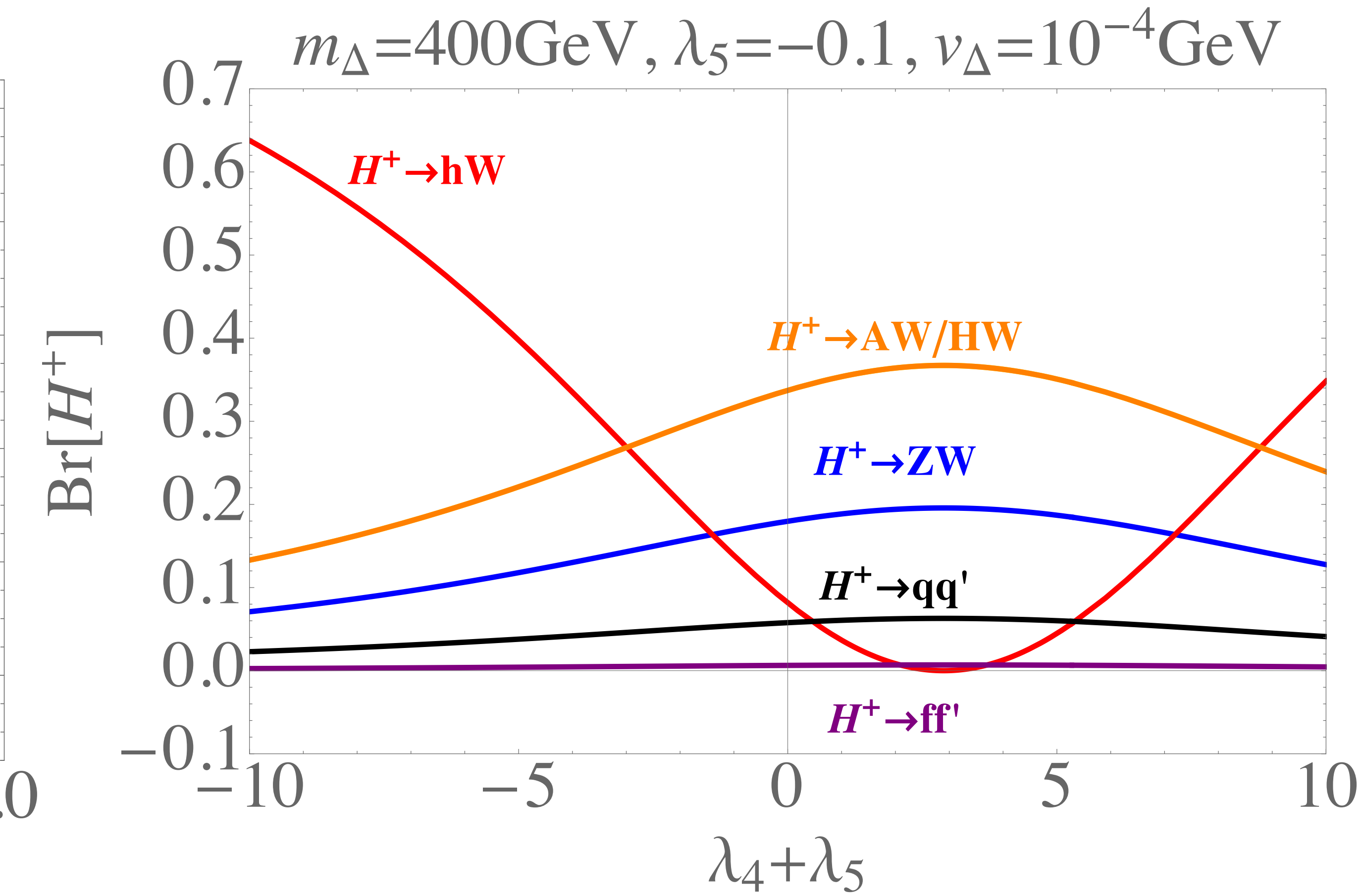


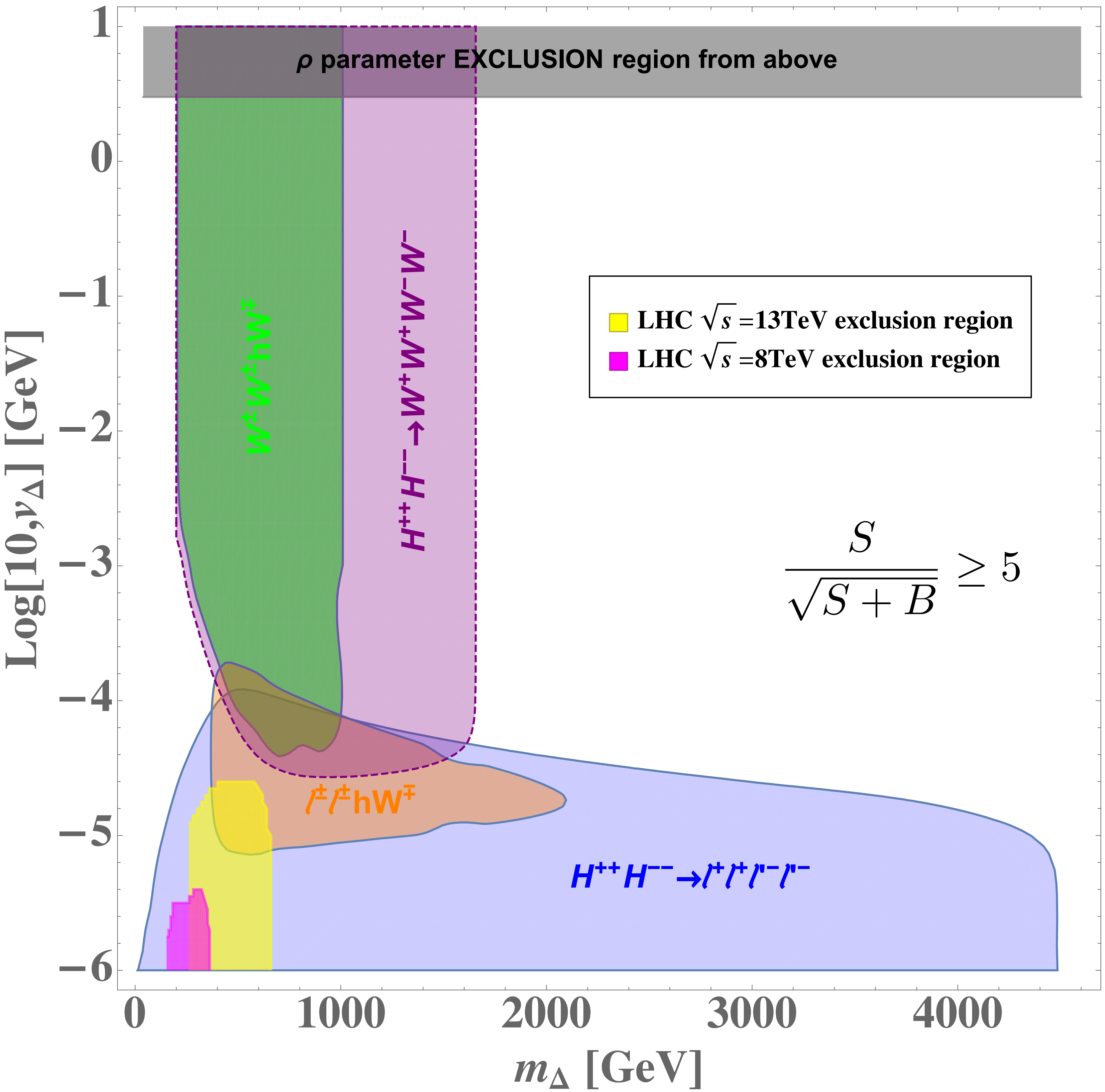


$$pp \to H^{++}H^{--} \text{ and } pp \to H^{\pm\pm}H^{\mp}$$

$$H^{\pm\pm} \to \ell^\pm\ell^\pm \ (W^\pm W^\pm) \text{ and } H^{\mp} \to hW^{\mp}$$

small v_Δ ($\ell^\pm\ell^\pm$) — large v_Δ ($W^\pm W^\pm$)

