

Exploring the global symmetry structure of the Higgs potential
via
same-sign pair production of charged Higgs bosons

Kentarou Mawatari
켄타로 마와타리



[[arXiv:1906.09101](https://arxiv.org/abs/1906.09101)]

work with Masashi Aiko and Shinya Kanemura (Osaka U.)

No BSM so far...

ATLAS SUSY Searches* - 95% CL Lower Limits

July 2018

Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L} dt [fb^{-1}]$	Mass limit	Reference	
Inclusive Searches	$q\bar{q}, \bar{q} \rightarrow q\bar{q}^0$	0 mono-jet	2-6 jets	Yes	36.1	\bar{q} [2x, 8x Degen]	$m(\tilde{q}_1^0) < 100$ GeV
		1-3 jets	Yes	36.1	\bar{q} [1x, 8x Degen]	$m(\tilde{q}) - m(\tilde{q}_1^0) = 5$ GeV	
	$\bar{g}\bar{g}, \bar{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	\bar{g}	$m(\tilde{g}_1^0) < 200$ GeV
		3 e, μ	4 jets	-	36.1	\bar{g}	$m(\tilde{g}) - m(\tilde{q}_1^0) = 900$ GeV
	$\bar{g}\bar{g}, \bar{g} \rightarrow q\bar{q}(t\bar{t})\tilde{\chi}_1^0$	3 e, μ	4 jets	-	36.1	\bar{g}	$m(\tilde{g}_1^0) < 800$ GeV
		e, μ	2 jets	Yes	36.1	\bar{g}	$m(\tilde{g}) - m(\tilde{q}_1^0) = 50$ GeV
$\bar{g}\bar{g}, \bar{g} \rightarrow q\bar{q}WZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	\bar{g}	$m(\tilde{g}_1^0) < 400$ GeV	
	3 e, μ	4 jets	-	36.1	\bar{g}	$m(\tilde{g}) - m(\tilde{q}_1^0) = 200$ GeV	
$\bar{g}\bar{g}, \bar{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	36.1	\bar{g}	$m(\tilde{g}_1^0) < 200$ GeV	
	3 e, μ	4 jets	-	36.1	\bar{g}	$m(\tilde{g}) - m(\tilde{q}_1^0) = 300$ GeV	
3rd gen. squarks direct production	$\bar{t}_1\bar{t}_1, \bar{b}_1\bar{b}_1 \rightarrow b\bar{b}_1/\bar{t}_1\bar{t}_1$	Multiple	Multiple	Yes	36.1	\bar{t}_1	$m(\tilde{t}_1^0) = 300$ GeV, $BR(\tilde{t}_1^0) = 1$
		Multiple	Multiple	Yes	36.1	\bar{b}_1	$m(\tilde{b}_1^0) = 300$ GeV, $BR(\tilde{b}_1^0) = BR(\tilde{t}_1^0) = 0.5$
	Multiple	Multiple	Yes	36.1	\bar{b}_1	$m(\tilde{b}_1^0) = 200$ GeV, $m(\tilde{t}_1^0) = 300$ GeV, $BR(\tilde{b}_1^0) = 1$	
	$\bar{t}_1\bar{t}_1, \bar{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $t\bar{t}_1^0$	Multiple	Multiple	Yes	36.1	\bar{t}_1	$m(\tilde{t}_1^0) = 60$ GeV
		Multiple	Multiple	Yes	36.1	\bar{t}_1	$m(\tilde{t}_1^0) = 200$ GeV
	$\bar{t}_1\bar{t}_1, \tilde{H}$ LSP	Multiple	Multiple	Yes	36.1	\bar{t}_1	$m(\tilde{t}_1^0) = 1$ GeV
		Multiple	Multiple	Yes	36.1	\bar{t}_1	$m(\tilde{t}_1^0) = 150$ GeV, $m(\tilde{t}_1^0) - m(\tilde{t}_1^0) = 5$ GeV, $\tilde{t}_1 = \tilde{t}_L$
	$\bar{t}_1\bar{t}_1, \tilde{H}$ Well-Tempered LSP	Multiple	Multiple	Yes	36.1	\bar{t}_1	$m(\tilde{t}_1^0) = 300$ GeV, $m(\tilde{t}_1^0) - m(\tilde{t}_1^0) = 5$ GeV, $\tilde{t}_1 = \tilde{t}_L$
		Multiple	Multiple	Yes	36.1	\bar{t}_1	$m(\tilde{t}_1^0) = 150$ GeV, $m(\tilde{t}_1^0) - m(\tilde{t}_1^0) = 5$ GeV, $\tilde{t}_1 = \tilde{t}_L$
	$\bar{t}_1\bar{t}_1, \tilde{t}_1 \rightarrow c\bar{c}\tilde{\chi}_1^0$	0	2c	Yes	36.1	\bar{t}_1	$m(\tilde{t}_1^0) = 0$ GeV
0		mono-jet	Yes	36.1	\bar{t}_1	$m(\tilde{t}_1, \tilde{t}_1) - m(\tilde{t}_1^0) = 50$ GeV	
$\bar{t}_1\bar{t}_1, \tilde{t}_1 \rightarrow c\bar{c}\tilde{\chi}_1^0$	0	mono-jet	Yes	36.1	\bar{t}_1	$m(\tilde{t}_1, \tilde{t}_1) - m(\tilde{t}_1^0) = 5$ GeV	
	0	mono-jet	Yes	36.1	\bar{t}_1	$m(\tilde{t}_1, \tilde{t}_1) - m(\tilde{t}_1^0) = 5$ GeV	
$\bar{t}_2\bar{t}_2, \tilde{t}_2 \rightarrow t\bar{t} + h$	1-2 e, μ	4 b	Yes	36.1	\bar{t}_2	$m(\tilde{t}_2^0) = 0$ GeV, $m(\tilde{t}_2) - m(\tilde{t}_2^0) = 180$ GeV	
EW direct	$\tilde{\chi}_1^0\tilde{\chi}_2^0$ via WZ	2-3 e, μ	-	Yes	36.1	$\tilde{\chi}_1^0/\tilde{\chi}_2^0$	$m(\tilde{\chi}_1^0) = 0$
		e, μ	≥ 1	Yes	36.1	$\tilde{\chi}_1^0/\tilde{\chi}_2^0$	$m(\tilde{\chi}_1^0) - m(\tilde{\chi}_2^0) = 10$ GeV
	$\tilde{\chi}_1^0\tilde{\chi}_2^0$ via Wh	$\ell\ell/\gamma\gamma/bb$	-	Yes	20.3	$\tilde{\chi}_1^0/\tilde{\chi}_2^0$	$m(\tilde{\chi}_1^0) = 0$
		2 τ	-	Yes	36.1	$\tilde{\chi}_1^0/\tilde{\chi}_2^0$	$m(\tilde{\chi}_1^0) = 0$
$\tilde{\chi}_1^0\tilde{\chi}_1^0/\tilde{\chi}_2^0\tilde{\chi}_2^0, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}\nu(\tilde{\tau}\nu), \tilde{\chi}_2^0 \rightarrow \tilde{\tau}\nu(\tilde{\tau}\nu)$	2 e, μ	0	Yes	36.1	$\tilde{\chi}_1^0$	$m(\tilde{\chi}_1^0) = 0, m(\tilde{\tau}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{\chi}_2^0))$	
	2 e, μ	≥ 1	Yes	36.1	$\tilde{\chi}_1^0$	$m(\tilde{\chi}_1^0) - m(\tilde{\chi}_2^0) = 100$ GeV, $m(\tilde{\tau}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{\chi}_2^0))$	
$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0	$\geq 3b$	Yes	36.1	\tilde{H}	$m(\tilde{H}) = 0$	
	4 e, μ	0	Yes	36.1	\tilde{H}	$BR(\tilde{H} \rightarrow h\tilde{G}) = 1$	
Long-lived particles	Direct $\tilde{\chi}_1^0\tilde{\chi}_1^0$ prod., long-lived $\tilde{\chi}_1^0$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^0$	Pure Wino
		SMP	-	-	3.2	$\tilde{\chi}_1^0$	Pure Higgsino
	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	Multiple	-	-	32.8	\tilde{g}	$\tau(\tilde{g}) = 100$ ns, 0.2 ns
GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$	$1 < \tau(\tilde{\chi}_1^0) < 3$ ns, SPS8 model	
$\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow e\bar{e}\nu/\mu\bar{\mu}\nu$	displ. $e\bar{e}/\mu\bar{\mu}$	-	-	20.3	\tilde{g}	$6 < \tau(\tilde{\chi}_1^0) < 1000$ ns, $m(\tilde{\chi}_1^0) = 1$ TeV	
RPV	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e\mu/\tau\mu$	e, μ, τ	-	-	3.2	$\tilde{\nu}_\tau$	$\lambda_{11}^{\tau e} = 0.11, \lambda_{12}^{\tau e} = 0.07$
		4 e, μ	0	Yes	36.1	$\tilde{\nu}_\tau$	$m(\tilde{\nu}_\tau) = 100$ GeV
	$\tilde{\chi}_1^0\tilde{\chi}_1^0/\tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell/\nu\nu$	Multiple	-	-	36.1	$\tilde{\chi}_1^0$	$BR(\tilde{\chi}_1^0 \rightarrow h\tilde{G}) = 1$
		Multiple	-	-	36.1	$\tilde{\chi}_1^0$	$BR(\tilde{\chi}_1^0 \rightarrow h\tilde{G}) = 1$
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q\bar{q}q$	Multiple	-	-	36.1	\tilde{g}	Large $A_{1,2}^{\tilde{g}}$	
	Multiple	-	-	36.1	\tilde{g}	$A_{1,2}^{\tilde{g}} = 2e-4, 2e-5$	
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{b} / \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow t\bar{b}$	Multiple	-	-	36.1	\tilde{g}	$A_{1,2}^{\tilde{g}} = 1, 1e-2$	
	Multiple	-	-	36.1	\tilde{g}	$A_{1,2}^{\tilde{g}} = 2e-4, 1e-2$	
$\tilde{t}_1\bar{t}_1, \tilde{t}_1 \rightarrow b\bar{b}$	0	2 jets + 2 b	-	36.7	\tilde{t}_1	$[qq, bb]$	
	2 e, μ	2 b	-	36.1	\tilde{t}_1	$BR(\tilde{t}_1 \rightarrow b\bar{b}) > 20\%$	

