2HDM @ a High Energy Muon Collider

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work in progress

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Outline

- Higgses in 2HDM
- Pair Production of BSM Higgs @ muon collider
- Fermion associated single production
- Conclusion

Why 2HDM?

Models with extended Higgs sector: arise in natural theories of EWSB

- Higgs sector of MSSM/NMSSM
- Generic 2HDM
- Little Higgs, twin Higgs ...
- Composite Higgs models ...

- SM+singlet: parametrized by a simple mixing parameter
- 2HDM: covers board class of known models
- Allow for convenient parametrization
- Many features shared by many extended EWSB sectors

2HDM Higgs Sector

- **Two Higgs Doublet Model (CP-conserving)**

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ (v_i + \phi_i^0 + iG_i)/\sqrt{2} \end{pmatrix}$$

$$v_u^2 + v_d^2 = v^2 = (246\text{GeV})^2$$
$$\tan\beta = v_u/v_d$$

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}, \quad \begin{aligned} A &= -G_1 \sin\beta + G_2 \cos\beta \\ H^\pm &= -\phi_1^\pm \sin\beta + \phi_2^\pm \cos\beta \end{aligned}$$

after EWSB, 5 physical Higgses

CP-even Higgses: h, H , CP-odd Higgs: A, Charged Higgses: $H^\pm$

- **Search for extra Higgses**
  - ➡ Precision Higgs study: couplings of the SM-like Higgs
  - ➡ Direct search of extra Higgses: direct evidence for BSM new physics

2HDM Higgs Sector

- **h/H VV coupling**

$$g_{H^0VV} = \frac{m_V^2}{v}\cos(\beta-\alpha), \quad g_{h^0VV} = \frac{m_V^2}{v}\sin(\beta-\alpha)$$

- **Higgs-Higgs-V coupling**

$$g_{AH^0Z} = -\frac{g\sin(\beta-\alpha)}{2\cos\theta_w}(p_{H^0}-p_A)^\mu, \quad g_{Ah^0Z} = \frac{g\cos(\beta-\alpha)}{2\cos\theta_w}(p_{h^0}-p_A)^\mu,$$

$$g_{H^\pm H^0W^\mp} = \frac{g\sin(\beta-\alpha)}{2}(p_{H^0}-p_{H^\pm})^\mu, \quad g_{H^\pm h^0W^\mp} = \frac{g\cos(\beta-\alpha)}{2}(p_{h^0}-p_{H^\pm})^\mu,$$

$$g_{H^\pm AW^\mp} = \frac{g}{2}(p_A-p_{H^\pm})^\mu,$$

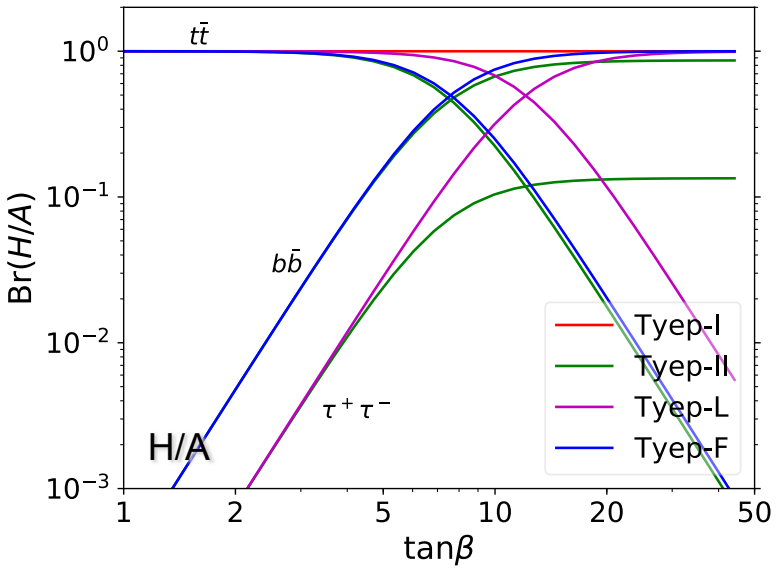
Two non-SM like Higgses have unsuppressed couplings to gauge boson.

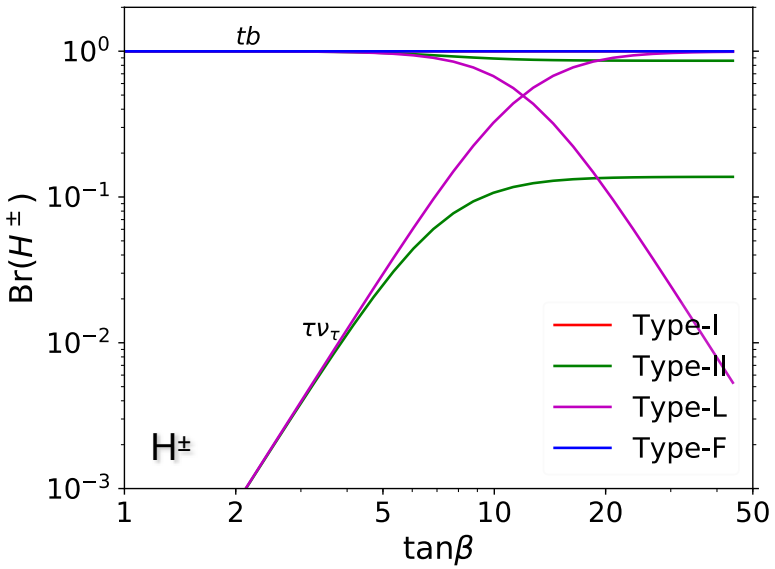
Alignment limit ◉ **h 125 GeV, cos(β-α)~0**

Four Types of 2HDMs

- **Flavor limits: Type I, Type II, lepton-specific, flipped,...**

Types	Φ_1	Φ_2	κ_A^u	κ_A^d	κ_A^e
Type-I		$u,\ d,\ \ell$	$\cot\beta$	$-\cot\beta$	$-\cot\beta$
Type-II	$d,\ \ell$	u	$\cot\beta$	$\tan\beta$	$\tan\beta$
Type-L	ℓ	$u,\ d,$	$\cot\beta$	$-\cot\beta$	$\tan\beta$
Type-F	d	$u,\ \ell$	$\cot\beta$	$\tan\beta$	$-\cot\beta$