Model discovery

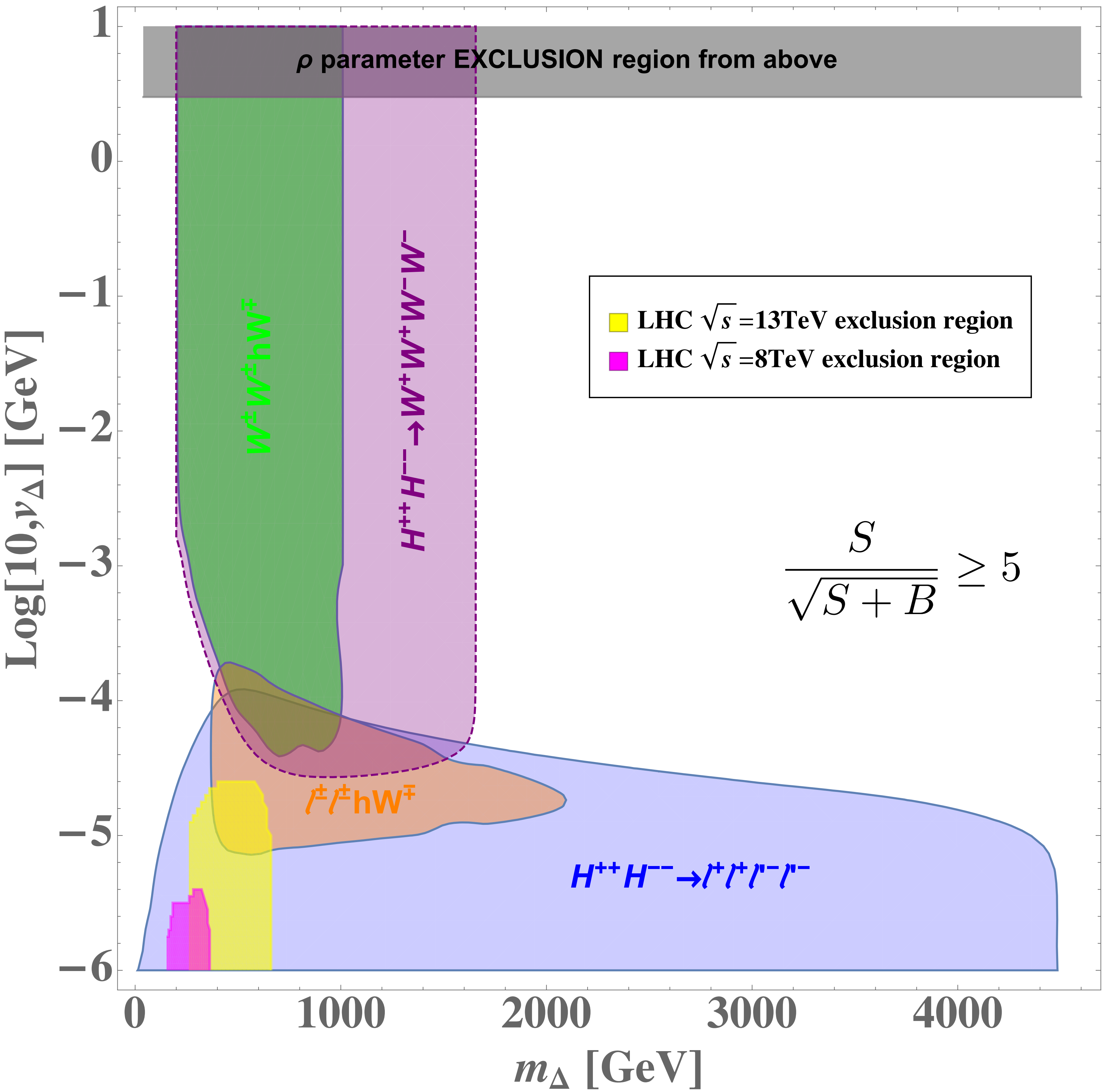


$$\lambda_2 = 0.2$$
$$\lambda_3 = 0$$
$$\lambda_4 = 0$$
$$\lambda_5 = -0.1$$

ATLAS, JHEP03, 041(2015)

ATLAS, Eur. Phys. J C78 (2018)

Model discovery



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$$m^2_{H^{\pm\pm}} \simeq m^2_\Delta - \frac{\lambda_5}{2} v^2_\Phi$$

$$m_\Delta \geq 0\,\text{GeV}$$
$$\Leftrightarrow m_{H^{\pm\pm}} \geq 54.78\,\text{GeV}$$

LEP constraints automatically satisfied

OPAL (1992, 2002)

Higgs portal parameter determination

$$\Delta m = |m_{H^{\pm\pm}} - m_{H^{\pm}}| \approx |m_{H^{\pm}} - m_{H,A}| \approx \frac{|\lambda_5| v_\Phi^2}{8 m_\Delta} \approx \frac{|\lambda_5| v^2}{8 m_\Delta}$$

Upon discovery, λ_5 can be determined readily by the mass splitting.

Higgs portal parameter determination

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Upon discovery, λ_5 can be determined readily by the mass splitting.

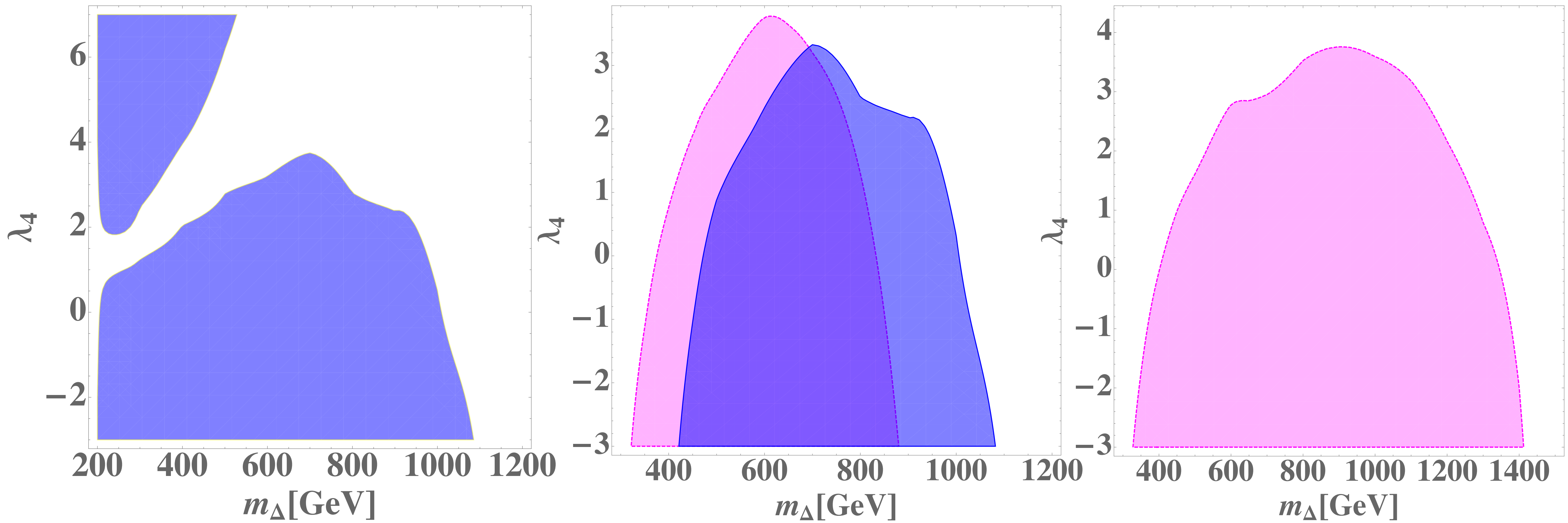
Can determine λ_4 from precise measurements on Br($H^\pm \to hW^\pm$) after discovery.

Parameter scan on the v_Δ-m_Δ plane and BDT analysis for

$$pp \to H^{\pm\pm} H^\mp \to \ell^\pm \ell^\pm h W^\mp / W^\pm W^\pm h W^\mp$$

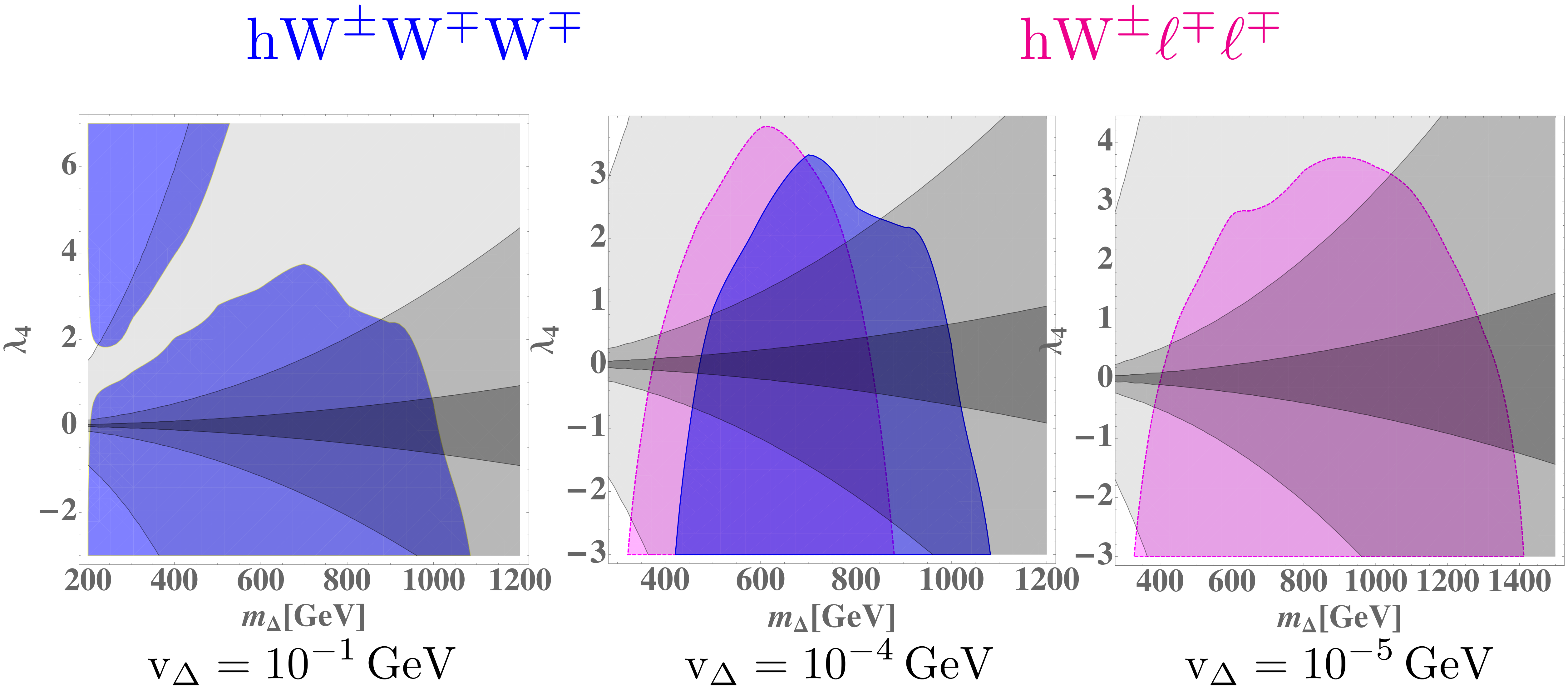
Higgs portal parameter determination

$\mathrm{hW^{\pm}W^{\mp}W^{\mp}}$ $\mathrm{hW^{\pm}\ell^{\mp}\ell^{\mp}}$



$\mathrm{v}_\Delta = 10^{-1}$ GeV $\mathrm{v}_\Delta = 10^{-4}$ GeV $\mathrm{v}_\Delta = 10^{-5}$ GeV

Higgs portal parameter determination



$R_{h\gamma\gamma} = 1.16^{+0.20}_{-0.18}$ (LHC)

$R_{h\gamma\gamma} = 1 \pm 0.05$ (FCC-ee)

$R_{h\gamma\gamma} = 1 \pm 0.01$ (FCC-hh)

ATLAS&CMS, JHEP08, 045 (2016)

Contino et al, CERN Yellow Report (2017)

Summary

1. Can generate neutrino masses through a type-II seesaw mechanism and explain BAU via EW baryogenesis. Same-sign di-lepton channel is the smoking-gun signature.
2. $pp \to H^{++}H^{--}/H^{\pm\pm}H^{\mp}$ with $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}/W^{\pm}W^{\pm}$, $H^{\pm} \to hW^{\pm}$ could cover a significant portion of the CTHM parameter space for model discovery.
3. Upon discovery, the Higgs portal parameter λ_5 can be determined from the mass splitting, λ_4 can be determined from precise measurements on Br($H^{\pm} \to hW^{\pm}$)
4. $h \to \gamma\gamma$ decay rate can indirectly help λ_4 determination by excluding a large part of the parameter space.

