# 2HDM @ a High Energy Muon Collider



### Shufang Su • U. of Arizona

T. Han, S. Li, SS, W. Su, Y. Wu, 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)

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

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

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

#### after EWSB, 5 physical Higgses

CP-even Higgses: h, H, CP-odd Higgs: A, Charged Higgses: H±

- Search for extra Higgses
  - → Precision Higgs study: couplings of the SM-like Higgs
  - → Direct search of extra Higgses: direct evidence for BSM new physics S. Su

### 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

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

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

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

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

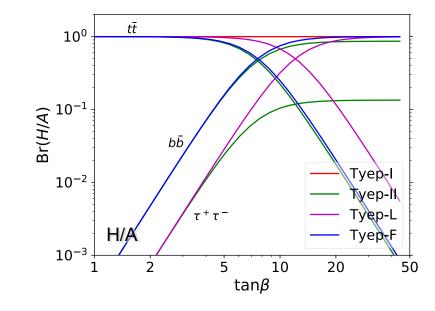
Alignment limit 

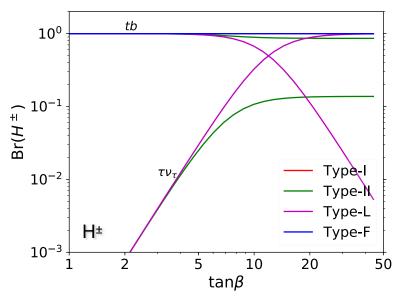
• h 125 GeV, cos(β-α)~0

### Four Types of 2HDMs

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

Types	$\Phi_1$	$\Phi_2$	$\kappa_A^u$	$\kappa_A^d$	$\kappa_A^e$
Type-I		$u,d,\ell$	$\cot \beta$	$-\cot \beta$	$-\cot \beta$
Type-II	$d,\ell$	u	$\cot \beta$	$\tan \beta$	$\tan \beta$
Type-L	$\ell$	u, d,	$\cot \beta$	$-\cot \beta$	$\tan \beta$
Type-F	d	$u,\ell$	$\cot \beta$	$\tan \beta$	$-\cot \beta$



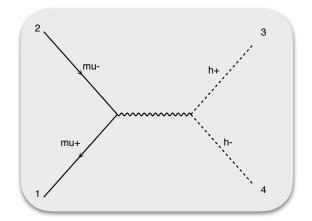


### Pair Production

#### Pair production

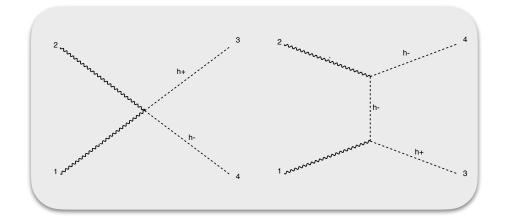
#### **Annihilation**

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



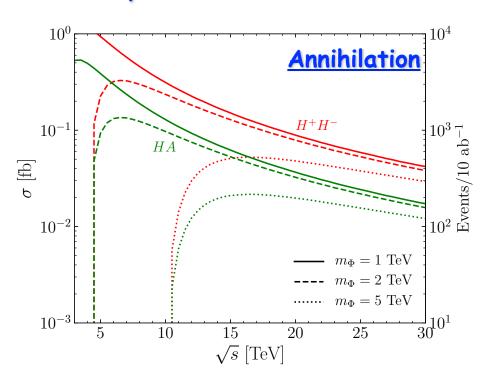
#### **VBF**

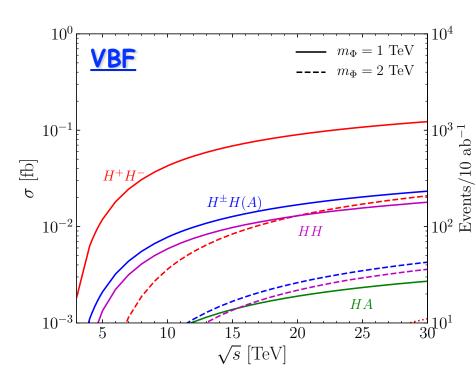
$$\mu^{+}\mu^{-} \to V_{1}V_{2} \to H^{+}H^{-}, HA, H^{\pm}H(A), HH/AA$$