Pair Production

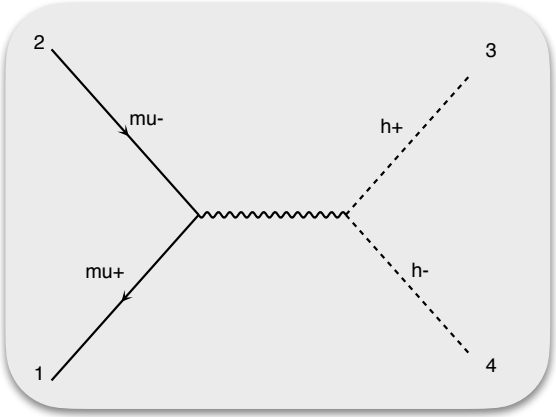
- **Pair production**

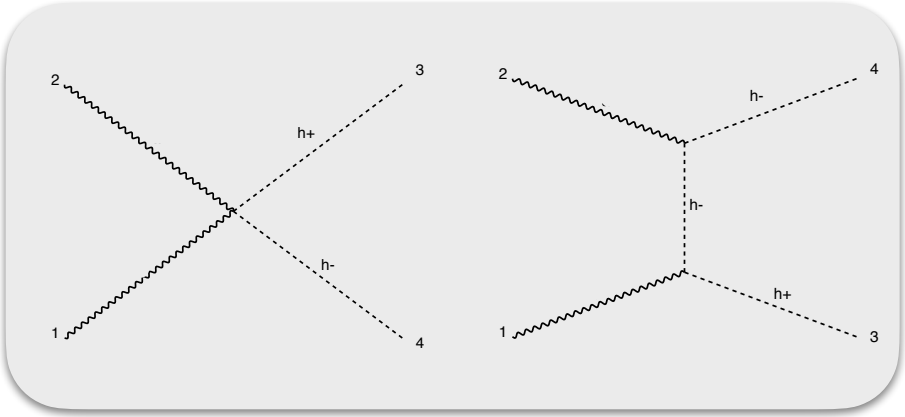
Annihilation

$$\mu^+\mu^- \to \gamma^*, Z^* \to H^+H^-$$
$$\mu^+\mu^- \to Z^* \to HA$$

VBF

$$\mu^+\mu^- \to V_1V_2 \to$$
$$H^+H^-,\ HA,\ H^\pm H(A), HH/AA$$





Pair Production

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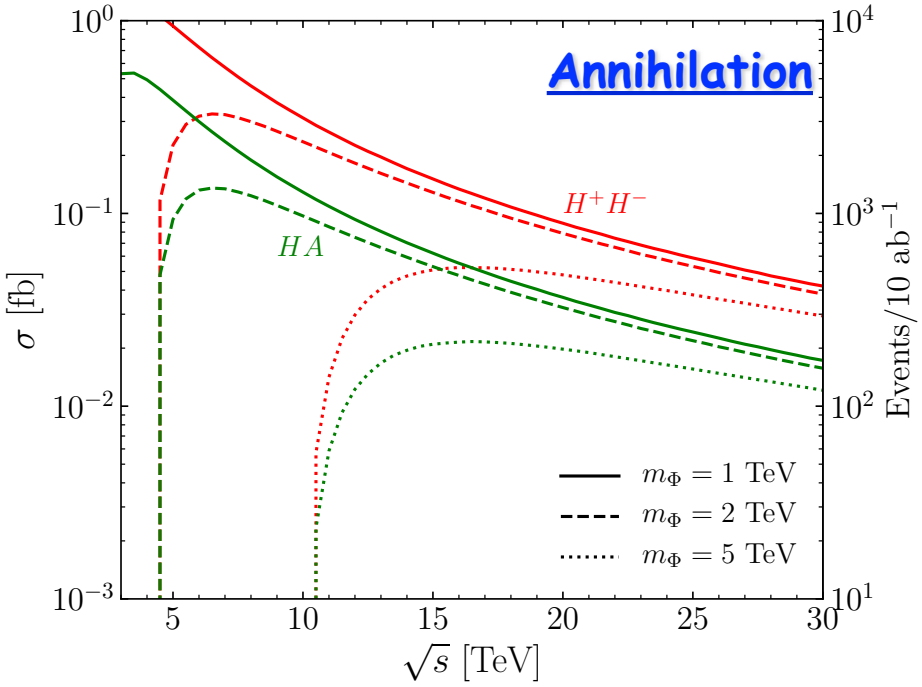