Back up

CTHM setup

SM Higgs Doublet

$$\Phi = \begin{bmatrix} \varphi^+ \\ \frac{1}{\sqrt{2}}(\varphi + i\chi) \end{bmatrix}$$

Complex triplet (1,3,2)

$$\Delta = \begin{bmatrix} \frac{\Delta^+}{\sqrt{2}} & H^{++} \\ \frac{1}{\sqrt{2}}(\delta + i\eta) & -\frac{\Delta^+}{\sqrt{2}} \end{bmatrix}$$

Potential

$$V(\Phi, \Delta) = -m^2\Phi^\dagger\Phi + M^2\mathrm{Tr}(\Delta^\dagger\Delta) + \left[\mu\Phi^{\mathrm{T}}\mathrm{i}\tau_2\Delta^\dagger\Phi + \mathrm{h.c.}\right] + \lambda_1(\Phi^\dagger\Phi)^2$$
$$+ \lambda_2\left[\mathrm{Tr}(\Delta^\dagger\Delta)\right]^2 + \lambda_3\mathrm{Tr}[\Delta^\dagger\Delta\Delta^\dagger\Delta] + \lambda_4(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_5\Phi^\dagger\Delta\Delta^\dagger\Phi$$

Kinetic Lagrangian

$$\mathcal{L}_{\mathrm{kin}} = (D_\mu\Phi)^\dagger(D^\mu\Phi) + \mathrm{Tr}[(\mathrm{D}_\mu\Delta)^\dagger(\mathrm{D}^\mu\Delta)]$$

$$D_\mu\Phi = \left(\partial_\mu + i\frac{g}{2}\tau^a W_\mu^a + i\frac{g'Y_\Phi}{2}B_\mu\right)\Phi$$

$$D_\mu\Delta = \partial_\mu\Delta + i\frac{g}{2}[\tau^a W_\mu^a, \Delta] + i\frac{g'Y_\Delta}{2}B_\mu\Delta$$

Model key features: Type-II seesaw mechanism

$$\mathcal{L}_Y = (h_\nu)_{ij} \overline{L^{ic}} i\tau_2 \Delta L^j + \text{h.c.}$$

$$\xrightarrow{\text{EWSB}} (m_\nu)_{ij} = \sqrt{2}(h_\nu)_{ij} v_\Delta \longrightarrow \text{h}_\nu \text{ can be } \mathcal{O}(1)$$

Lepton number violated by 2, and we have the same-sign di-lepton channel for the doubly charged component of the triplet--Smoking-gun signature for the triplet

Model key features

$$\begin{pmatrix} \varphi^\pm \\ \Delta^\pm \end{pmatrix} = \begin{pmatrix} \cos\beta_\pm & -\sin\beta_\pm \\ \sin\beta_\pm & \cos\beta_\pm \end{pmatrix} \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix}$$

$$\begin{pmatrix} \chi \\ \eta \end{pmatrix} = \begin{pmatrix} \cos\beta_0 & -\sin\beta_0 \\ \sin\beta_0 & \cos\beta_0 \end{pmatrix} \begin{pmatrix} G^0 \\ A \end{pmatrix}$$

$$\begin{pmatrix} \varphi \\ \delta \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

$$\sin\beta_\pm = \frac{\sqrt{2}v_\Delta}{\sqrt{v_\Phi^2 + 2v_\Delta^2}}$$

$$\sin\beta_0 = \frac{2v_\Delta}{\sqrt{v_\Phi^2 + 4v_\Delta^2}}$$

$$\tan 2\alpha = \frac{v_\Delta}{v_\Phi} \cdot \frac{2v_\Phi\lambda_{45} - \frac{2\sqrt{2}\mu v_\Phi}{v_\Delta}}{2v_\Phi\lambda_1 - \frac{v_\Phi\mu}{\sqrt{2}v_\Delta} - \frac{2v_\Delta^2\lambda_{23}}{v_\Phi}}$$

$$\lambda_{ij} \equiv \lambda_i + \lambda_j$$

$$v \equiv \sqrt{v_\Delta^2 + v_\Phi^2} = 246\,\text{GeV}$$

Model key features

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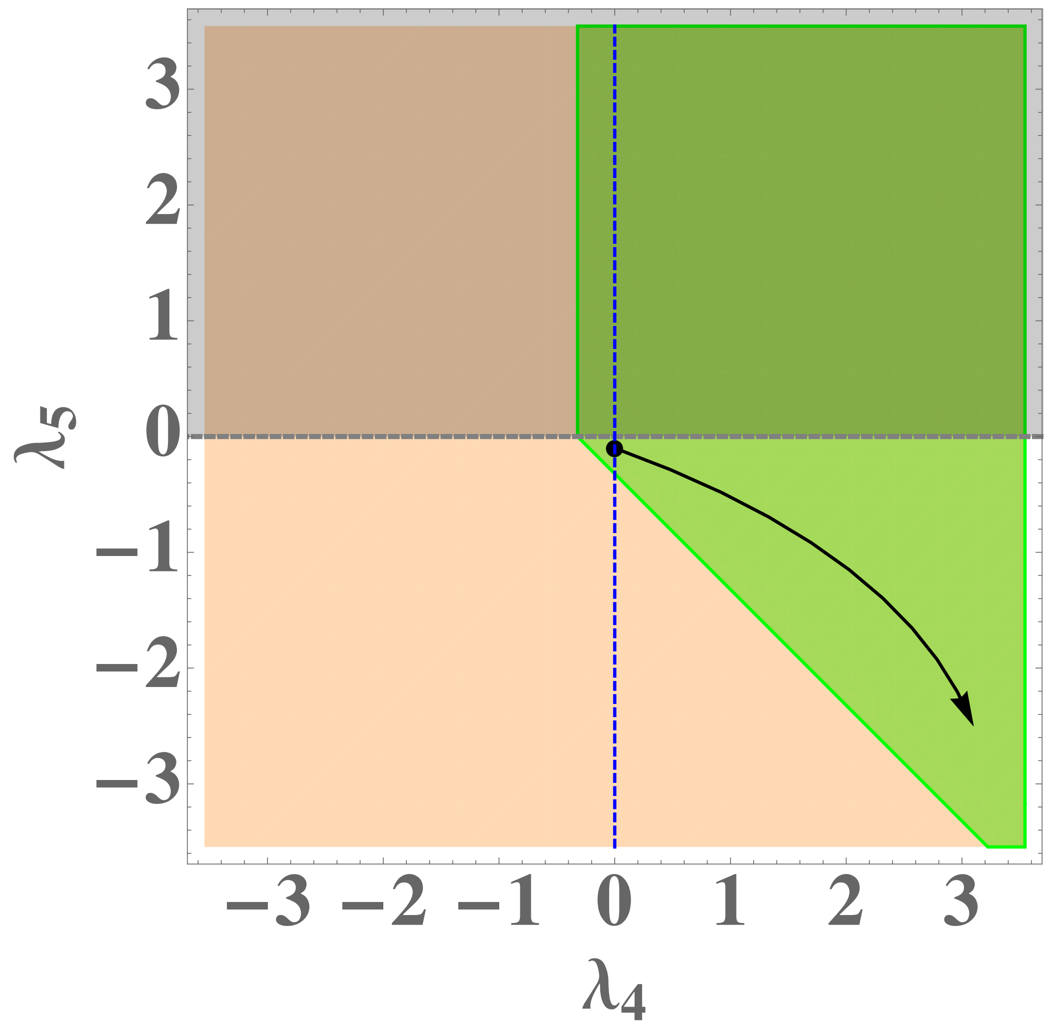
?

Vertex	Coupling
hAZ	$-\frac{g}{2\cos\theta_W}(\cos\alpha\sin\beta_0 - 2\sin\alpha\cos\beta_0)$
HZZ	$\frac{2iem_Z}{\sin 2\theta_W}(2\sin\beta_0\cos\alpha - \cos\beta_0\sin\alpha)$
HW^+W^-	$igm_Z\cos\theta_W(\sin\beta_0\cos\alpha - \cos\beta_0\sin\alpha)$
hH^-W^+	$\frac{ig}{2}(\sin\beta_\pm\cos\alpha - \sqrt{2}\cos\beta_\pm\sin\alpha)$

RGE running

RGE running



Tree-level vacuum stability
Perturbative unitarity

Arhrib et al, PRD84, 095005 (2011)

Bonilla et al, PRD92, 075028 (2015)