### Pair Production

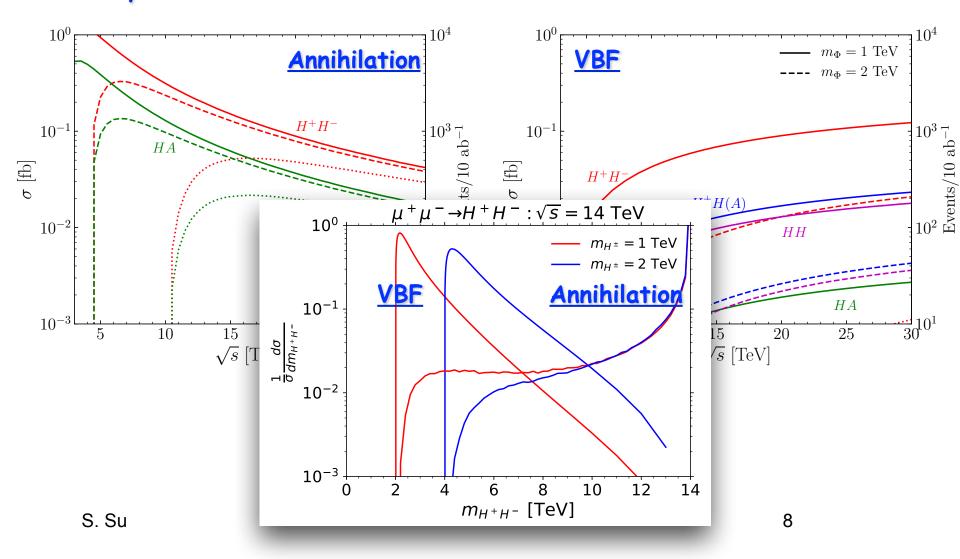
#### Pair production



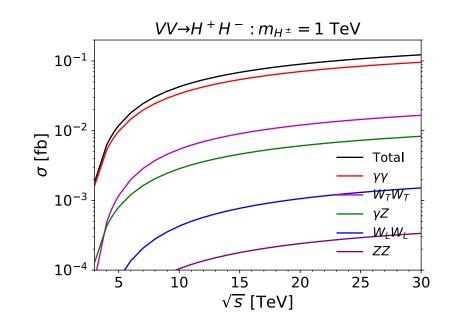


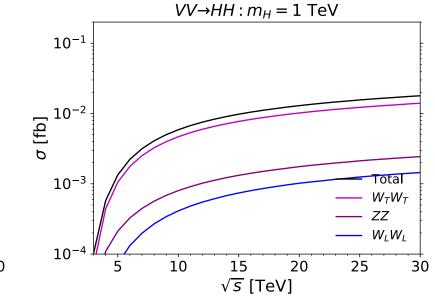
### Pair Production

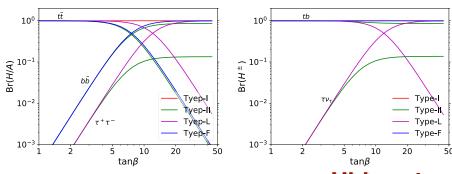
#### Pair production



## Four Types of 2HDMs

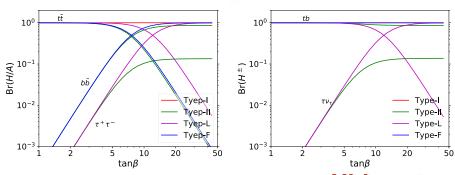






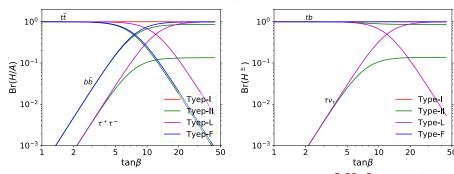
Hbb  $\infty$  tan β Hττ  $\infty$  tan β

	production	Type-I	Type-II	Type-F	Type-L
	$H^+H^-$		$tar{\ell}$		
small $\tan \beta < 5$	HA/HH/AA		$t^{\frac{1}{2}}$		
	$H^\pm H/A$		$tar{t}$		
	$H^+H^-$		$tar{b},ar{t}b$	$tb,  au u_{ au}$	
intermediate $\tan \beta$	HA/HH/AA	$oxed{tar{t},tar{t}} oxed{tar{t},bar{b}}$		$t\bar{t}, \tau^+\tau^-$	
$\beta$	$H^\pm H/A$	$tb, tar{t}$	$tb, tar{t}; tb, bar{b}$	5	$b, t\bar{t}; tb, \tau^+\tau^-;$
				$\tau \nu_{\tau}, t\bar{t}; \ \tau \nu_{\tau}, \tau^{+}\tau^{-}$	
	$H^+H^-$	$tar{b},ar{t}b$	$tb, tb( au u_{ au})$ $tar{b}, ar{t}$		$\tau^+  u_{ au},  au^-  u_{ au}$
large $\tan \beta > 10$	HA/HH/AA	t ar t, t ar t	$t\bar{t}, t\bar{t}$ $b\bar{b}, b\bar{b}( au^+ au^-)$ $b\bar{b}, b\bar{b}( au^+ au^-)$		$\tau^+\tau^-, \tau^+\tau^-$
	$H^\pm H/A$	$\left  \begin{array}{c c} tb, tar{t} & tb( au u_{ au}), bar{b}( au^+ au^-) \end{array} \right $		$tb, bar{b}$	$ au^{\pm} u_{ au},  au^{+} au^{-}$