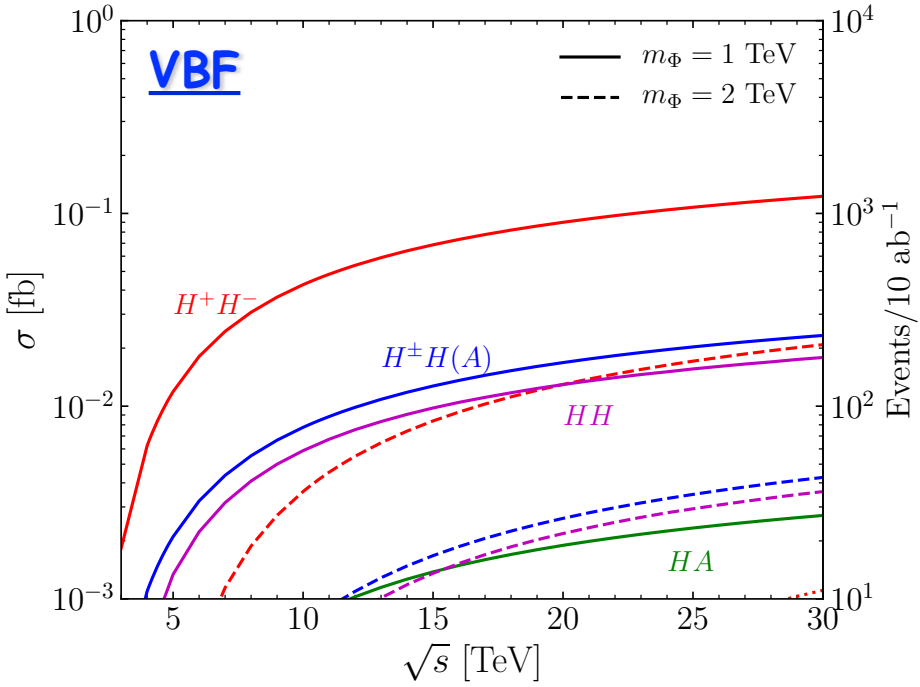

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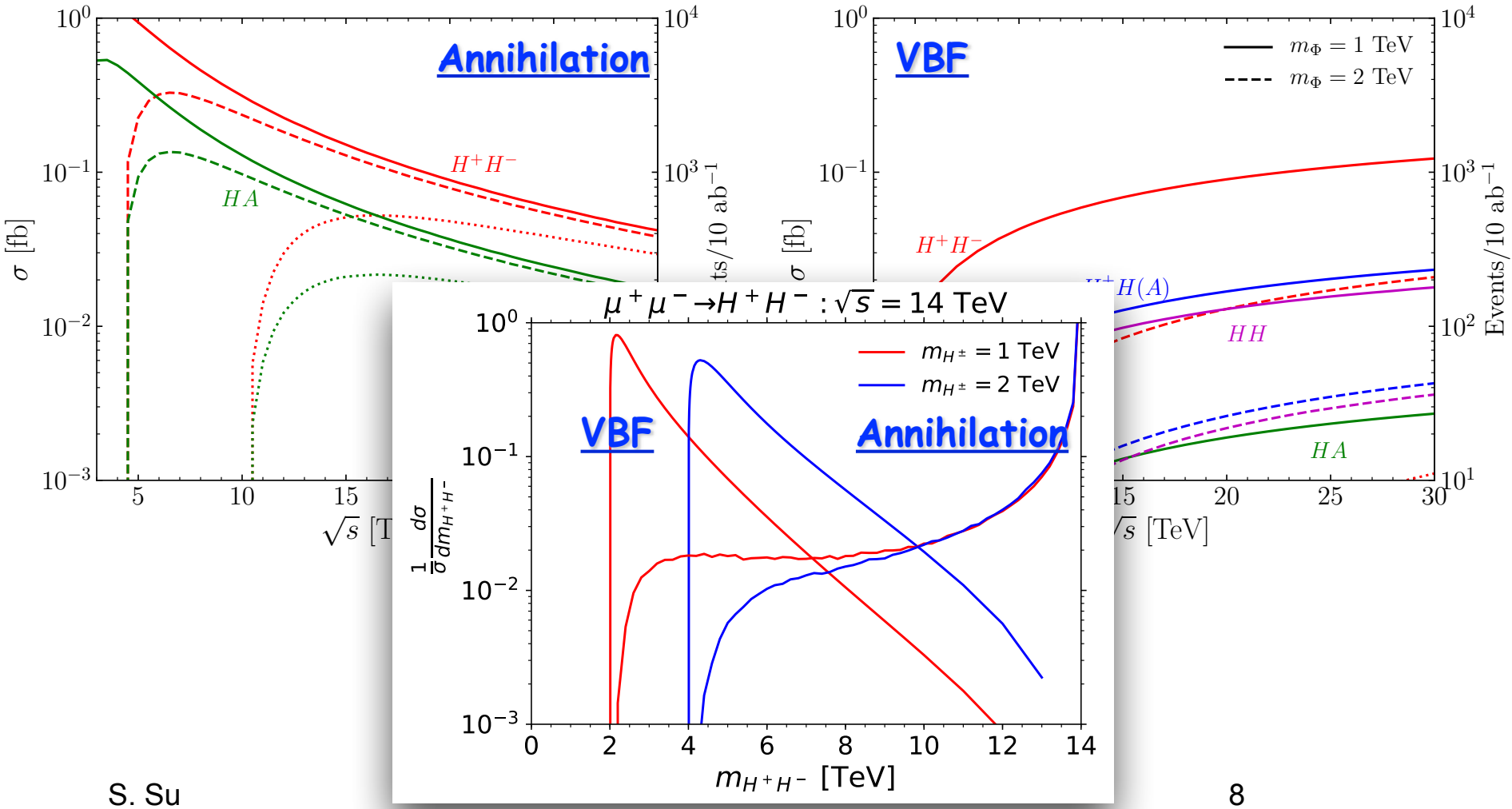