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Mass limits for SUSY particles

ATLAS Preliminary

$\sqrt{s} = 7, 8, 13$ TeV

Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L} dt [fb^{-1}]$	Limit	Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1-4 j	Yes	36.1	M_0 7.7 TeV
	ADD non-resonant $\gamma\gamma$	2 γ	-	-	36.7	M_2 8.6 TeV
	ADD OBH	-	2 j	-	37.0	M_{BH} 8.9 TeV
	ADD BH high Σp_T	$\geq 1 e, \mu$	$\geq 2 j$	-	3.2	M_{BH} 8.2 TeV
	ADD BH multijet	-	$\geq 3 j$	-	3.6	M_{BH} 9.55 TeV
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2 γ	-	-	36.7	G_{KK} mass 4.1 TeV
Gauge bosons	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	G_{KK} mass 2.3 TeV
	Bulk RS $g_{KK} \rightarrow t\bar{t}$	1 e, μ	$\geq 1 b, \geq 1 J/2 J$	Yes	36.1	g_{KK} mass 3.8 TeV
	ZUED / RPP	1 e, μ	$\geq 2 b, \geq 3 j$	Yes	36.1	KK mass 1.8 TeV
	SSM $Z' \rightarrow \ell\ell$	2 e, μ	-	-	36.1	Z' mass 4.5 TeV
CI	CI $qqqq$	-	2 j	-	37.0	A 21.8 TeV η_{LL}
	CI $\ell\ell qq$	2 e, μ	-	-	36.1	A 40.0 TeV η_{LL}
	CI $tttt$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	A 2.57 TeV
	Axial-vector mediator (Dirac DM)	0 e, μ	1-4 j	Yes	36.1	M_{med} 1.55 TeV
	Colored scalar mediator (Dirac DM)	0 e, μ	1-4 j	Yes	36.1	M_{med} 1.67 TeV
	VV $\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, $\leq 1 j$	Yes	3.2	M_s 700 GeV
	Scalar LQ 1st gen	2 e	$\geq 2 j$	-	3.2	LQ mass 1.1 TeV
	Scalar LQ 2nd gen	2 e, μ	$\geq 2 j$	-	3.2	LQ mass 1.05 TeV
	Scalar LQ 3rd gen	1 e, μ	$\geq 1 b, \geq 3 j$	Yes	20.3	LQ mass 640 GeV
	Excited fermions/heavy quarks	VLQ $TT \rightarrow Ht/Zt/Wb + X$	multi-channel	-	-	36.1
VLQ $BB \rightarrow Wt/Zb + X$		multi-channel	-	-	36.1	B mass 1.34 TeV
VLQ $T_{5/3} T_{5/3} / T_{5/3} \rightarrow Wt + X$		2(SS) $\geq 3 e, \mu \geq 1 b, \geq 1 j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	
VLQ $Y \rightarrow Wb + X$		1 e, μ	$\geq 1 b, \geq 1 j$	Yes	3.2	Y mass 1.44 TeV
VLQ $B \rightarrow Hb + X$		0 $e, \mu, 2 \gamma$	$\geq 1 b, \geq 1 j$	Yes	79.8	B mass 1.21 TeV
Excited fermions/heavy quarks	VLQ $QQ \rightarrow WqWq$	1 e, μ	$\geq 4 j$	Yes	20.3	Q mass 690 GeV
	Excited quark $q^* \rightarrow qg$	-	2 j	-	37.0	q^* mass 6.0 TeV
	Excited quark $q^* \rightarrow q\gamma$	1 γ	1 j	-	36.7	q^* mass 5.3 TeV
	Excited quark $b^* \rightarrow bg$	-	1 b, 1 j	-	36.1	b^* mass 2.6 TeV
	Excited lepton ℓ^*	3 e, μ	-	-	20.3	ℓ^* mass 3.0 TeV
	Excited lepton ν^*	3 e, μ, τ	-	-	20.3	ν^* mass 1.6 TeV
Other	Type III Seesaw	1 e, μ	$\geq 2 j$	Yes	79.8	N^0 mass 560 GeV
	LRSM Majorana ν	2 e, μ	2 j	-	20.3	N^0 mass 2.0 TeV
	Higgs triplet $H^{++} \rightarrow \ell\ell$	2,3,4 e, μ (SS)	-	-	36.1	H^{++} mass 870 GeV
	Higgs triplet $H^{++} \rightarrow \ell\tau$	3 e, μ, τ	-	-	20.3	H^{++} mass 400 GeV
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV
	Multi-charged particles	-	-	-	20.3	multi-charged particle mass 785 GeV
	Magnetic monopoles	-	-	-	7.0	monopole mass 1.34 TeV