RGE running

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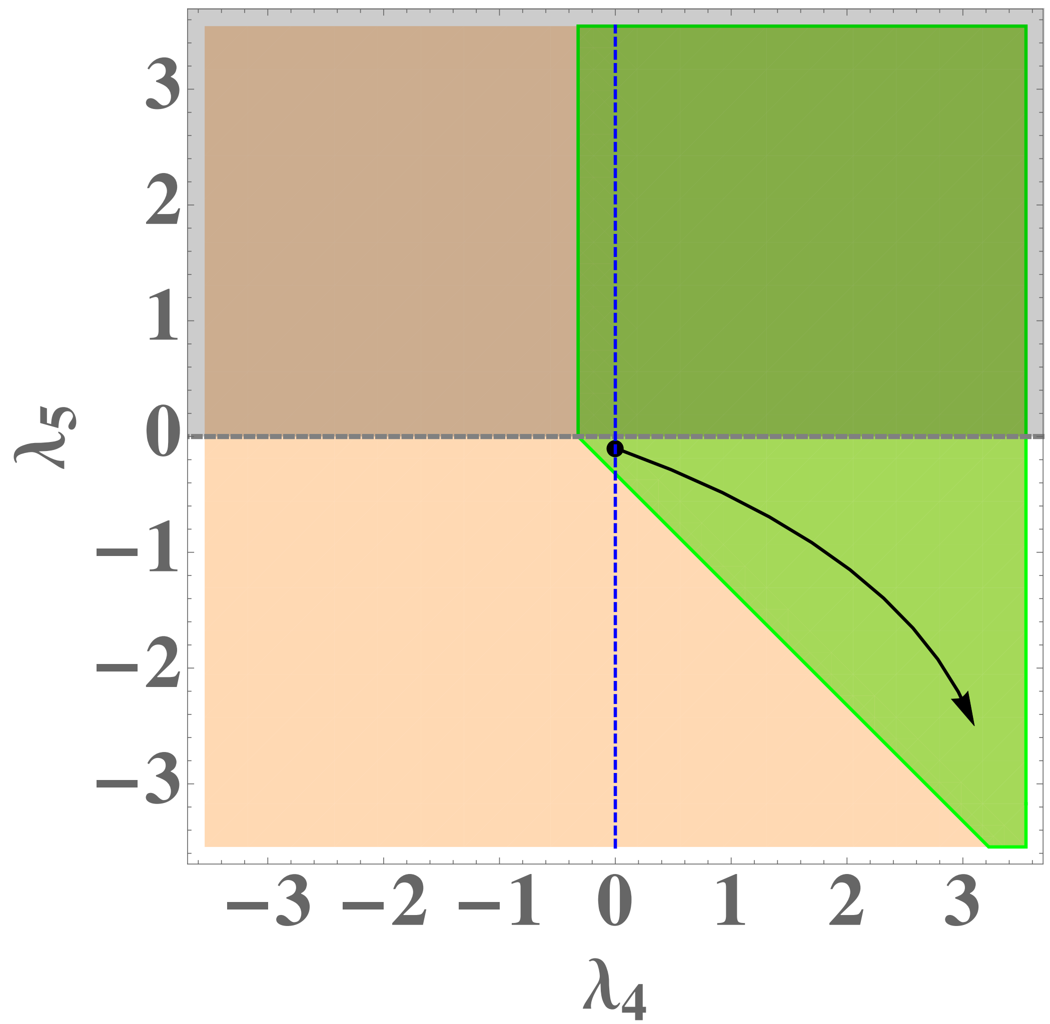

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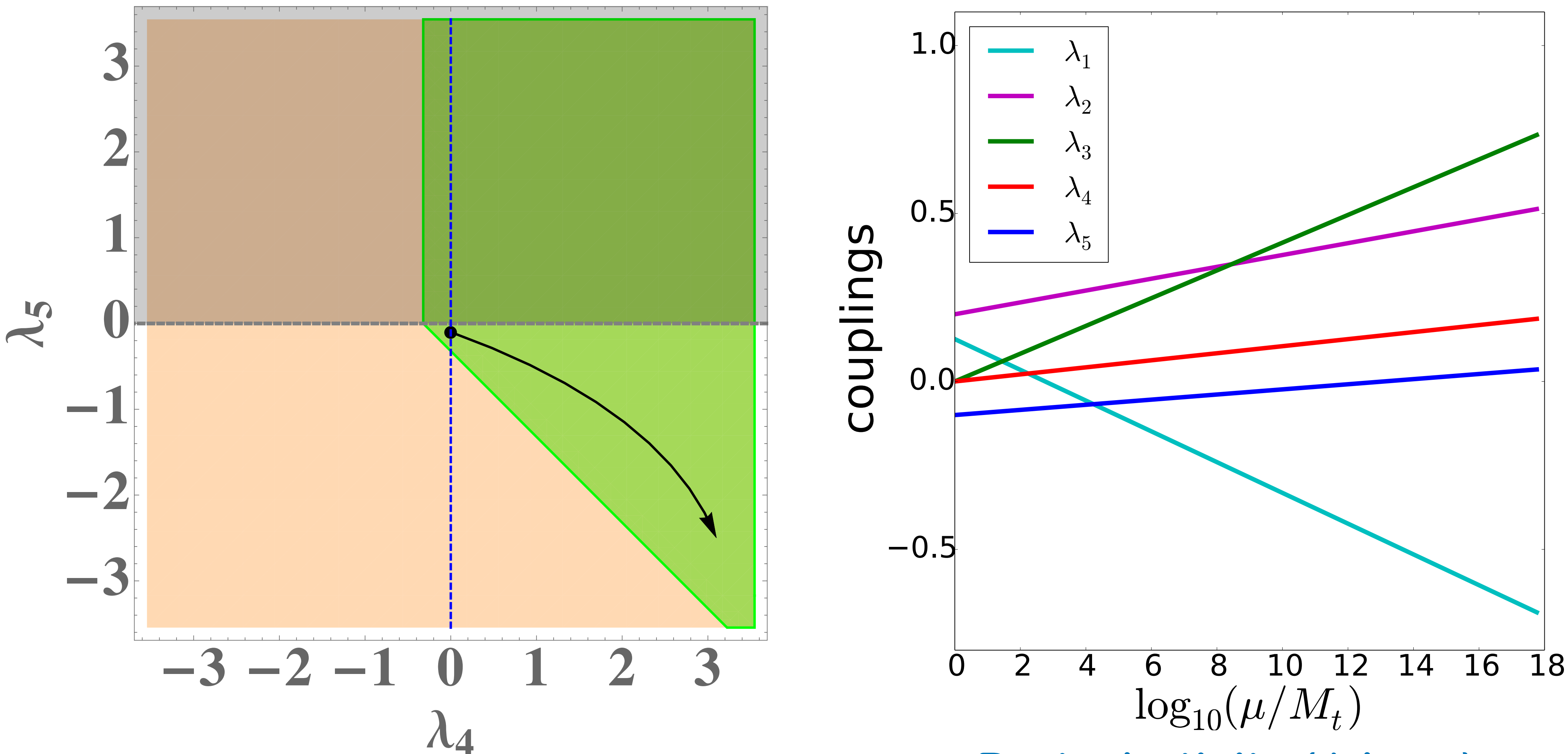


Tree-level vacuum stability

Perturbative unitarity

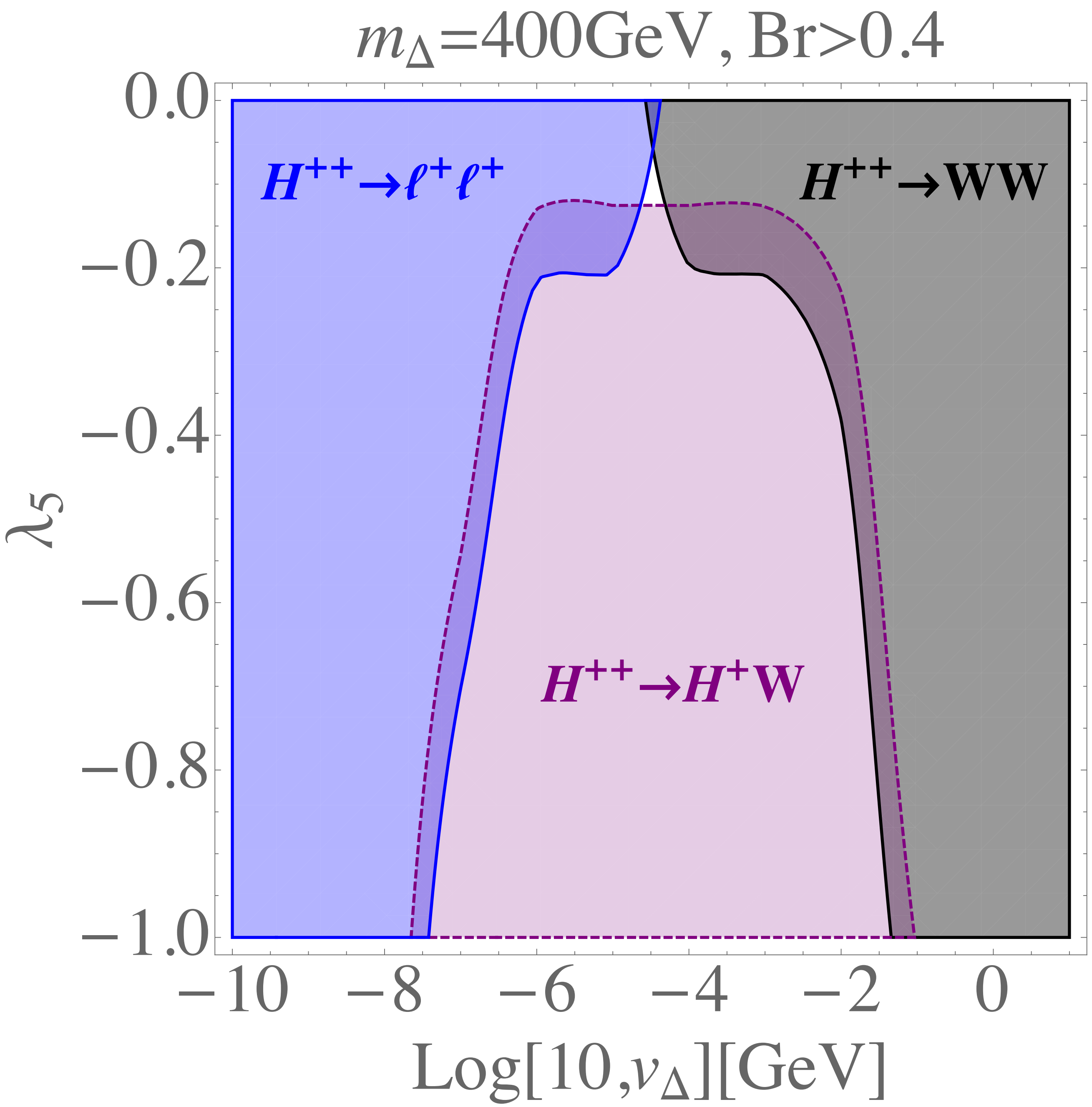
Perturbativity (1-loop)