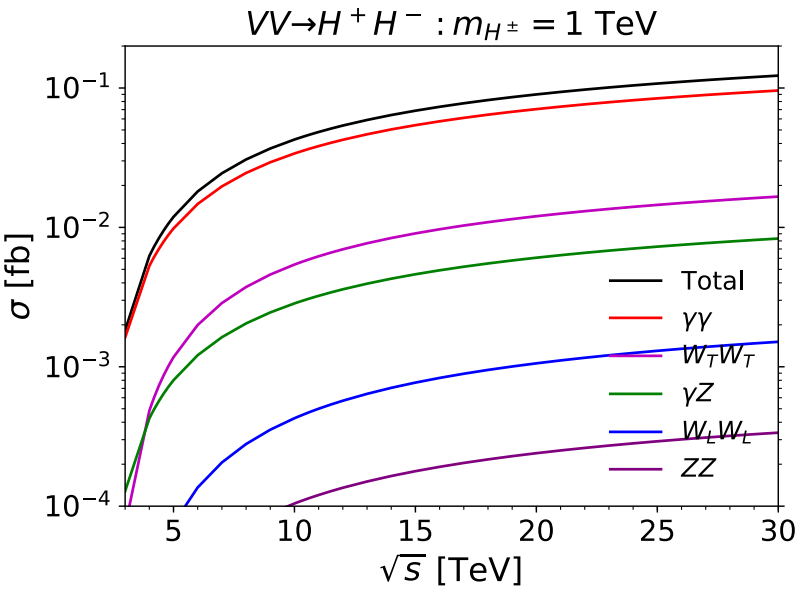
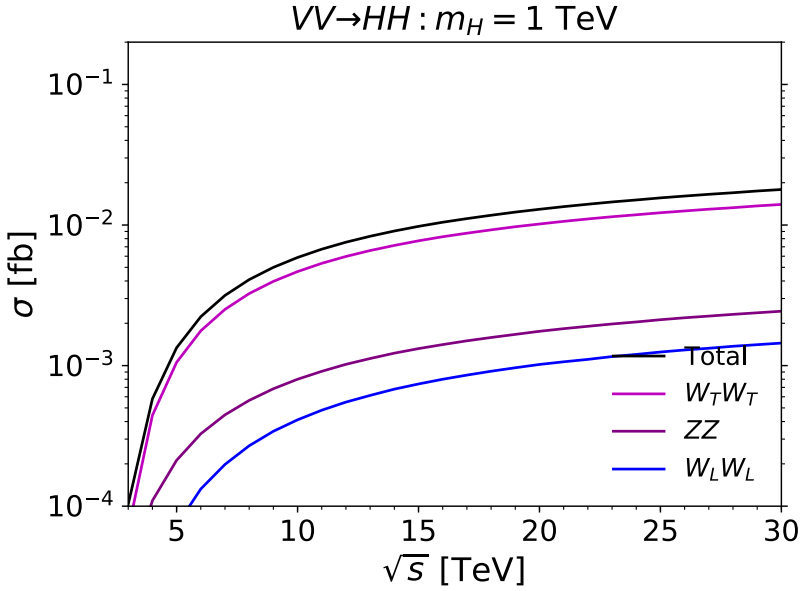
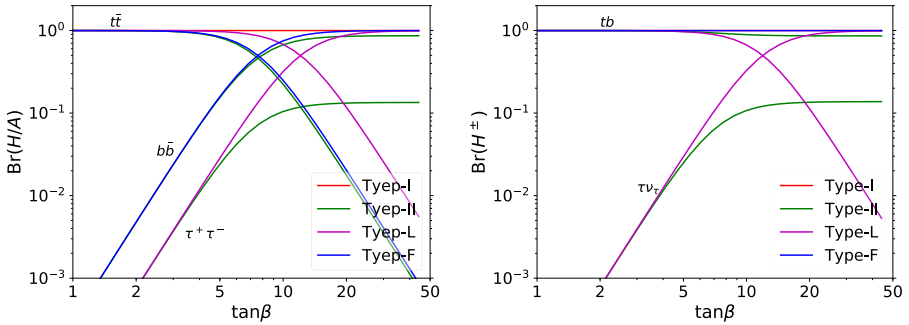