#### Hbb $\infty$ tan β Hττ $\infty$ tan β

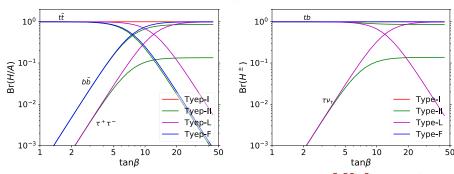
	production	Type-I	Type-II	Type-F	Type-L
	$H^+H^-$		tt	$o, ar{t}b$	
small $\tan \beta < 5$	HA/HH/AA		$t ar{t}, t ar{t}$		
	$H^{\pm}H/A$		$tb, tar{t}$		
	$H^+H^-$	$tar{b},ar{t}b$			$tb,  au u_ au$
intermediate $\tan \beta$	HA/HH/AA	$t ar{t}, t ar{t}$	$tar{t},bar{b}$		$t\bar{t},  au^+ au^-$
	$H^{\pm}H/A$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



Hbb  $\infty$  tan β Hττ  $\infty$  tan β

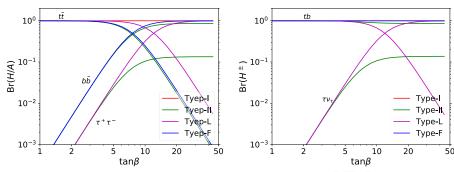
	I							
	production	Type-I	Type-II	Type-F	Type-L			
	$H^+H^-$		$tar{ar{b}},ar{t}b$					
small $\tan \beta < 5$	HA/HH/AA		$tar{t},tar{t}$					
	$H^\pm H/A$		$t\ell$					
	$H^+H^-$		$tar{b},ar{t}b$	$tb, au u_{ au}$				
intermediate tan R	HA/HH/AA	$\overline{tar{t},tar{t}}$ $tar{t},bar{b}$			$tar{t}, au^+ au^-$			
$ $ intermediate $\tan \beta$	$H^\pm H/A$	$tb, tar{t}$ $tb, tar{t};  tb, bar{b}$		<del>-</del> )	$tb, t\bar{t}; tb, \tau^+\tau^-;$			
				$\langle  au  u_{ au}, t ar{t}; \  au  u_{ au},  au^+  au^-  angle$				
	$H^+H^-$	$tar{b},ar{t}b$	$tb, tb( au u_ au)$	$tar{b},ar{t}b$	$ au^+ u_ au, au^- u_ au$			
large $\tan \beta > 10$	HA/HH/AA	$t ar{t}, t ar{t}$	$b\bar{b}, b\bar{b}( au^+ au^-)$	$bar{b}, bar{b}$	$ au^+ au^-, au^+ au^-$			
	$H^\pm H/A$	$tb, tar{t}$	$b(\tau\nu_{\tau}), b\bar{b}(\tau^{+}\tau^{-})$	$tb, bar{b}$	$ au^\pm u_ au, au^+ au^-$			

Hττ ∝ tan β



Hbb  $\infty$  tan β Hττ  $\infty$  tan β

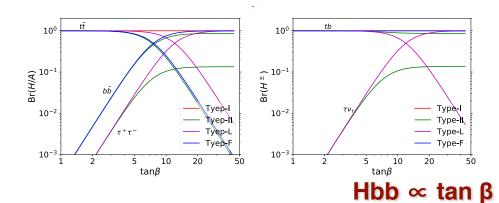
	production	Type-I	Type-II	Type-F	Type-L		
	$H^+H^-$		$tar{b},ar{t}b$				
small $\tan \beta < 5$	HA/HH/AA	$t ar{t}, t ar{t}$					
	$H^{\pm}H/A$		$t\ell$				
	$H^+H^-$	$tar{b},ar{t}b$			$tb,  au u_{ au}$		
intermediate tan R	HA/HH/AA	$tar{t}, tar{t}$ $tar{t}, bar{b}$			$tar{t}, au^+ au^-$		
intermediate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