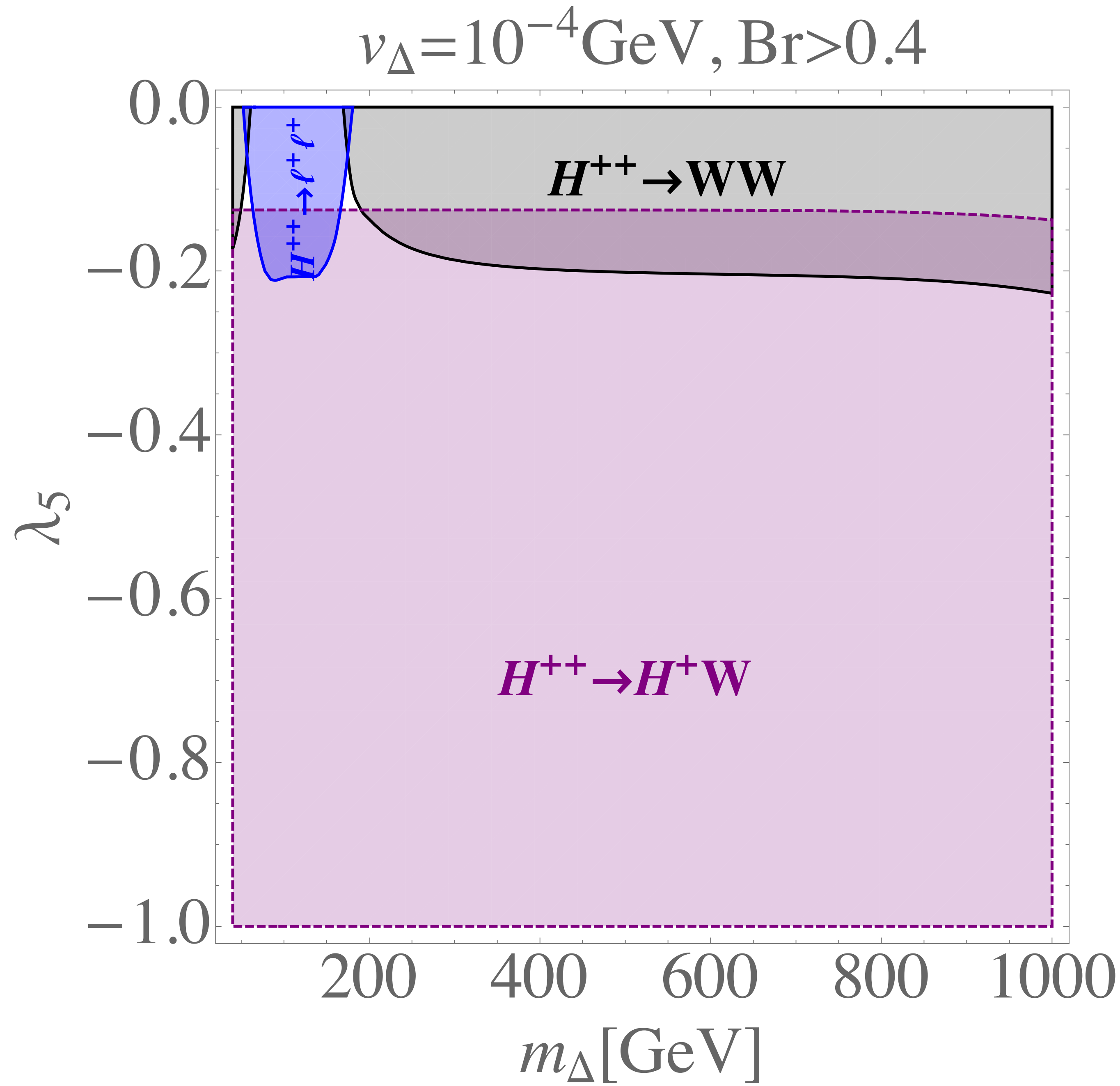
Chao et al (2012), Riesselmann et al (2012)

Machacek and Vaughn (1983, 1984, 1985)

Production and decay

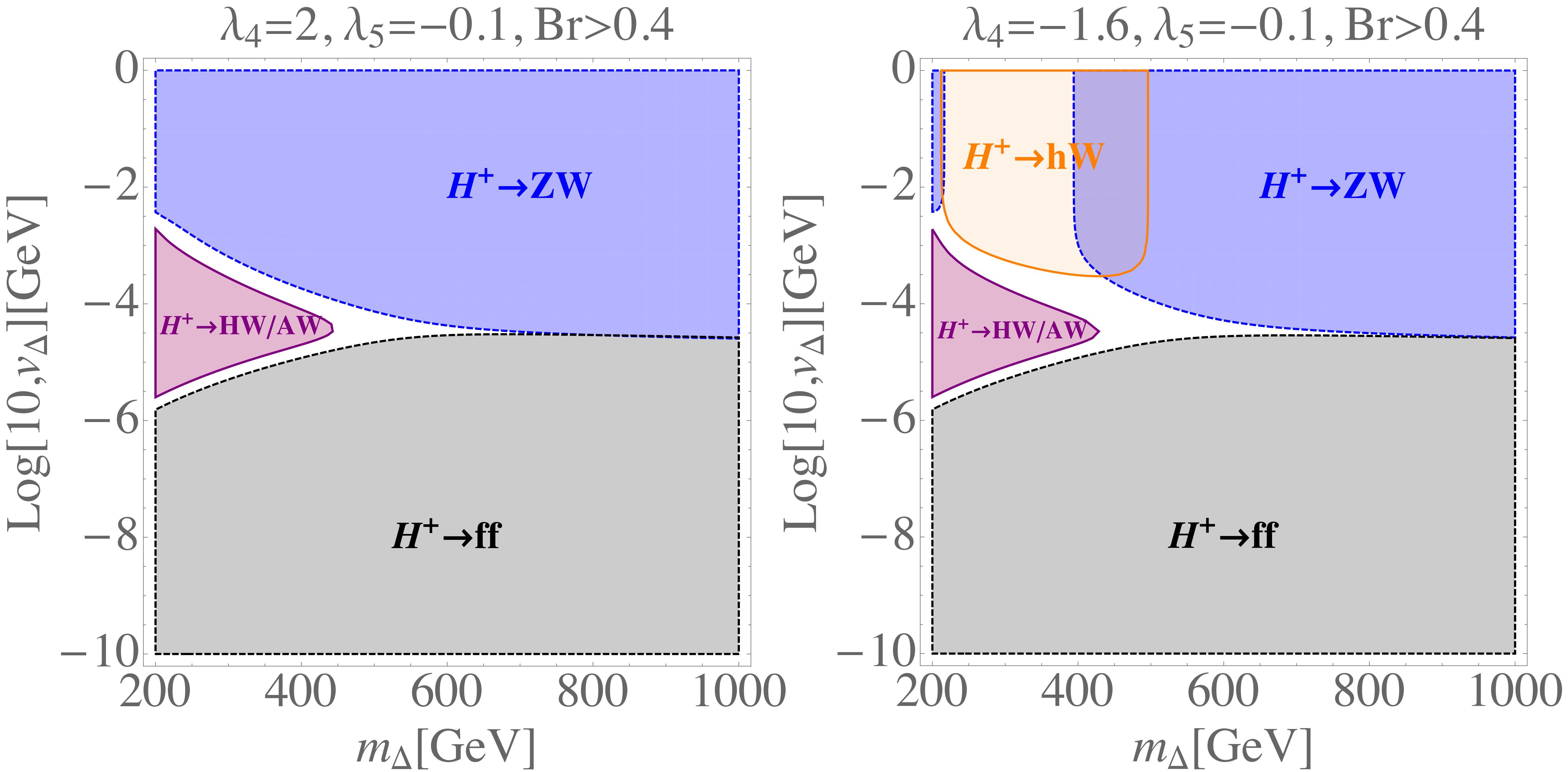
$\mathrm{H}^{\pm\pm}$





Production and decay

$H^{\pm}$



Production and decay

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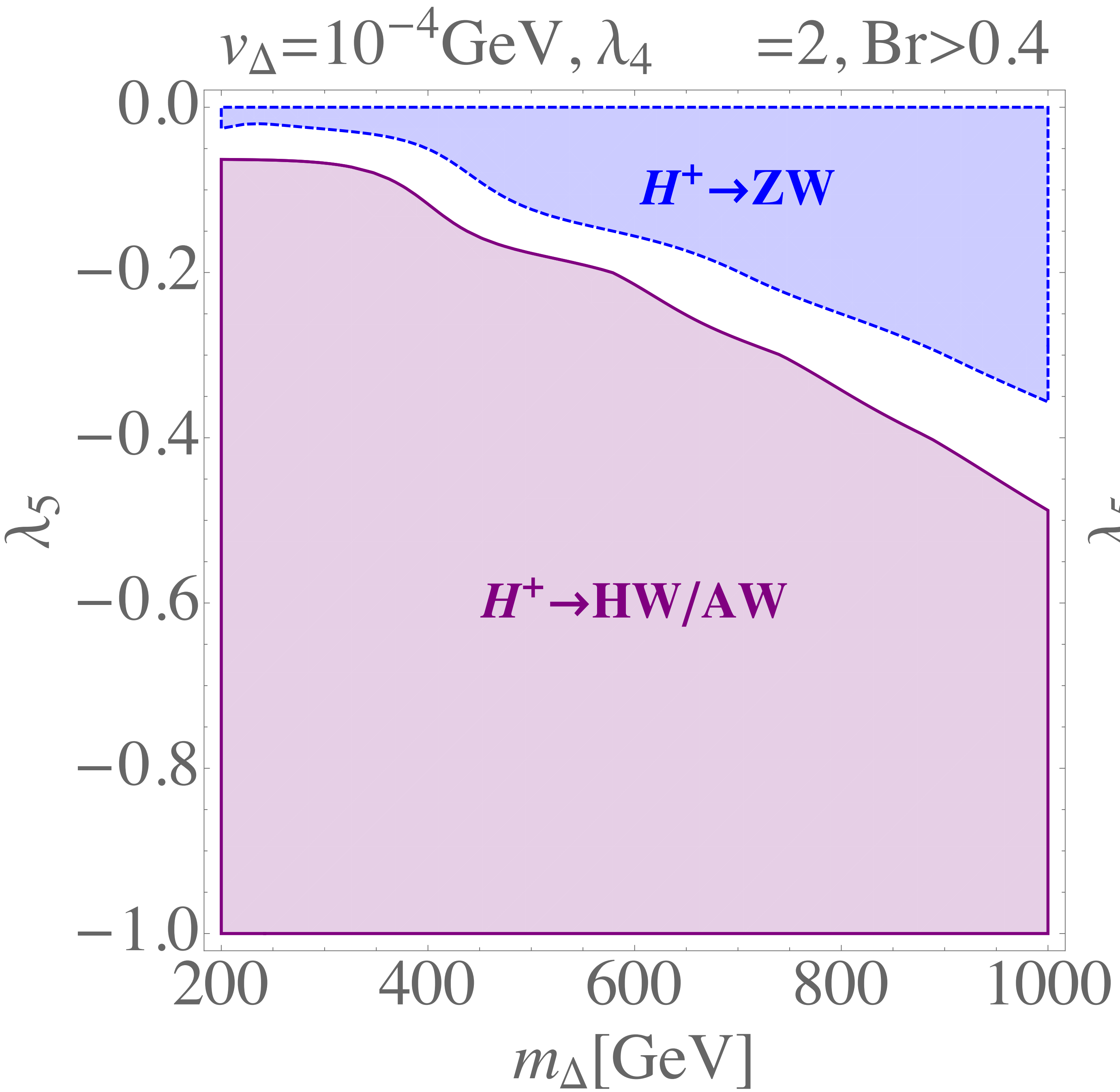