Four Types of 2HDMs





Distinguish 2HDMs



Hbb ∝ tan β **Hττ ∝ tan β**

	production	Type-I	Type-II	Type-F	Type-L
small $\tan\beta < 5$	H^+H^- $HA/HH/AA$ $H^\pm H/A$	$t\bar{b}, \bar{t}b$ $t\bar{t}, t\bar{t}$ $tb, t\bar{t}$			
intermediate $\tan\beta$	H^+H^- $HA/HH/AA$ $H^\pm H/A$	$t\bar{b}, \bar{t}b$ $t\bar{t}, t\bar{t}$ $tb, t\bar{t}$	$t\bar{t}, b\bar{b}$ $tb, t\bar{t};\ tb, b\bar{b}$		$tb, \tau\nu_\tau$ $t\bar{t}, \tau^+\tau^-$ $tb, t\bar{t};\ tb, \tau^+\tau^-;$ $\tau\nu_\tau, t\bar{t};\ \ \tau\nu_\tau, \tau^+\tau^-$
large $\tan\beta > 10$	H^+H^- $HA/HH/AA$ $H^\pm H/A$	$t\bar{b}, \bar{t}b$ $t\bar{t}, t\bar{t}$ $tb, t\bar{t}$	$tb, tb(\tau\nu_\tau)$ $b\bar{b}, b\bar{b}(\tau^+\tau^-)$ $tb(\tau\nu_\tau), b\bar{b}(\tau^+\tau^-)$	$t\bar{b}, \bar{t}b$ $b\bar{b}, b\bar{b}$ $tb, b\bar{b}$	$\tau^+\nu_\tau, \tau^-\nu_\tau$ $\tau^+\tau^-, \tau^+\tau^-$ $\tau^\pm\nu_\tau, \tau^+\tau^-$

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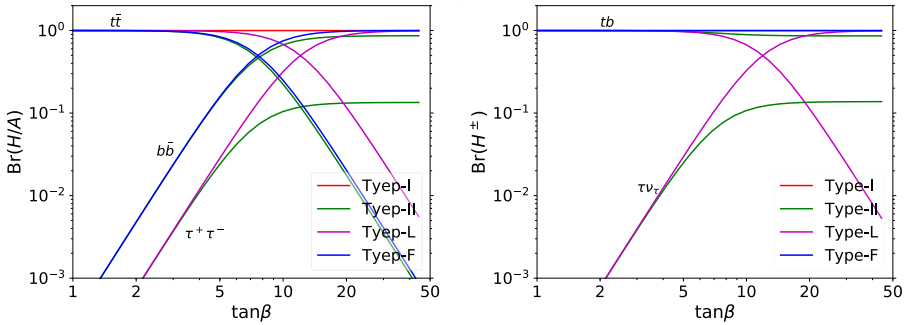

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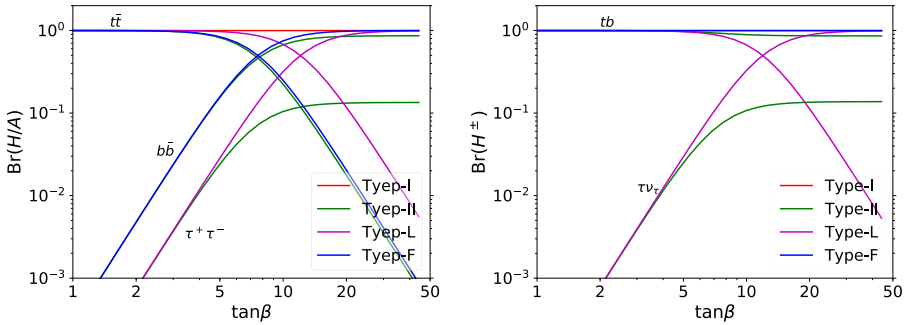