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

Mass limits for non-SUSY particles

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

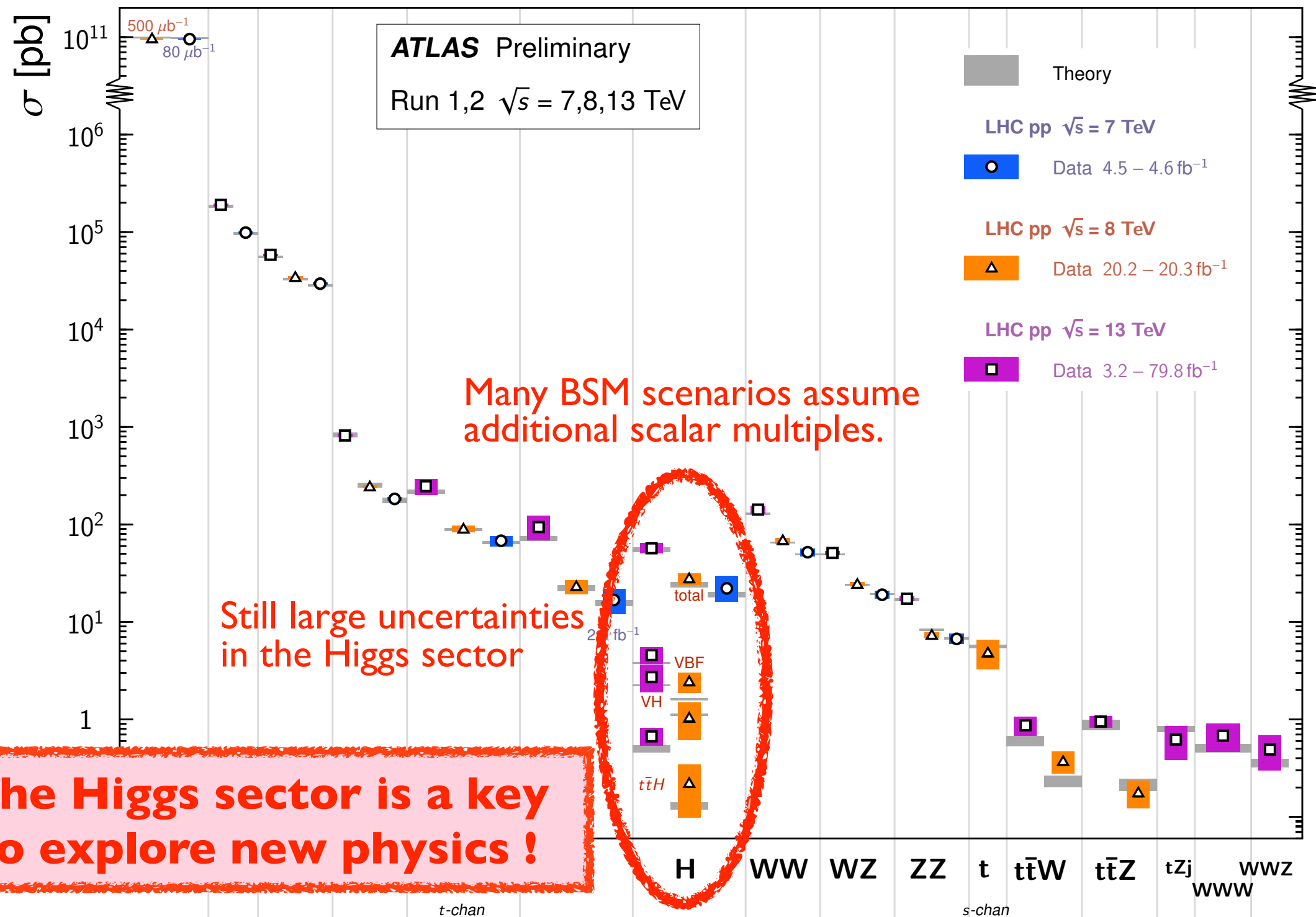
Status: July 2018

ATLAS Preliminary
 $\int \mathcal{L} dt = (3.2 - 79.8) fb^{-1}$
 $\sqrt{s} = 8, 13$ TeV

Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L} dt [fb^{-1}]$	Limit	Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1-4 j	Yes	36.1	M_0 7.7 TeV
	ADD non-resonant $\gamma\gamma$	2 γ	-	-	36.7	M_2 8.6 TeV
	ADD OBH	-	2 j	-	37.0	M_{BH} 8.9 TeV
	ADD BH high Σp_T	$\geq 1 e, \mu$	$\geq 2 j$	-	3.2	M_{BH} 8.2 TeV
	ADD BH multijet	-	$\geq 3 j$	-	3.6	M_{BH} 9.55 TeV
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2 γ	-	-	36.7	G_{KK} mass 4.1 TeV
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	G_{KK} mass 2.3 TeV
	Bulk RS $g_{KK} \rightarrow t\bar{t}$	1 e, μ	$\geq 1 b, \geq 1 J/2 J$	Yes	36.1	g_{KK} mass 3.8 TeV
	ZUED / RPP	1 e, μ	$\geq 2 b, \geq 3 j$	Yes	36.1	KK mass 1.8 TeV
	Gauge bosons	SSM $Z' \rightarrow \ell\ell$	2 e, μ	-	-	36.1
SSM $Z' \rightarrow \tau\tau$		2 τ	-	-	36.1	Z' mass 2.42 TeV
Leptophobic $Z' \rightarrow b\bar{b}$		-	2 b	-	36.1	Z' mass 2.1 TeV
Leptophobic $Z' \rightarrow t\bar{t}$		1 e, μ	$\geq 1 b, \geq 1 J/2 J$	Yes	36.1	Z' mass 3.0 TeV
CI	CI $qqqq$	-	2 j	-	37.0	A 21.8 TeV η_{LL}
	CI $\ell\ell qq$	2 e, μ	-	-	36.1	A 40.0 TeV η_{LL}
	CI $tttt$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	A 2.57 TeV
	Axial-vector mediator (Dirac DM)	0 e, μ	1-4 j	Yes	36.1	M_{med} 1.55 TeV
	Colored scalar mediator (Dirac DM)	0 e, μ	1-4 j	Yes	36.1	M_{med} 1.67 TeV
	VV $\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, $\leq 1 j$	Yes	3.2	M_s 700 GeV
LQ	Scalar LQ 1st gen	2 e	$\geq 2 j$	-	3.2	LQ mass 1.1 TeV
	Scalar LQ 2nd gen	2 e, μ	$\geq 2 j$	-	3.2	LQ mass 1.05 TeV
	Scalar LQ 3rd gen	1 e, μ	$\geq 1 b, \geq 3 j$	Yes	20.3	LQ mass 640 GeV
Excited fermions/heavy quarks	VLQ $TT \rightarrow Ht/Zt/Wb + X$	multi-channel	-	-	36.1	T mass 1.37 TeV
	VLQ $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV
	VLQ $T_{5/3} T_{5/3} / T_{5/3} \rightarrow Wt + X$	2(SS) $\geq 3 e, \mu \geq 1 b, \geq 1 j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	
	VLQ $Y \rightarrow Wb + X$	1 e, μ	$\geq 1 b, \geq 1 j$			

LHC data \approx Standard Model (SM)

Standard Model Total Production Cross Section Measurements *Status: March 2019*



Non-minimal Higgs sector

- HSM: Higgs singlet model (a real singlet scalar)

$$V(\Phi, S) = m_\Phi^2 |\Phi|^2 + \lambda |\Phi|^4 + \mu_{\Phi S} |\Phi|^2 S + \lambda_{\Phi S} |\Phi|^2 S^2 + t_S S + m_S^2 S^2 + \mu_S S^3 + \lambda_S S^4$$

[free parameters] $m_H, M^2 (\equiv 2m_S^2), \mu_S, \lambda_S, \alpha$

- THDM: Two Higgs doublet model

$$V(\Phi_1, \Phi_2) = m_1^2 |\Phi_1|^2 + m_2^2 |\Phi_2|^2 - m_3^2 (\Phi_1^\dagger \Phi_2 + \text{h.c.}) \\ + \frac{1}{2} \lambda_1 |\Phi_1|^4 + \frac{1}{2} \lambda_2 |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 |\Phi_1^\dagger \Phi_2|^2 + \frac{1}{2} \lambda_5 [(\Phi_1^\dagger \Phi_2)^2 + \text{h.c.}]$$

[free parameters] $m_H, m_A, m_{H^\pm}, M^2 (\equiv m_3^2 / s_\beta c_\beta), \tan \beta, s_{\beta-\alpha} (\geq 0), \text{Sign}(c_{\beta-\alpha})$

- 
- additional Higgs bosons (H, A, H[±], ...)
 - deviations of the h(125) couplings from the SM

Kanemura, Kikuchi, KM, Sakurai, Yagyu
H-COUP [1803.01456, 1906.10070]

Especially, charged Higgs bosons can provide striking signals of an extended Higgs sector.

Contents of the talk

1. Introduction
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 - Feynman rules
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 - productions
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 - signal sensitivity at the LHC and beyond
4. Summary

Feynman Rules in THDMs (Gauge)

Vertices	$g_{\phi V_1 V_2}$
$hW_\mu^+ W_\nu^-$	$\frac{g^2}{2} v s_{\beta-\alpha}$
$HW_\mu^+ W_\nu^-$	$\frac{g^2}{2} v c_{\beta-\alpha}$
$hZ_\mu Z_\nu$	$\frac{g_Z^2}{4} v s_{\beta-\alpha}$
$HZ_\mu Z_\nu$	$\frac{g_Z^2}{4} v c_{\beta-\alpha}$
$G^\pm Z_\mu W_\nu^\mp$	$-\frac{gg_Z}{2} v s_W^2$
$G^\pm A_\mu W_\nu^\mp$	$\frac{eg}{2} v$

mixing between $h(125)$ and H

$$s_{\beta-\alpha} \equiv \sin(\beta - \alpha)$$

* alignment limit $s_{\beta-\alpha} = 1$

$h(125) = \text{SM-like}$

Vertices	$g_{\phi_1 \phi_2 V}$
$hG^\pm W_\mu^\mp$	$\mp i \frac{g}{2} s_{\beta-\alpha}$
$HG^\pm W_\mu^\mp$	$\mp i \frac{g}{2} c_{\beta-\alpha}$
$G^0 G^\pm W_\mu^\mp$	$-\frac{g}{2}$
$hH^\pm W_\mu^\mp$	$\mp i \frac{g}{2} c_{\beta-\alpha}$
$HH^\pm W_\mu^\mp$	$\pm i \frac{g}{2} s_{\beta-\alpha}$
$AH^\pm W_\mu^\mp$	$-\frac{g}{2}$
$G^+ G^- Z_\mu$	$i \frac{g_Z}{2} c_{2W}$
$H^+ H^- Z_\mu$	$i \frac{g_Z}{2} c_{2W}$
$hG^0 Z_\mu$	$-\frac{g_Z}{2} s_{\beta-\alpha}$
hAZ_μ	$-\frac{g_Z}{2} c_{\beta-\alpha}$
$HG^0 Z_\mu$	$-\frac{g_Z}{2} c_{\beta-\alpha}$
HAZ_μ	$\frac{g_Z}{2} s_{\beta-\alpha}$
$G^+ G^- A_\mu$	ie
$H^+ H^- A_\mu$	ie