Hbb  $\infty$  tan β Hττ  $\infty$  tan β

	production	Type-II Type-II		Type-F	Type-L			
	$H^+H^-$		$tar{\ell}$					
small $\tan \beta < 5$	HA/HH/AA		$tar{t},tar{t}$					
	$H^{\pm}H/A$		$t\ell$					
	$H^+H^-$		$tar{b},ar{t}b$	$tb,  au u_{ au}$				
intermodiate top Q	HA/HH/AA	$t ar{t}, t ar{t}$ $t ar{t}, b ar{b}$			$t\bar{t},  au^+ au^-$			
$ $ intermediate $\tan \beta$	$H^{\pm}H/A$	$tb, tar{t}$ $tb, tar{t};  tb, bar{b}$		- )	$tb, t\bar{t}; tb, \tau^+\tau^-;$			
				$\tau \nu_{\tau}, t\bar{t}; \ \tau \nu_{\tau}, \tau^{+}\tau^{-}$				
	$H^+H^-$	$tar{b},ar{t}b$	$tb, tb( au u_ au)$	$tar{b},ar{t}b$	$ au^+ u_ au,  au^- u_ au$			
large $\tan \beta > 10$	HA/HH/AA	$ig  tar{t}, tar{t} \ ig  bar{b}, bar{b}( au^+ au^-)$		$bar{b}, bar{b}$	$ au^+ au^-, au^+ au^-$			
	$H^\pm H/A$	$tb, tar{t}$	$tb(\tau\nu_{\tau}), b\bar{b}(\tau^{+}\tau^{-})$	$tb,bar{b}$	$ au^{\pm} u_{ au}, au^{+} au^{-}$			

Hττ ∝ tan β



	production	Type-I	Type-II	Type-F	Type-L
	$H^+H^-$		$tar{\ell}$		
small $\tan \beta < 5$	HA/HH/AA		$t\bar{t}$	$\overline{t},t\overline{t}$	
	$H^{\pm}H/A$		$t\ell$		
	$H^+H^-$	$tar{b},ar{t}b$			$tb,  au u_{ au}$
intermediate $\tan \beta$	HA/HH/AA	$oxed{tar{t}, tar{t}} oxed{tar{t}, bar{b}}$		$t\bar{t},  au^+ au^-$	
$\beta$	$H^{\pm}H/A$	$tb, tar{t}$	$tb, tar{t};  tb, bar{b}$		$tb, t\bar{t}; tb, \tau^+\tau^-;$
				$\tau \nu_{\tau}, t\bar{t}; \ \tau \nu_{\tau}, \tau^{+}\tau^{-}$	
	$H^+H^-$	$tar{b},ar{t}b$	$tb, tb( au u_{ au})$	$tar{b},ar{t}b$	$ au^+ u_ au, au^- u_ au$
large $\tan \beta > 10$	HA/HH/AA	$ \hspace{.06cm} t \bar{t}, t \bar{t} \hspace{.06cm}   \hspace{.06cm} b \bar{b}, b \bar{b} ( au^+  au^-) \hspace{.06cm}   \hspace{.06cm} b \bar{b}, b$		$bar{b}, bar{b}$	$ au^+ au^-, au^+ au^-$
	$H^{\pm}H/A$	$tb, tar{t}$	$b(\tau\nu_{\tau}), b\bar{b}(\tau^{+}\tau^{-})$	$tb, bar{b}$	$ au^{\pm} u_{ au},  au^{+} au^{-}$

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

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

(fb)	(ToV)	$t \bar{t} b \bar{b}$		$tar{t}tar{t}$		$bar{b}bar{b}$	
$\sigma$ (fb) $\sqrt{s}$ (TeV)	$\mu^+\mu^-$	VBF	$\mu^+\mu^-$	VBF	$\mu^+\mu^-$	VBF	
	6	$6.7 \times 10^{-4}$	$\lesssim 10^{-13}$	_	_	_	_
$H^+H^-$	14	$2.3 \times 10^{-3}$	$1.1 \times 10^{-4}$	_	_	_	_
	30	$1.4 \times 10^{-3}$	$5.2 \times 10^{-4}$	_	_	_	_
	6	$1.4 \times 10^{-3*}$	$4.0 \times 10^{-8}$	$6.1 \times 10^{-5}$	$\lesssim 10^{-14}$	$7.3 \times 10^{-6}$	$\lesssim 10^{-14}$
HA	14	$1.7 \times 10^{-3}$	$1.7 \times 10^{-4}$	$9.0 \times 10^{-4}$	$2.5 \times 10^{-5}$	$1.4\times10^{-4}$	$3.9 \times 10^{-6}$
	30	$7.9 \times 10^{-4}$	$6.8 \times 10^{-4}$	$6.5 \times 10^{-4}$	$1.7 \times 10^{-4}$	$\sim 10^{-4}$	$2.7 \times 10^{-5}$