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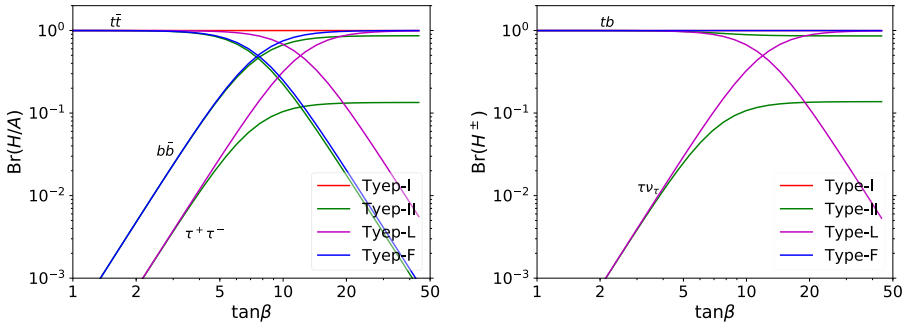

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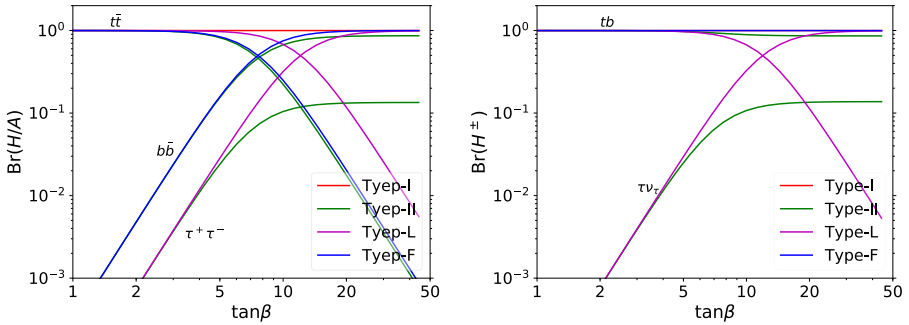

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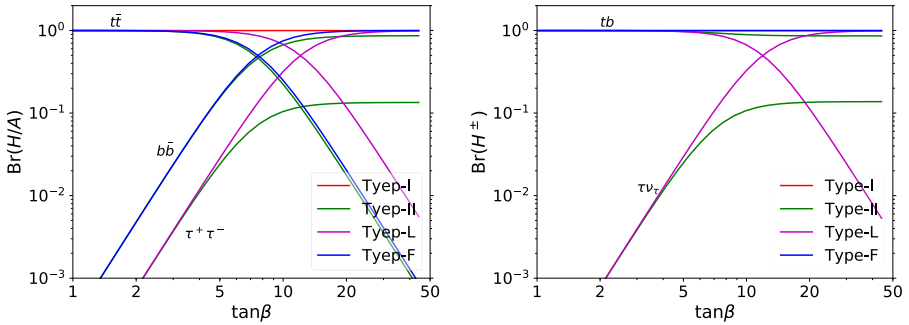

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Hττ ∝ tan β

SM Backgrounds

- **Signal: four 3rd generation quarks/leptons**
- **SM backgrounds**

$$p_T(t) > 100 \text{ GeV}, \quad p_T(b) > m_\Phi/5, \quad 10^\circ < \theta < 170^\circ. \quad \Delta R_{bb} > 0.4$$

for H^+H^- channel : $\quad m(t\bar{b}) > 0.9 M_{H^\pm}, \quad \theta_{tb} < 150^\circ,$

for HA channel : $\quad m(t\bar{t}),\ m(b\bar{b}) > 0.9 M_{H/A}, \quad \theta_{tt}, \theta_{bb} < 150^\circ.$

σ (fb)	$\sqrt{s}$ (TeV)	$t\bar{t}b\bar{b}$		$t\bar{t}t\bar{t}$		$b\bar{b}b\bar{b}$	
		$\mu^+\mu^-$	VBF	$\mu^+\mu^-$	VBF	$\mu^+\mu^-$	VBF
H^+H^-	6	6.7×10^{-4}	$\lesssim 10^{-13}$	–	–	–	–
	14	2.3×10^{-3}	1.1×10^{-4}	–	–	–	–
	30	1.4×10^{-3}	5.2×10^{-4}	–	–	–	–
HA	6	$1.4 \times 10^{-3*}$	4.0×10^{-8}	6.1×10^{-5}	$\lesssim 10^{-14}$	7.3×10^{-6}	$\lesssim 10^{-14}$
	14	1.7×10^{-3}	1.7×10^{-4}	9.0×10^{-4}	2.5×10^{-5}	1.4×10^{-4}	3.9×10^{-6}
	30	7.9×10^{-4}	6.8×10^{-4}	6.5×10^{-4}	1.7×10^{-4}	$\sim 10^{-4}$	2.7×10^{-5}

Can be sufficiently suppressed!