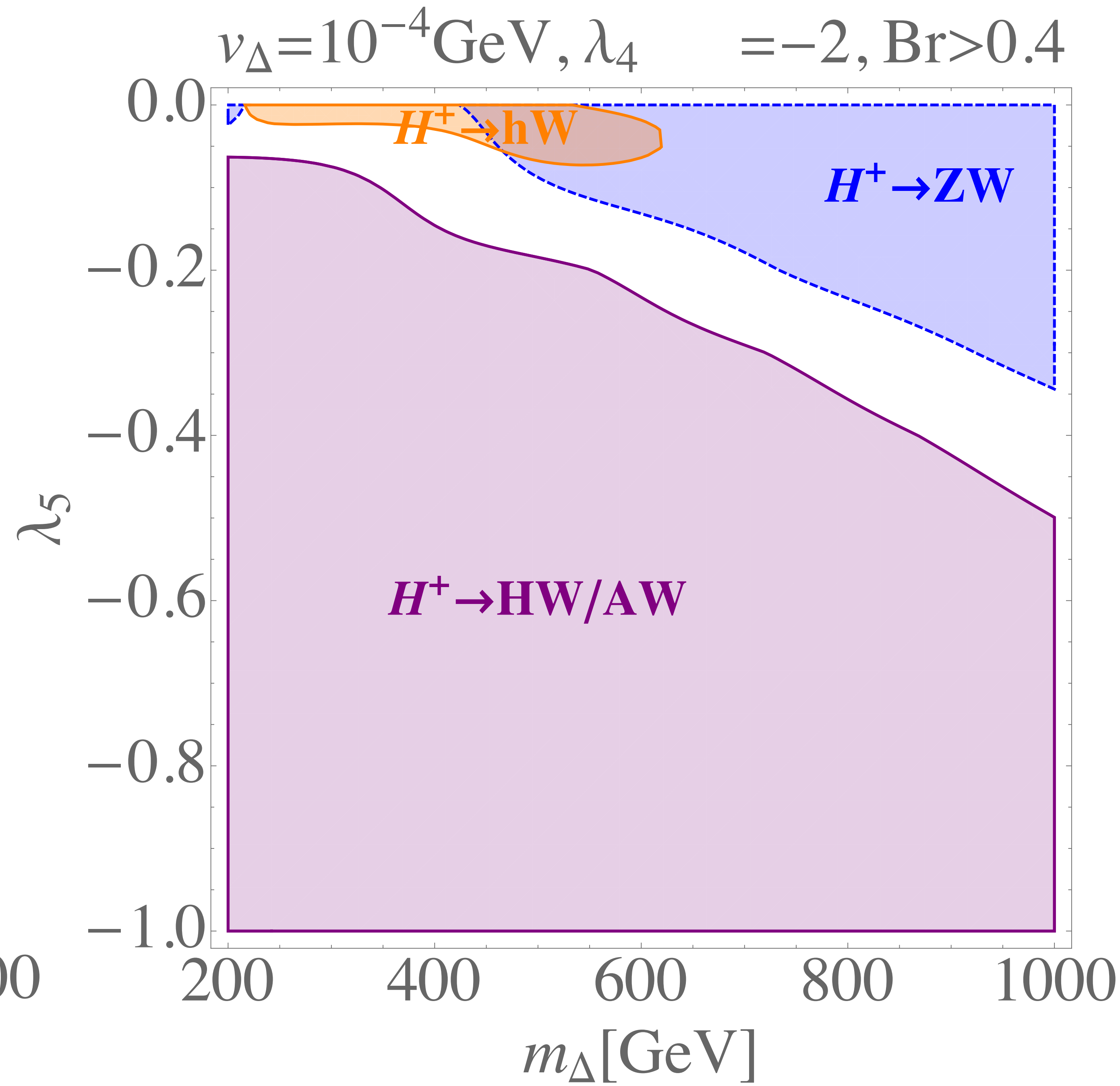

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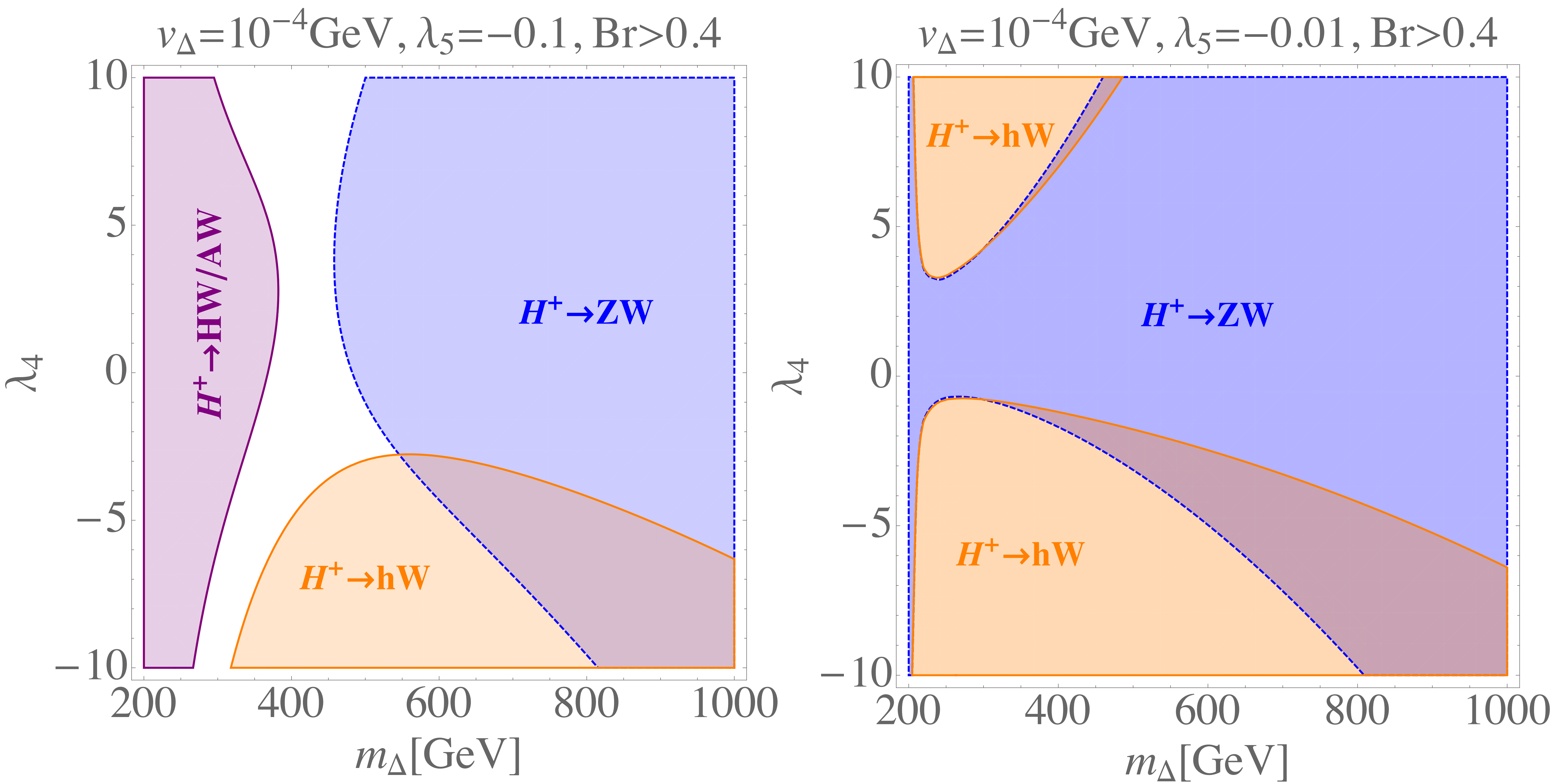