Vertices	$g_{\phi_1 \phi_2 V_1 V_2}$	Vertices	$g_{\phi_1 \phi_2 V_1 V_2}$
$hhW_\mu^+ W_\nu^-$	$\frac{g^2}{4}$	$G^\pm G^0 W_\mu^\mp Z_\nu$	$\pm i \frac{gg_Z}{2} s_W^2$
$HHW_\mu^+ W_\nu^-$	$\frac{g^2}{4}$	$H^\pm A W_\mu^\mp Z_\nu$	$\pm i \frac{gg_Z}{2} s_W^2$
$AAW_\mu^+ W_\nu^-$	$\frac{g^2}{4}$	$G^\pm H W_\mu^\mp Z_\nu$	$-\frac{gg_Z}{2} s_W^2 c_{\beta-\alpha}$
$G^0 G^0 W_\mu^+ W_\nu^-$	$\frac{g^2}{4}$	$H^\pm h W_\mu^\mp Z_\nu$	$-\frac{gg_Z}{2} s_W^2 c_{\beta-\alpha}$
$G^+ G^- W_\mu^+ W_\nu^-$	$\frac{g^2}{2}$	$G^\pm h W_\mu^\mp Z_\nu$	$-\frac{gg_Z}{2} s_W^2 s_{\beta-\alpha}$
$H^+ H^- W_\mu^+ W_\nu^-$	$\frac{g^2}{2}$	$H^\pm H W_\mu^\mp Z_\nu$	$\frac{gg_Z}{2} s_W^2 s_{\beta-\alpha}$
$hhZ_\mu Z_\nu$	$\frac{g_Z^2}{8}$	$H^\pm A W_\mu^\mp A_\nu$	$\mp \frac{eg}{2}$
$HHZ_\mu Z_\nu$	$\frac{g_Z^2}{8}$	$G^\pm G^0 W_\mu^\mp A_\nu$	$\mp \frac{eg}{2}$
$AAZ_\mu Z_\nu$	$\frac{g_Z^2}{8}$	$H^\pm h W_\mu^\mp A_\nu$	$\frac{eg}{2} c_{\beta-\alpha}$
$G^0 G^0 Z_\mu Z_\nu$	$\frac{g_Z^2}{8}$	$G^\pm H W_\mu^\mp A_\nu$	$\frac{eg}{2} c_{\beta-\alpha}$
$G^+ G^- Z_\mu Z_\nu$	$\frac{g_Z^2}{4} c_{2W}^2$	$G^+ G^- A_\mu Z_\nu$	$eg_Z c_{2W}$
$H^+ H^- Z_\mu Z_\nu$	$\frac{g_Z^2}{4} c_{2W}^2$	$H^+ H^- A_\mu Z_\nu$	$eg_Z c_{2W}$
$G^+ G^- A_\mu A_\nu$	e^2	$G^\pm h W_\mu^\mp A_\nu$	$\frac{eg}{2} s_{\beta-\alpha}$
$H^+ H^- A_\mu A_\nu$	e^2	$H^\pm H W_\mu^\mp A_\nu$	$-\frac{eg}{2} s_{\beta-\alpha}$

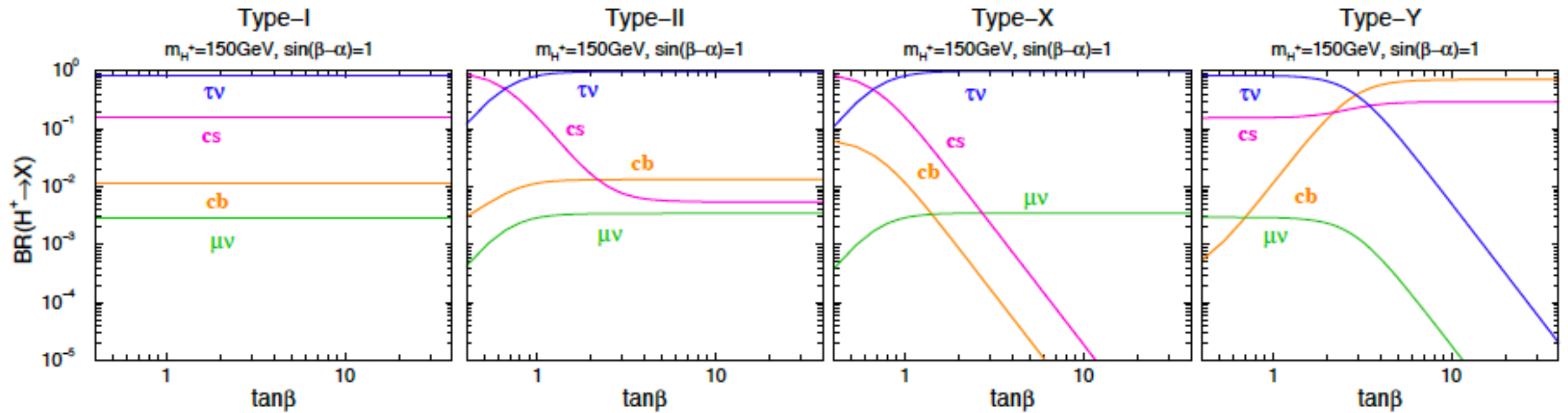
Feynman Rules in THDMs (Yukawa)

$$-\mathcal{L}_Y = Y_u \bar{Q}_L i\sigma_2 \Phi_u^* u_R + Y_d \bar{Q}_L \Phi_d d_R + Y_e \bar{L}_L \Phi_e e_R + \text{h.c.}$$

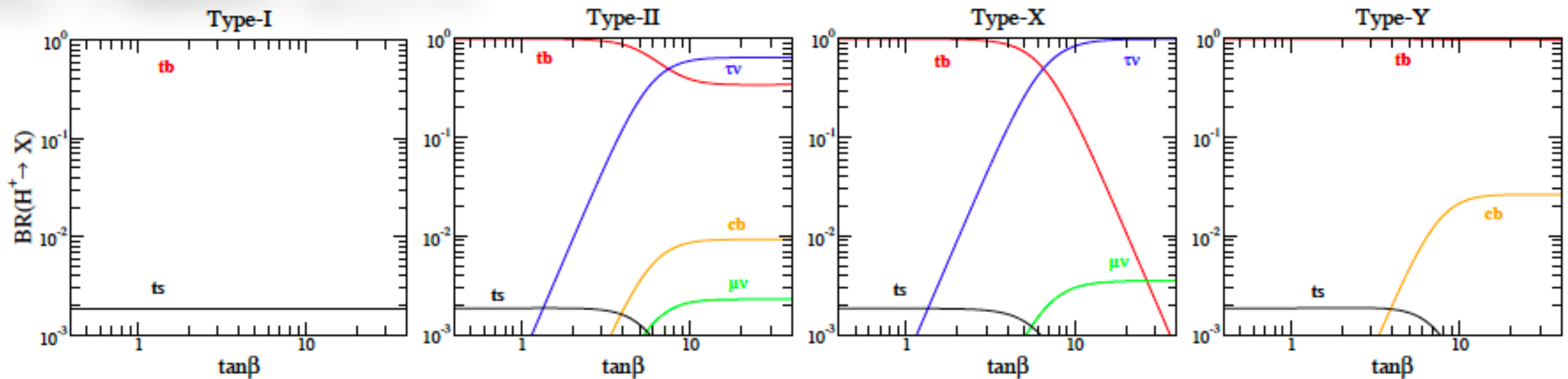
$$+ \frac{\sqrt{2}}{v} [V_{ud} \bar{u} (m_d \xi_d P_R - m_u \xi_u P_L) d H^+ + m_e \xi_e \bar{\nu} P_R e H^+ + \text{h.c.}]$$