Fermion Associated Production

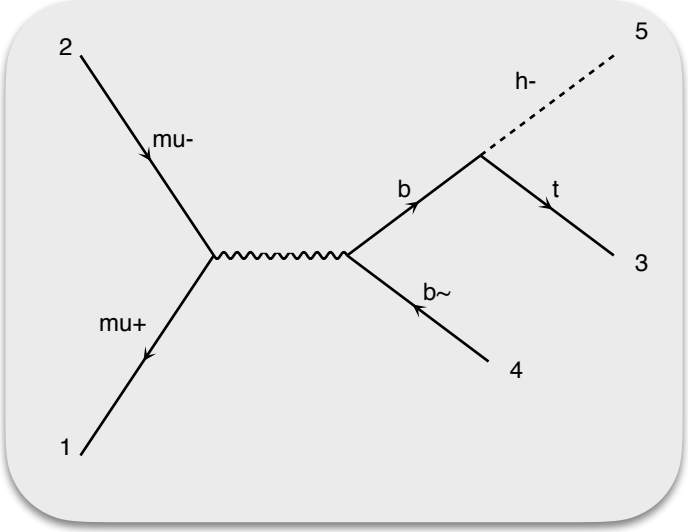
- **Fermion associated production**

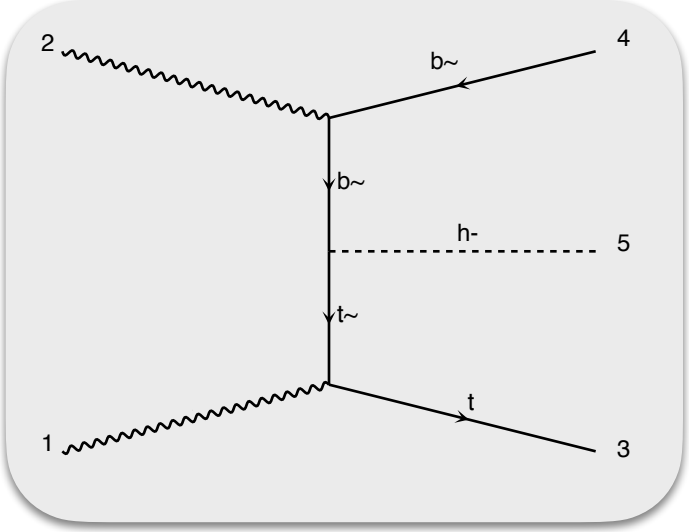
Annihilation

$$\mu^+\mu^- \to b\bar{b}H/A,\ t\bar{t}H/A,\ tbH^\pm,$$
$$\to \tau^+\tau^- H/A,\ \tau^\pm\nu_\tau H^\mp,$$

VBF

$$\mu^+\mu^- \to b\bar{b}H/A,\ t\bar{t}H/A,\ tbH^\pm,\ t\bar{t}H^\pm, b\bar{b}H^\pm, tbH/A,$$
$$\to \tau^+\tau^- H/A,\ \tau^\pm\nu_\tau H^\mp, \tau^+\tau^- H^\pm, \tau^\pm\nu_\tau H/A.$$





Fermion Associated Production

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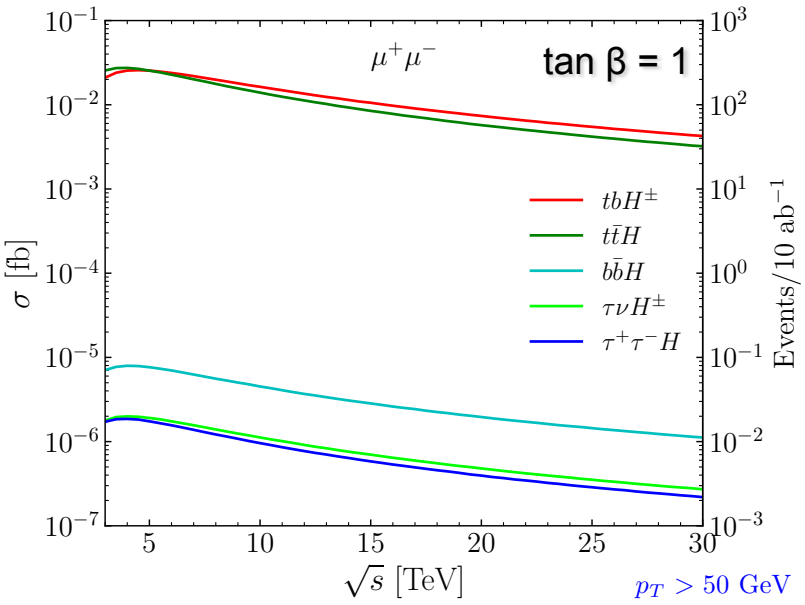
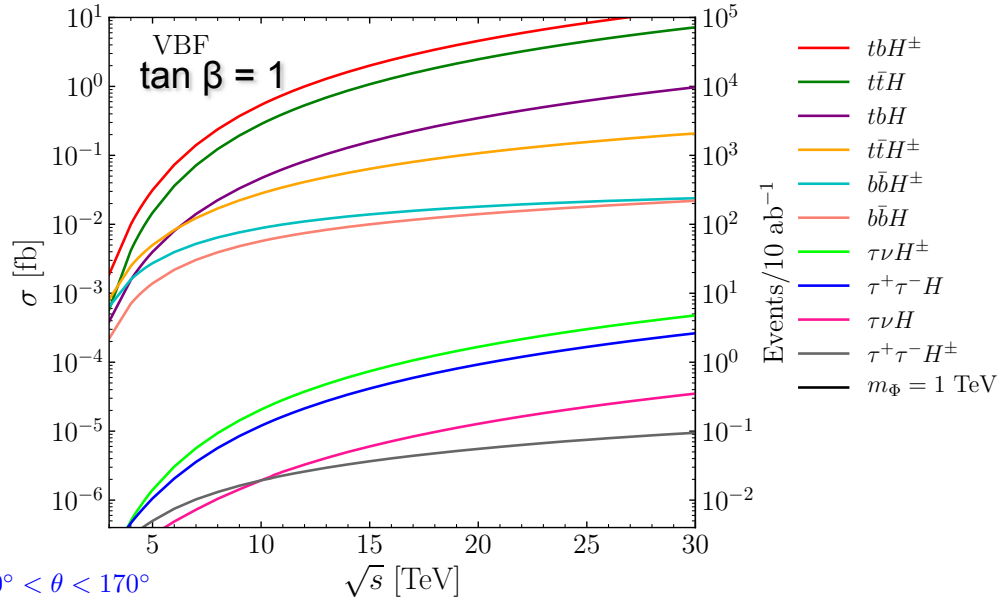
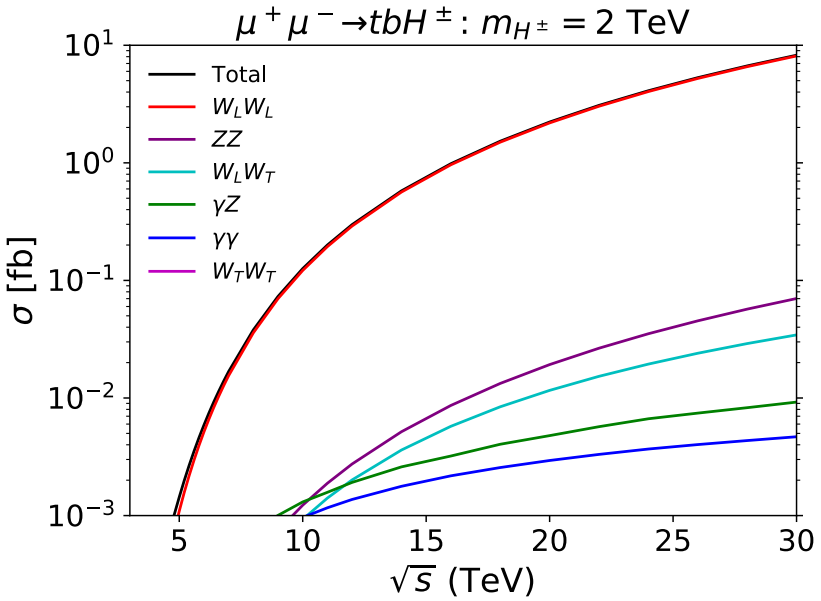
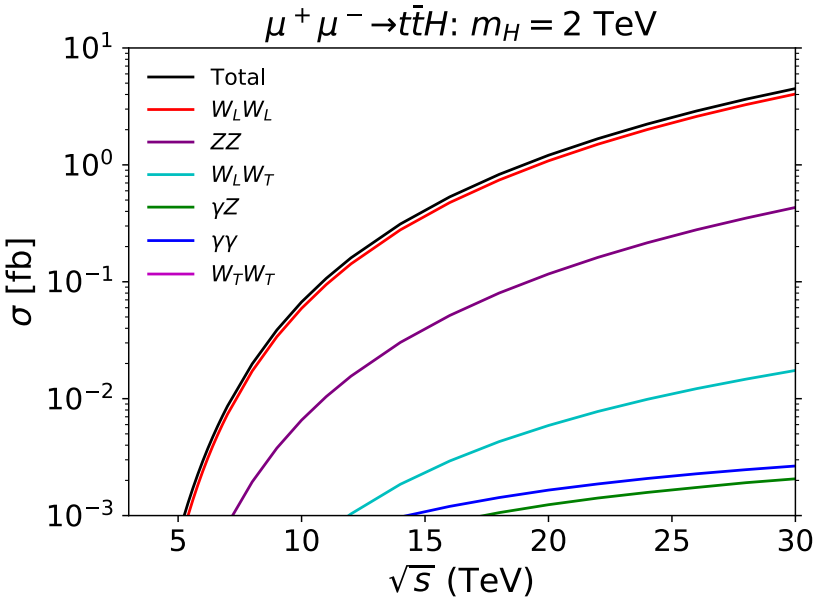