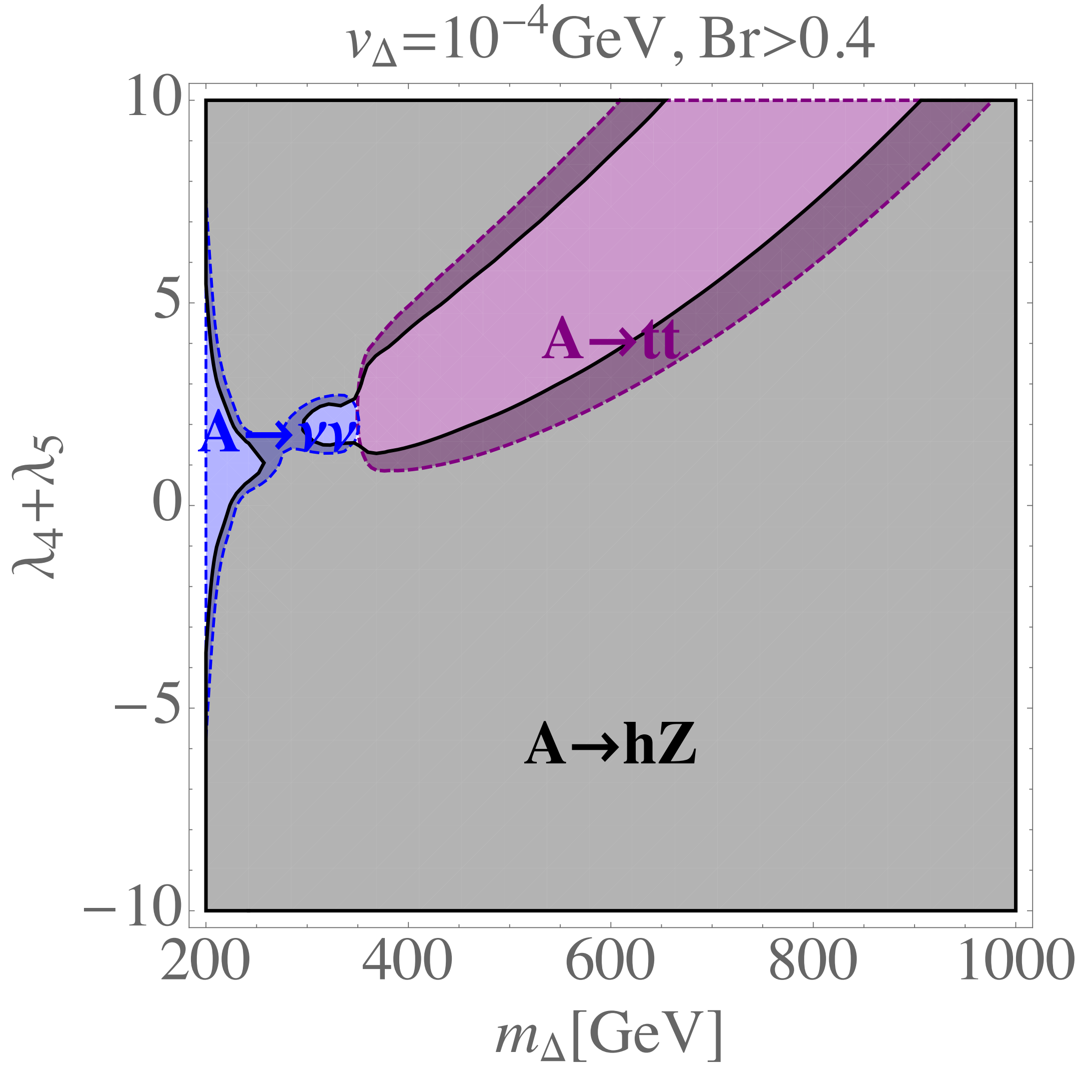
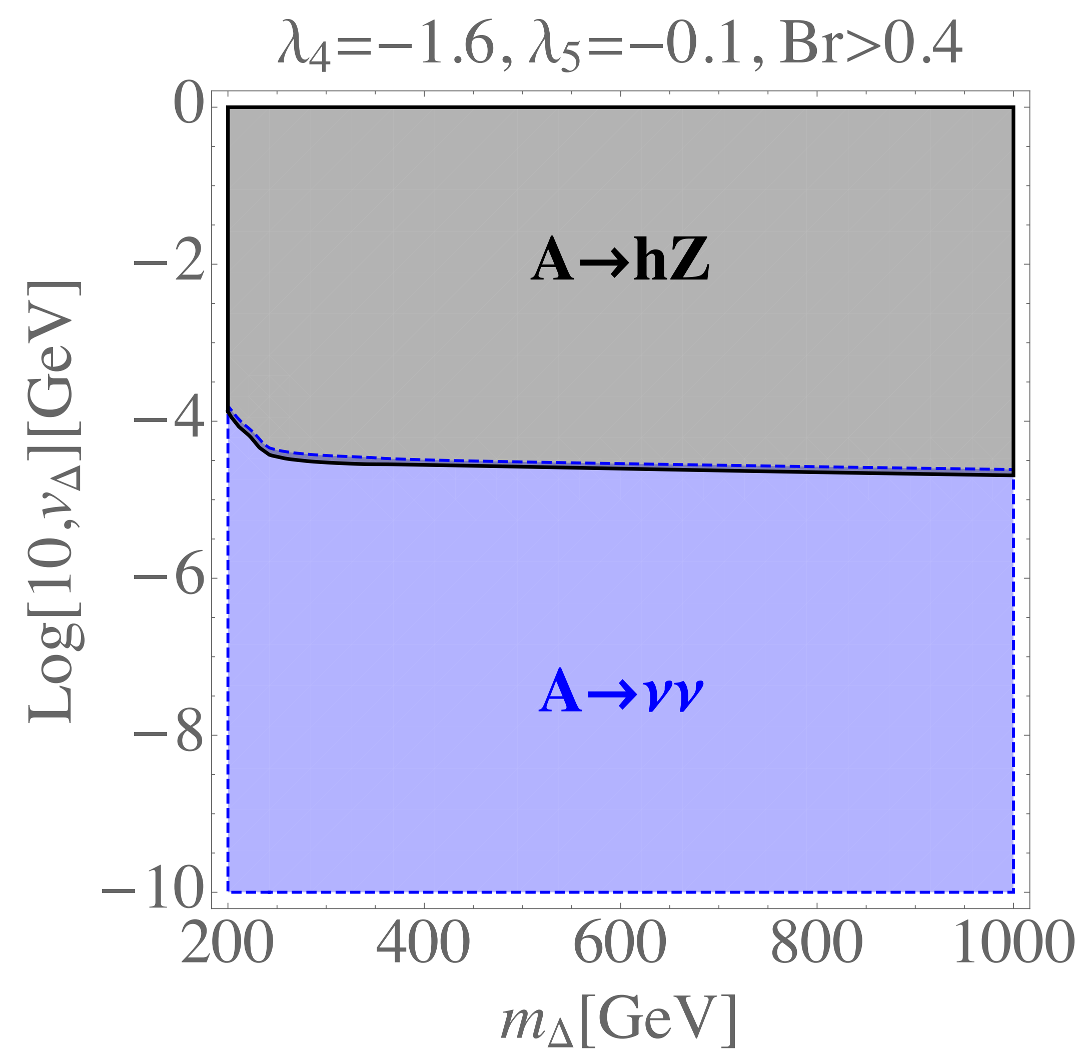
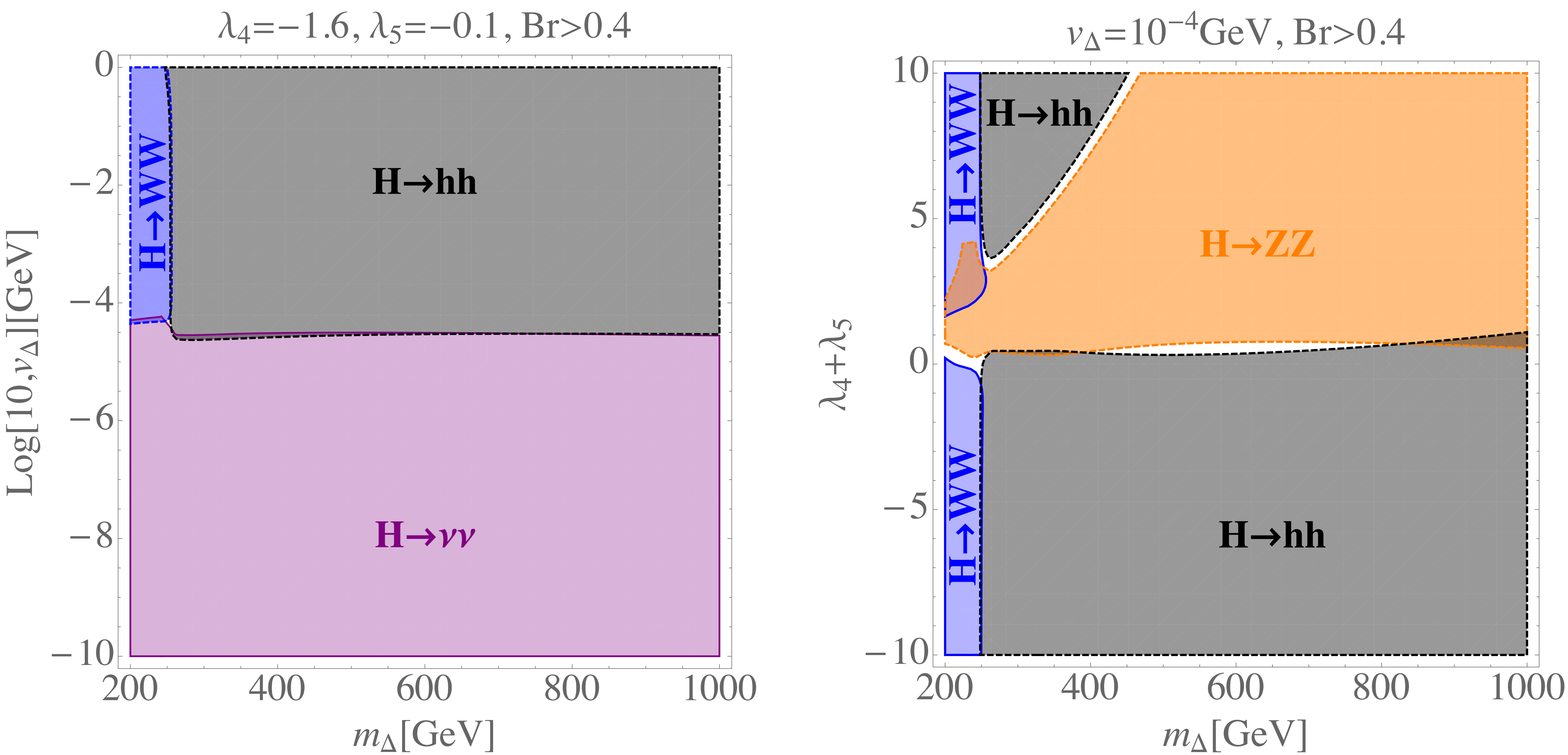