	Z ₂ charge							Mixing factor		
	Φ ₁	Φ ₂	Q _L	L _L	u _R	d _R	e _R	ξ _u	ξ _d	ξ _e
Type-I	+	-	+	+	-	-	-	cot β	cot β	cot β
Type-II	+	-	+	+	-	+	+	cot β	-tan β	-tan β
Type-X	+	-	+	+	-	-	+	cot β	cot β	-tan β
Type-Y	+	-	+	+	-	+	-	cot β	-tan β	cot β

Branching ratios ($m_{H^+} < m_t$ or $m_{H^+} > m_t$)

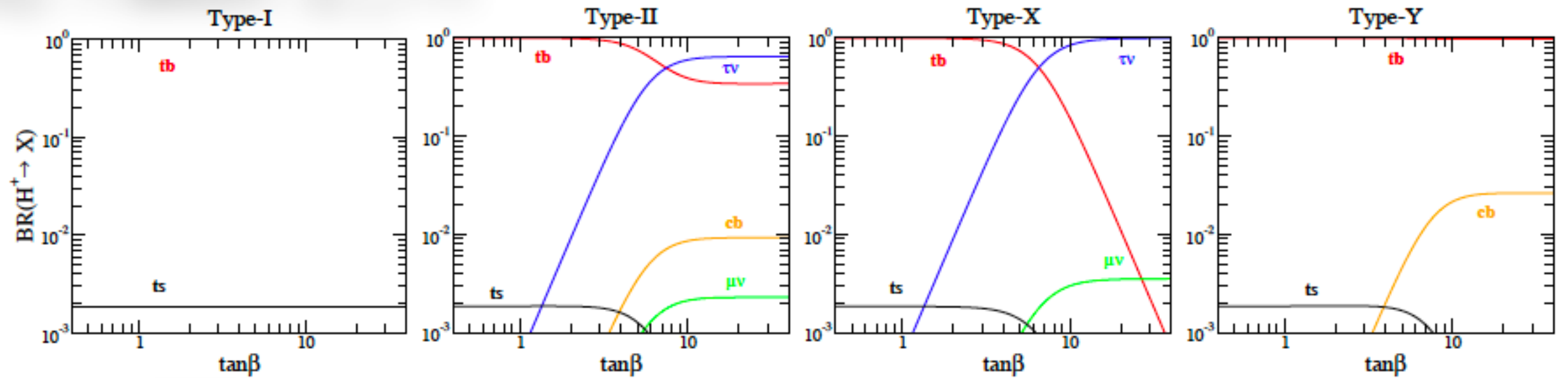


$m_{H^+} = 200\text{GeV}, s_{\beta-\alpha} = 1$

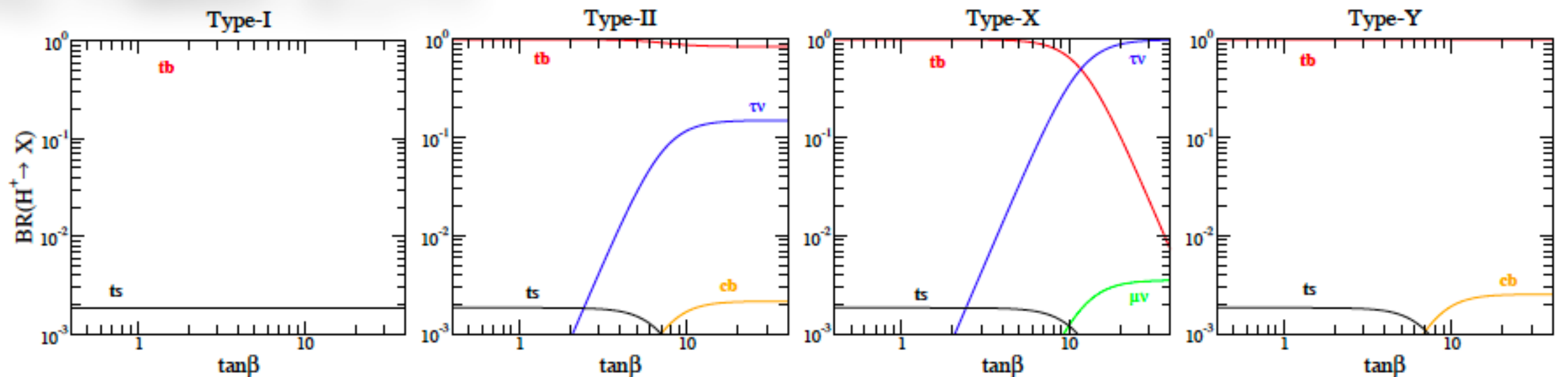


Branching ratios ($\sin(\beta - \alpha) = 1$)

$m_{H^+} = 200\text{GeV}, s_{\beta-\alpha} = 1$

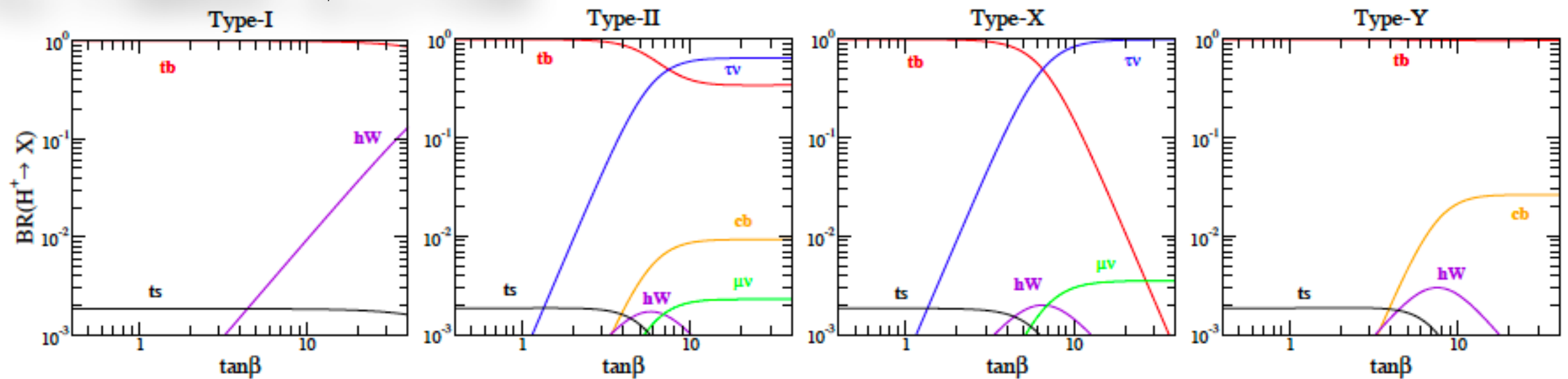


$m_{H^+} = 400\text{GeV}, s_{\beta-\alpha} = 1$

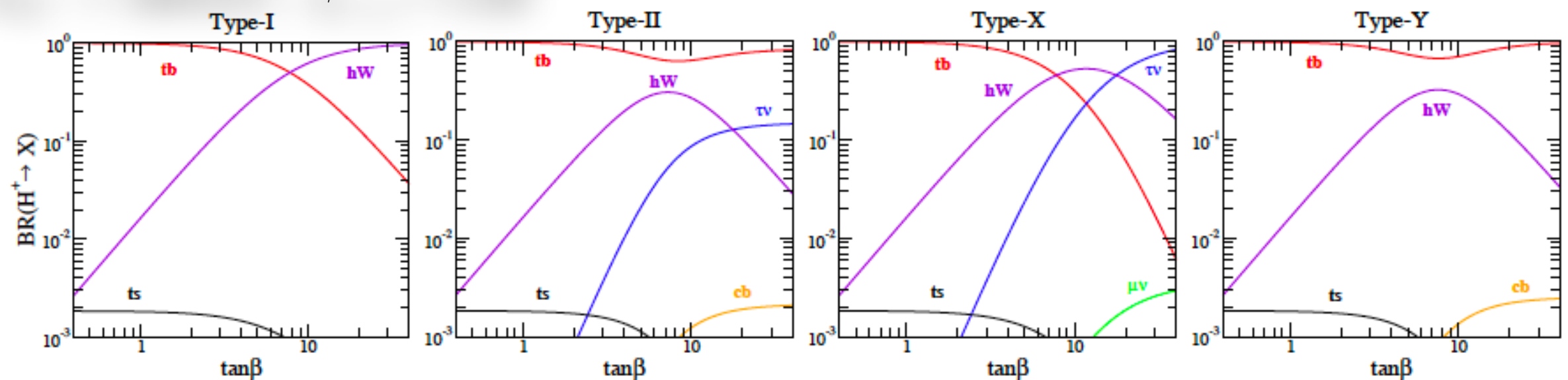


Branching ratios ($\sin(\beta - \alpha) \neq 1$)