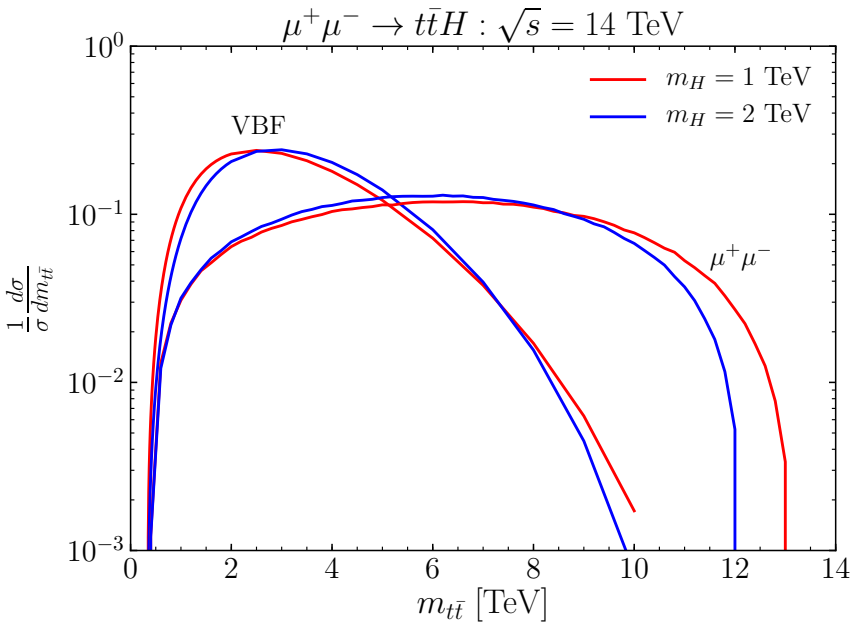
$p_T > 50$ GeV $10° < \theta < 170°$

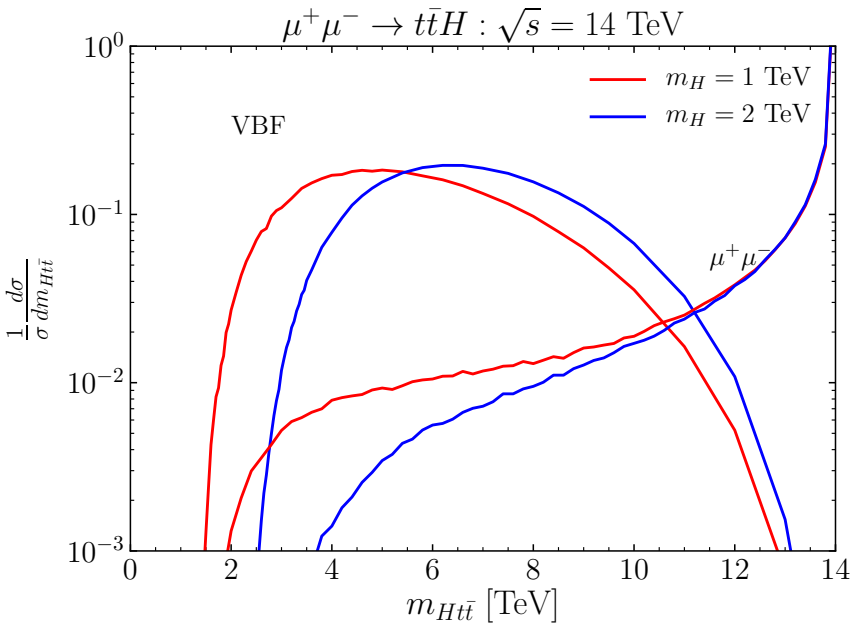
Four Types of 2HDMs





Annihilation vs. VBF





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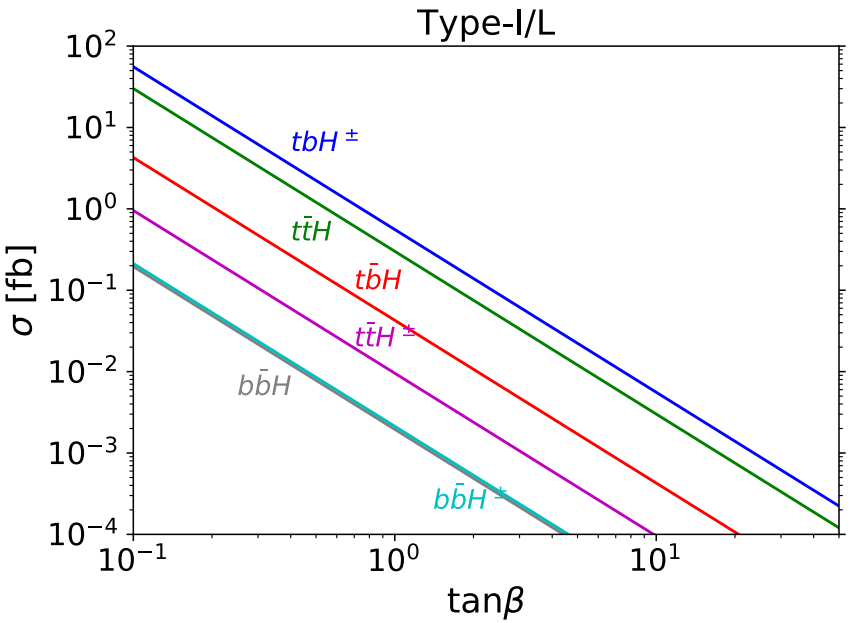

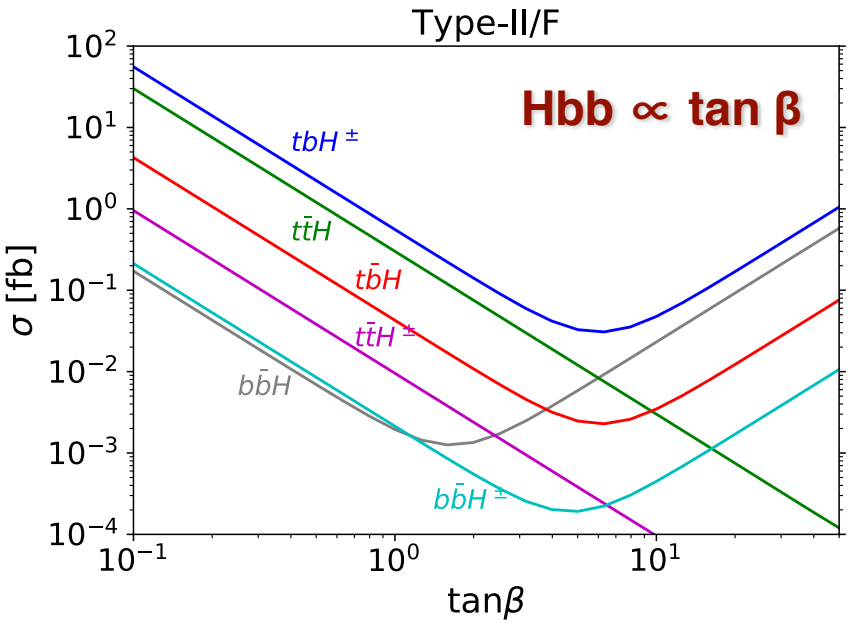

Distinguish 2HDMs

	production	Type-I	Type-II	Type-F	Type-L
small $\tan\beta < 5$	$tbH^{\pm}$	tb, tb			
	$t\bar{t}H/A$	$t\bar{t}, t\bar{t}$			
	(tbH/A)	$(tb, t\bar{t})$			
intermediate $\tan\beta$	$tbH^{\pm}$	tb, tb			$tb, tb;\ tb, \tau\nu_\tau$
	$t\bar{t}H/A$	$t\bar{t}, t\bar{t}$	$t\bar{t}, t\bar{t};\ t\bar{t}, b\bar{b}$		$t\bar{t}, t\bar{t};\ t\bar{t}, \tau^+\tau^-$
	$b\bar{b}H/A$	$-$	$b\bar{b}, t\bar{t};\ b\bar{b}, b\bar{b}$		$-$
	(tbH/A)	$(tb, t\bar{t})$	$(tb, t\bar{t};\ tb, b\bar{b})$		$(tb, t\bar{t};\ tb, \tau^+\tau^-)$
large $\tan\beta > 10$	$tbH^{\pm}$	tb, tb	$tb, tb(\tau\nu_\tau)$	tb, tb	$tb, \tau\nu_\tau$
	$t\bar{t}H/A$	$t\bar{t}, t\bar{t}$	$-$		$t\bar{t}, \tau^+\tau^-$
	$b\bar{b}H/A$	$-$	$b\bar{b}, b\bar{b}(\tau^+\tau^-)$	$b\bar{b}, b\bar{b}$	$-$
	(tbH/A)	$(tb, t\bar{t})$	$(tb, b\bar{b})$		$(tb, \tau^+\tau^-)$
very large $\tan\beta > 50$	$\tau^+\tau^-H/A$	$-$			$\tau^+\tau^-, \tau^+\tau^-$
	$\tau\nu_\tau H^{\pm}$	$-$			$\tau\nu_\tau, \tau\nu_\tau$

Conclusion

- High energy muon collider: discovery machine for BSM Higgses
- BSM Higgs pair production: annihilation dominant
- BSM Higgs single production in associated with fermion: VBF dominant
- SM BG: manageable
- possible to distinguish different types of 2HDM

An exciting journey ahead of us!