$v_\Delta=10^{-4}$GeV, Br>0.4
$\lambda_4+\lambda_5$
m_Δ[GeV]
A→tt
A→νν
A→hZ


$\lambda_4=-1.6$, $\lambda_5=-0.1$, Br>0.4
Log[10,v_Δ][GeV]
m_Δ[GeV]
A→hZ
A→νν



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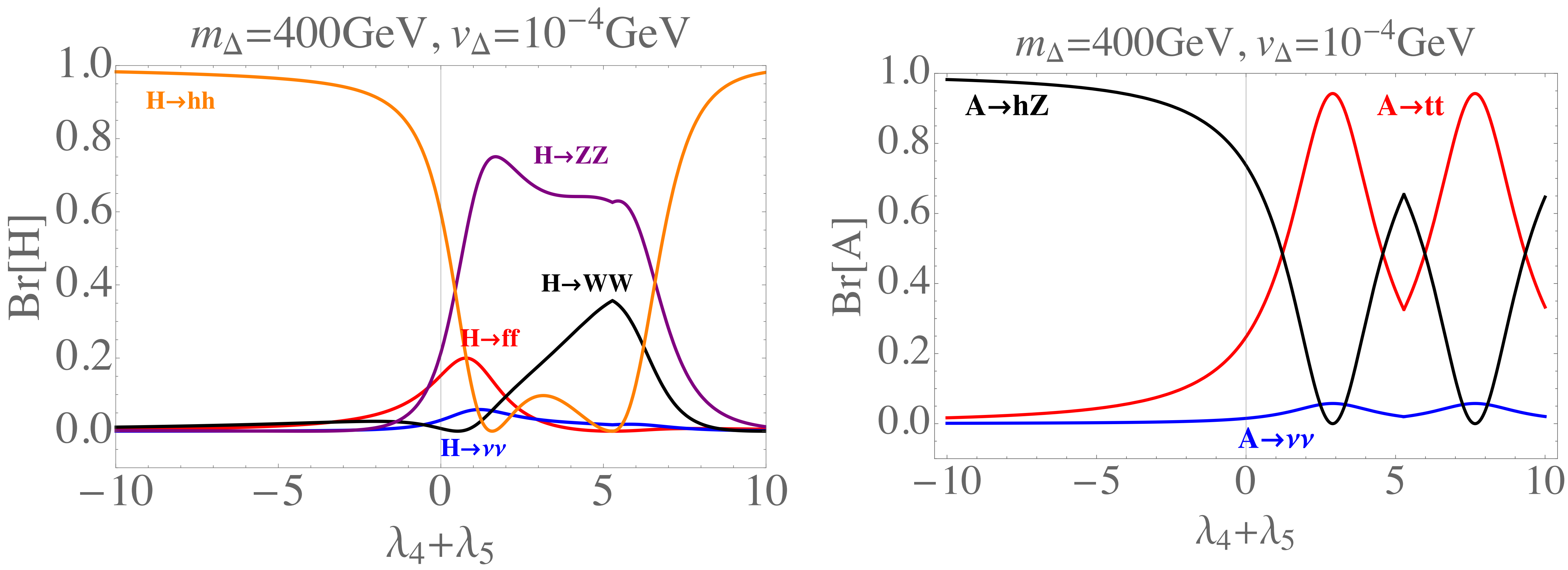
UMass-Amherst ACFI



m_Δ=400GeV, v_Δ=10^{-4}GeV
Br[H]
H→hh
H→ZZ
H→WW
H→ff
H→νν
$\lambda_4+\lambda_5$
m_Δ=400GeV, v_Δ=10^{-4}GeV
Br[A]
A→hZ
A→tt
A→νν
$\lambda_4+\lambda_5$

Signal and bkgs

Signal	$H^{++}H^{--} \to \ell^+\ell^+\ell'^-\ell'^-$ (for small v_Δ)
	$H^{++}H^{--} \to W^+W^+W^-W^- \to \ell^+\ell^+\ell'^-\ell'^-$ (for large v_Δ)
Background	$pp \to ZW^+W^- \to \ell^+\ell^-\ell'^+\ell''^- \not{E}_T$
	$pp \to ZZ \to \ell^+\ell^-\ell'^+\ell'^-$

$\not{E}_T$: Missing transverse energy; HT: Scalar sum of transverse momentum
$m_{H^{++}}$: Positively doubly-charged Higgs mass, $m_{H^{--}}$: Negatively doubly-charged Higgs mass
$p_{T,\ell^+}^{\text{leading}}$, $p_{T,\ell^+}^{\text{sub-leading}}$: Transverse momentum of the ℓ^+ with leading and sub-leading p_T respectively
$p_{T,\ell^-}^{\text{leading}}$, $p_{T,\ell^-}^{\text{sub-leading}}$: Transverse momentum of the ℓ^- with leading and sub-leading p_T respectively
$\Delta\phi_{\ell^+\ell^+}$, $\Delta R_{\ell^+\ell^+}$: $\Delta\phi$ and ΔR of the two positively charged leptons
$\Delta\phi_{\ell^-\ell^-}$, $\Delta R_{\ell^-\ell^-}$: $\Delta\phi$ and ΔR of the two negatively charged leptons
$m_{Z,1}$, $m_{Z,2}$: Two minimal combinations of the four leptons with same flavor and opposite charges

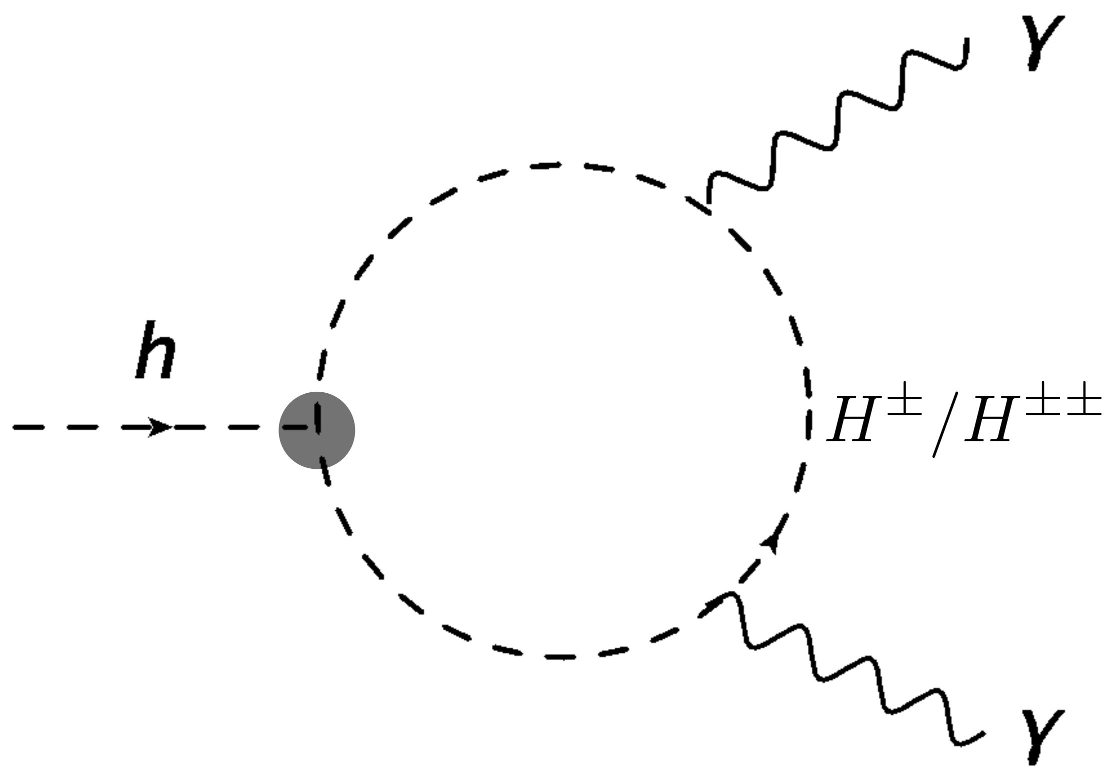
Signal and bkgs

Signal	$pp \to H^{\mp}H^{\pm\pm} \to hW^{\mp}\ell^{\pm}\ell^{\pm} \to b\bar{b}\ell'^{\mp}\ell^{\pm}\ell^{\pm}\not{E}_T$ (for intermediate v_Δ)
	$pp \to H^{\mp}H^{\pm\pm} \to hW^{\mp}W^{\pm}W^{\pm} \to b\bar{b}\ell'^{\mp}\ell^{\pm}\ell^{\pm}\not{E}_T$ (for large v_Δ)
Background	$pp \to hZW^{\pm} \to b\bar{b}\ell^{+}\ell^{-}\ell'^{\pm}\not{E}_T$
	$pp \to hZZ \to b\bar{b}\ell^{+}\ell^{-}\ell'^{+}\ell'^{-}$
	$pp \to ZW^{\pm}jj \to \ell^{+}\ell^{-}\ell'^{\pm}jj\not{E}_T$
	$pp \to t\bar{t}Z \to W^{+}bW^{-}\bar{b}\ell^{+}\ell^{-} \to b\bar{b}\ell'^{+}\ell''^{-}\ell^{+}\ell^{-}\not{E}_T$
	$pp \to ZW^{\pm}bb \to b\bar{b}\ell^{+}\ell^{-}\ell'^{\pm}\not{E}_T$
	$pp \to W^{+}W^{-}b\bar{b}j \to b\bar{b}\ell^{+}\ell'^{-}j\not{E}_T$
	$pp \to t\bar{t}W^{\pm} \to W^{+}bW^{-}\bar{b}\ell^{\pm}\not{E}_T \to b\bar{b}\ell'^{+}\ell''^{-}\ell^{\pm}\not{E}_T$
	$pp \to t\bar{t}j \to W^{+}bW^{-}\bar{b}j \to b\bar{b}\ell'^{+}\ell''^{-}j\not{E}_T$

Higgs portal parameter determination

$$R_{h\gamma\gamma} = \frac{\Gamma^{\rm NP}(h \to \gamma\gamma) + \Gamma^{\rm SM}(h \to \gamma\gamma)}{\Gamma^{\rm SM}(h \to \gamma\gamma)}$$

$$\lambda_4(\Phi^\dagger\Phi){\rm Tr}(\Delta^\dagger\Delta) + \lambda_5\Phi^\dagger\Delta\Delta^\dagger\Phi$$



Kanemura et al, PRD85, 115009 (2012)

Arhrib et al, JHEP04, 136 (2012)