$m_{H^+} = 200\text{GeV}, s_{\beta-\alpha} = 0.99$



$m_{H^+} = 400\text{GeV}, s_{\beta-\alpha} = 0.99$

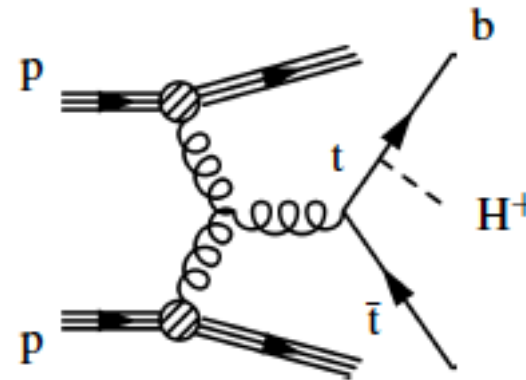


Charged Higgs boson productions

- for $m_{H^+} < m_t$

- top pair

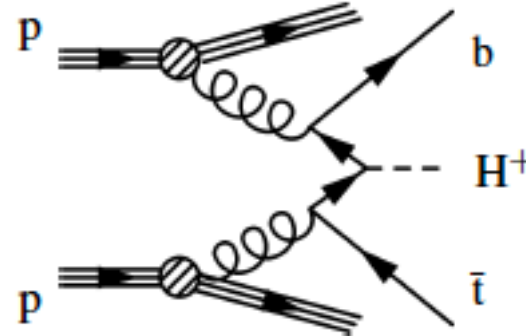
$$pp \rightarrow t\bar{t}, t \rightarrow H^+ b$$



- for $m_{H^+} > m_t$

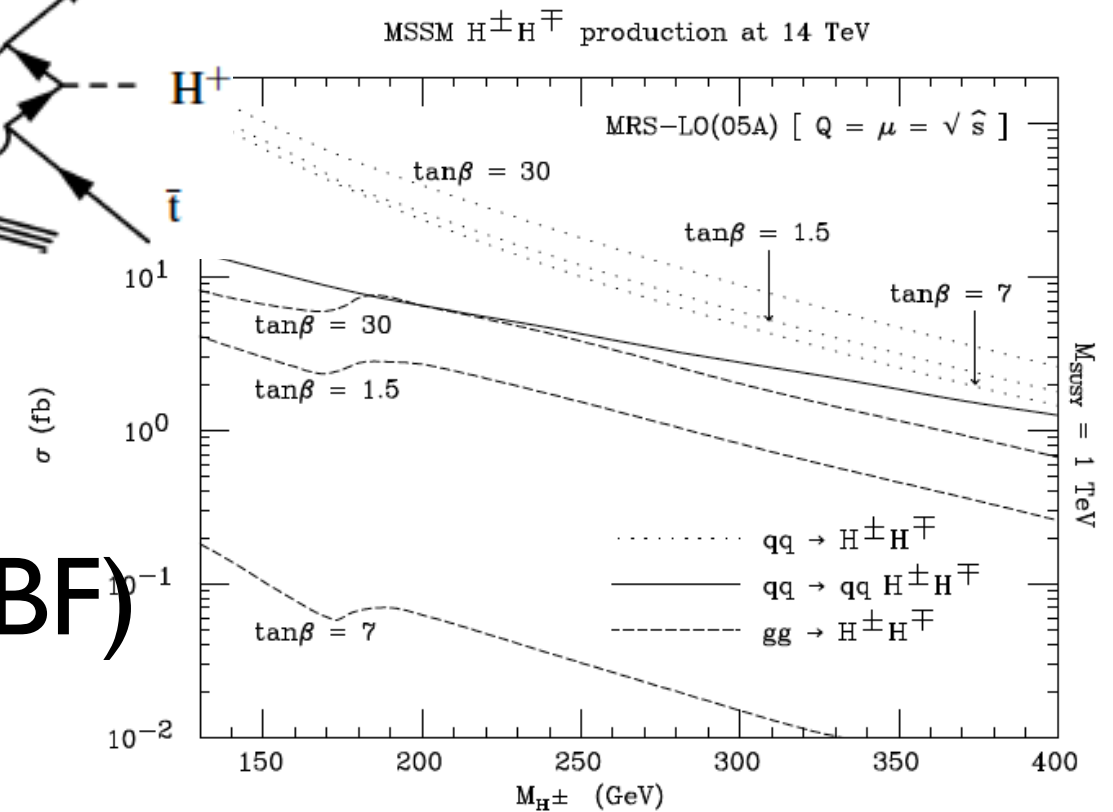
- single production

$$pp(g\bar{b}) \rightarrow H^+ \bar{t}$$

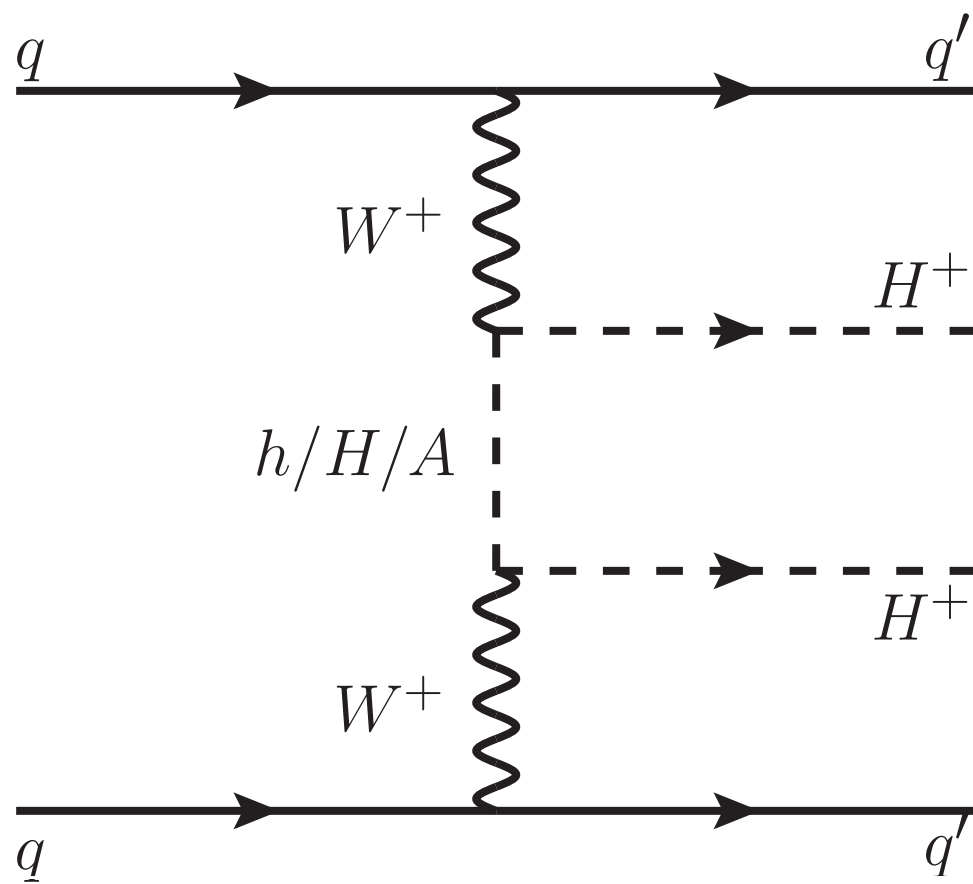


- pair production (DY/VBF)

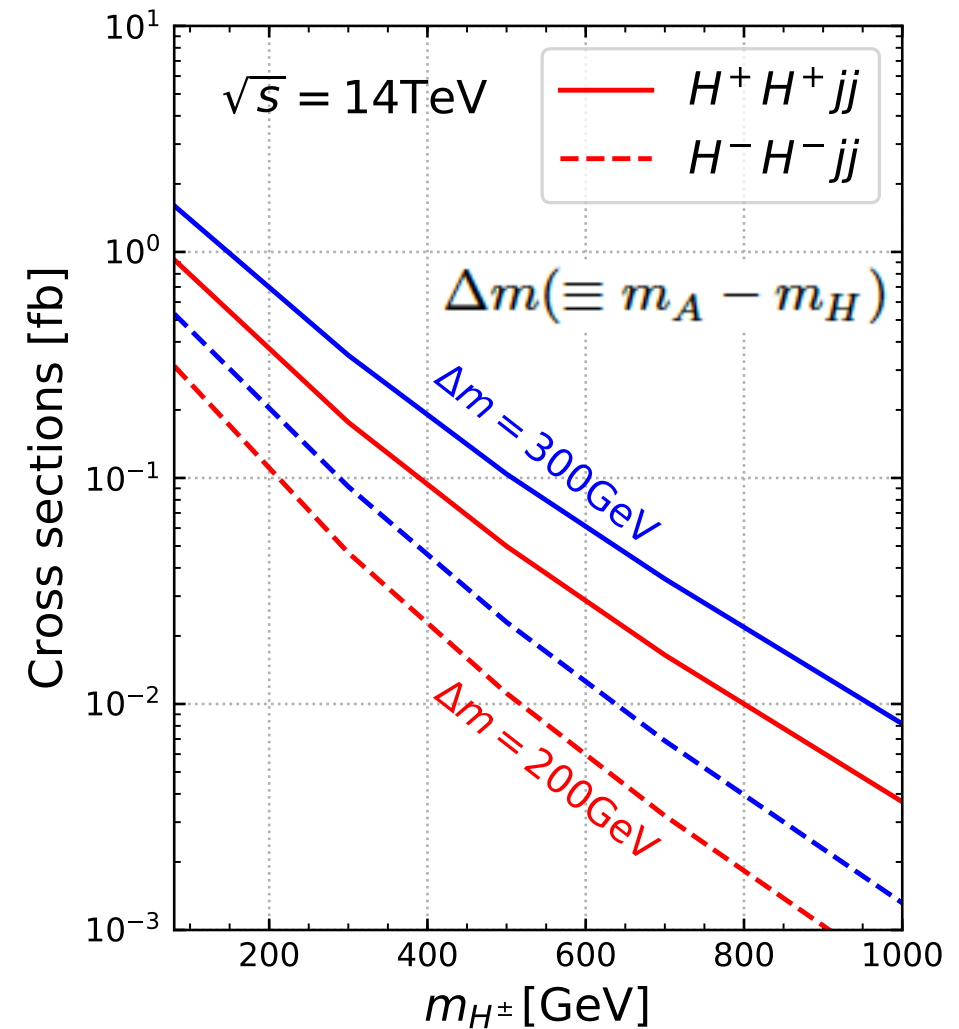
Alves, Plehn [hep-ph/0503135]
Moretti [hep-ph/0102116]



Same-sign pair production of charged Higgs bosons



Aiko, Kanemura, Mawatari [1906.09101]



$$\Delta m \rightarrow 0 \Rightarrow \sigma \rightarrow 0$$

symmetry?

Symmetry of the Higgs potential

$$V(\Phi_1, \Phi_2) = \sum_{i=1,2} m_i^2 |\Phi_i|^2 - (m_3^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}) \\ + \sum_{i=1,2} \left\{ \frac{1}{2} \lambda_i |\Phi_i|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 |\Phi_1^\dagger \Phi_2|^2 + \left[\frac{1}{2} \lambda_5 (\Phi_1^\dagger \Phi_2)^2 + (\lambda_6 |\Phi_1|^2 + \lambda_7 |\Phi_2|^2) \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] \right\}$$

- suppressed FCNC \rightarrow **Z₂ symmetry** $\rightarrow \lambda_6 = \lambda_7 = 0$
- **h(125) \sim SM-like** \rightarrow **alignment** $\rightarrow \lambda_1 = \lambda_2 = \lambda_3 + \lambda_4 + \lambda_5$

$$V_4 = \frac{1}{2} c_1 (|\Phi_1|^2 + |\Phi_2|^2)^2 \quad \leftarrow O(8) \\ + \frac{1}{2} c_2 (|\Phi_1|^2 - |\Phi_2|^2)^2 \quad \leftarrow O(4) \times O(4)' \quad \begin{aligned} c_1 &= \lambda_3 + (\lambda_4 + \lambda_5)/2 \\ c_2 &= c_3 = (\lambda_4 + \lambda_5)/2 = (m_H^2 - m_{H^\pm}^2)/v^2 \\ c_4 &= -(\lambda_4 - \lambda_5)/2 = (m_{H^\pm}^2 - m_A^2)/v^2 \end{aligned} \\ + \frac{1}{2} c_3 (\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1)^2 \quad \leftarrow O(4) \\ + \frac{1}{2} c_4 (\Phi_1^\dagger \Phi_2 - \Phi_2^\dagger \Phi_1)^2 \quad \leftarrow O(4)$$

- **$\rho \sim 1$** \rightarrow **custodial symmetry** $O(4) \simeq SU(2)_L \times SU(2)_R \rightarrow SU(2)_V \rightarrow$

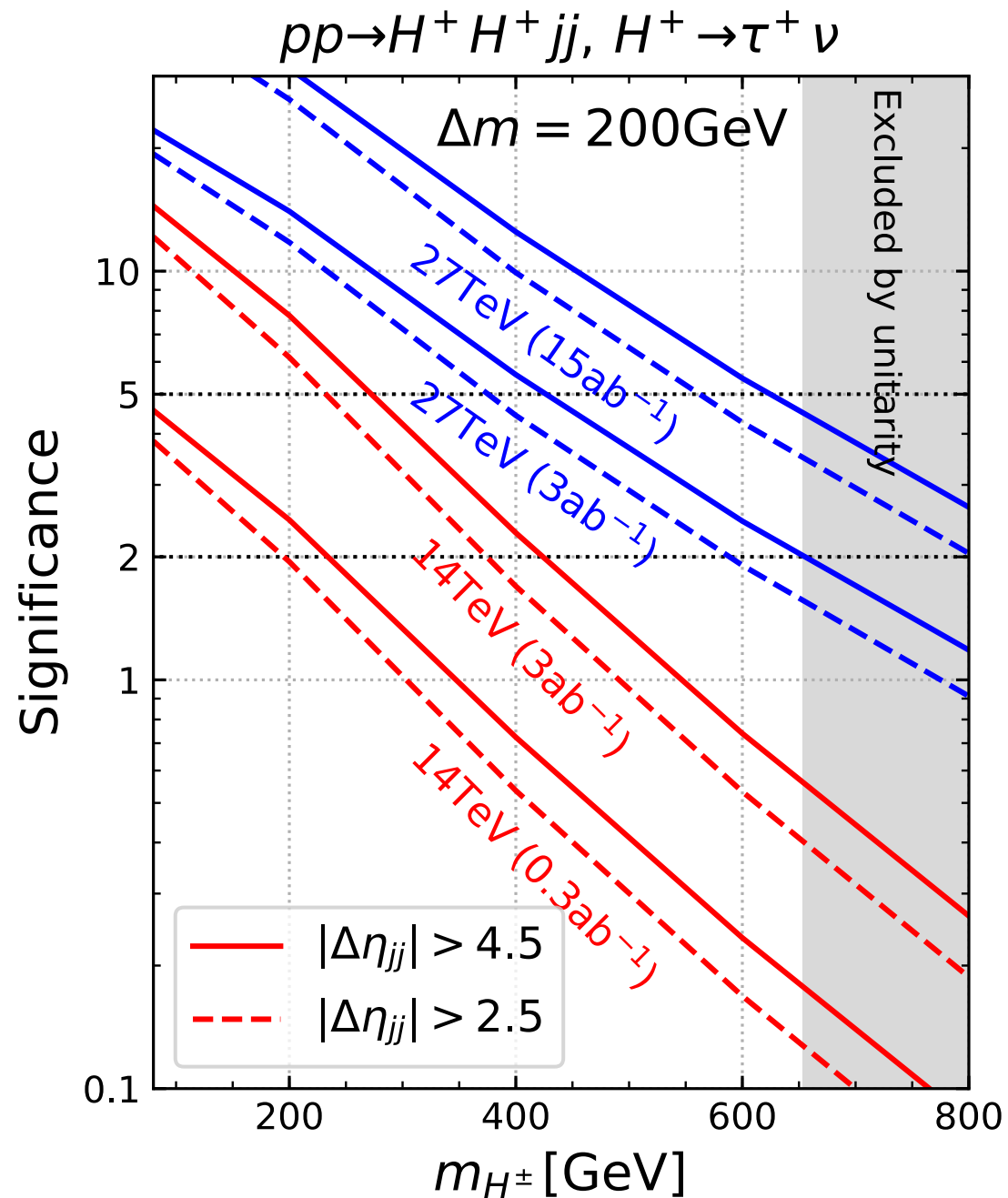
$$\begin{aligned} \text{(Case I : } m_{H^\pm}^2 = m_A^2) \quad c_1 = m_h^2/v^2 - \eta, \quad c_2 = c_3 = \eta, \quad c_4 = 0 \\ \text{(Case II : } m_{H^\pm}^2 = m_H^2) \quad c_1 = m_h^2/v^2, \quad c_2 = c_3 = 0, \quad c_4 = \eta \end{aligned} \quad \eta = (m_H^2 - m_A^2)/v^2$$

$V_4 \text{ respects } \begin{cases} O(8) \text{ if } \eta=0 \\ O(4) \text{ if } \eta \neq 0 \end{cases}$

 \longleftrightarrow

$\sigma(H^\pm H^\pm jj) \propto \eta$

Significance ($H^+ \rightarrow \tau\nu$)



- same-sign tau-pair with 2 forward jets

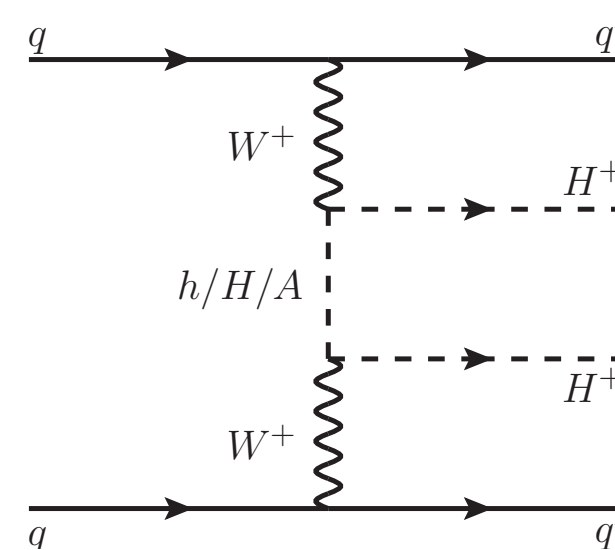
$$s = L \sigma_{pp \rightarrow H^+ H^+ jj}^{\text{VBF}} (B_{H^+ \rightarrow \tau\nu})^2 \epsilon_{\text{sel}}^\tau (\epsilon_\tau)^2$$

$$b = L \sigma_{pp \rightarrow W^+ W^+ jj}^{\text{VBF}} (B_{W^+ \rightarrow \tau\nu})^2 \epsilon_{\text{sel}}^\tau (\epsilon_\tau)^2$$

* Significance ($H^+ \rightarrow t\bar{b}$) in backup.

Exploring the global symmetry structure of the Higgs potential via same-sign pair production of charged Higgs bosons

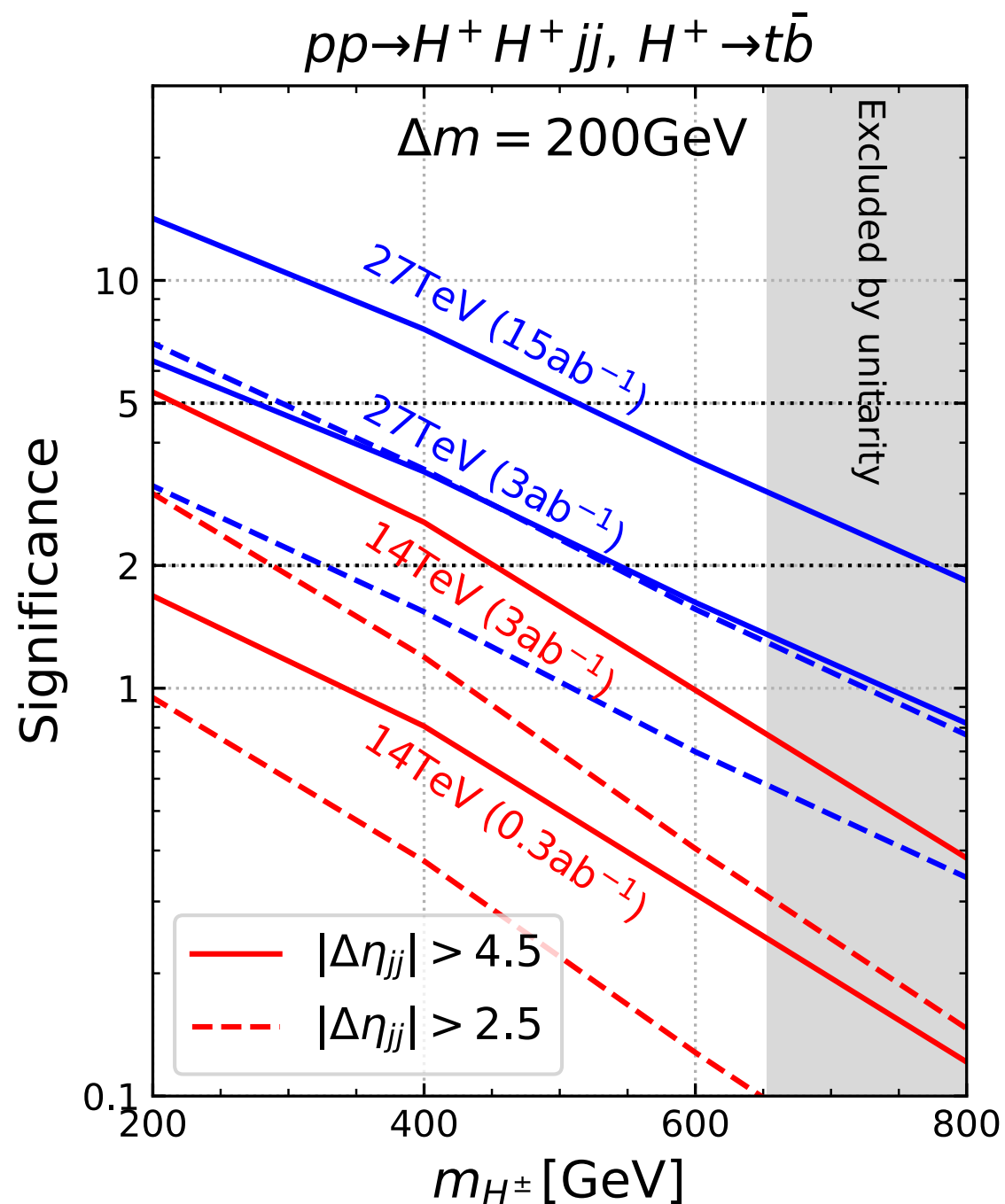
$$\begin{aligned}
 V_4 = & \frac{1}{2}c_1(|\Phi_1|^2 + |\Phi_2|^2)^2 && \leftarrow O(8) \\
 & + \frac{1}{2}c_2(|\Phi_1|^2 - |\Phi_2|^2)^2 && \leftarrow O(4) \times O(4)' \\
 & + \frac{1}{2}c_3(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1)^2 && \leftarrow O(4) \\
 & + \frac{1}{2}c_4(\Phi_1^\dagger \Phi_2 - \Phi_2^\dagger \Phi_1)^2 && \leftarrow O(4)
 \end{aligned}$$



- Charged Higgs bosons can provide striking signals of an extended Higgs sector.
- The same-sign pair production can be observed at the LHC and future higher-energy colliders.

backup

Significance ($H^+ \rightarrow t\bar{b}$)



- same-sign top-pair with 2 forward jets

$$s = L \sigma_{pp \rightarrow H^+ H^+ jj}^{\text{VBF}} (B_{H^+ \rightarrow t\bar{b}})^2 (B_{t \rightarrow bl+\nu})^2 \epsilon_{\text{sel}}^t (\epsilon_b)^2$$

$$b = L \sigma_{pp \rightarrow t\bar{t}t\bar{t}} (B_{t \rightarrow bl+\nu})^2 (B_{\bar{t} \rightarrow \bar{b}jj})^2 \epsilon_{\text{sel}}^t (\epsilon_b)^2$$

Cross sections