#### Can be sufficiently suppressed!

### Fermion Associated Production

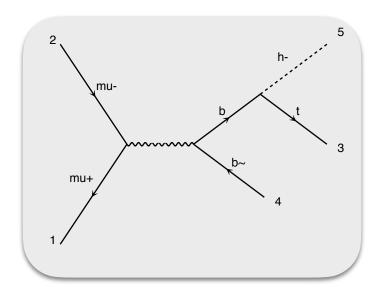
#### Fermion associated production

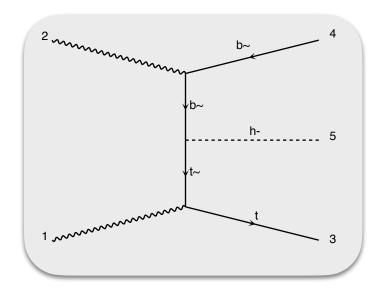
#### **Annihilation**

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

#### **VBF**

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

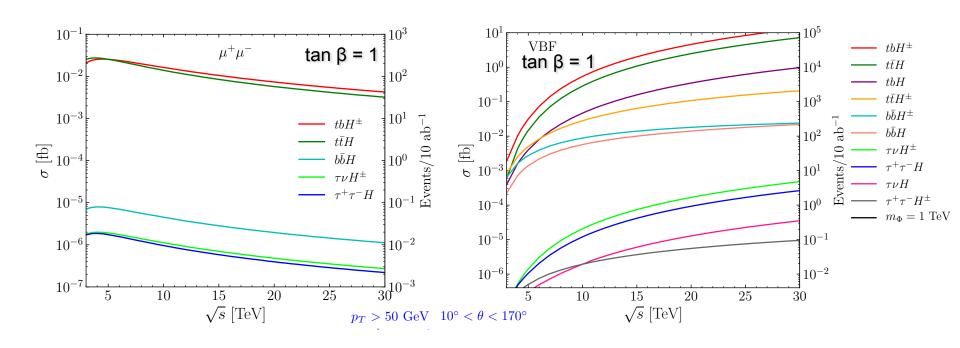




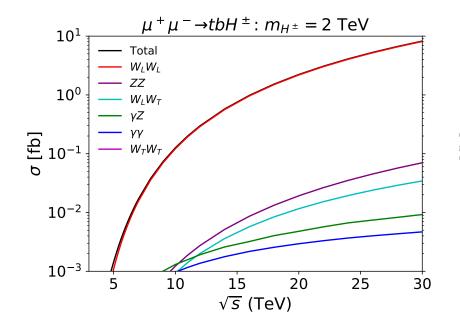
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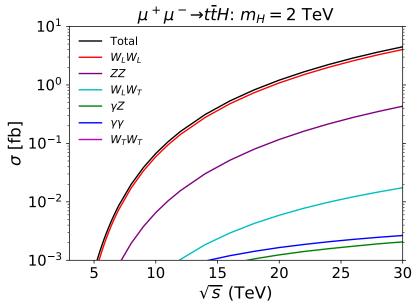
### Fermion Associated Production

#### Fermion associated production

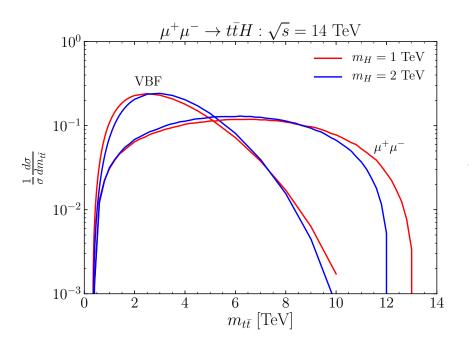


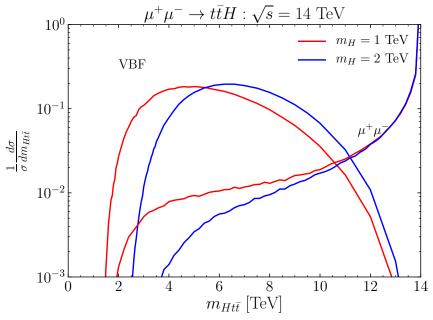
## Four Types of 2HDMs

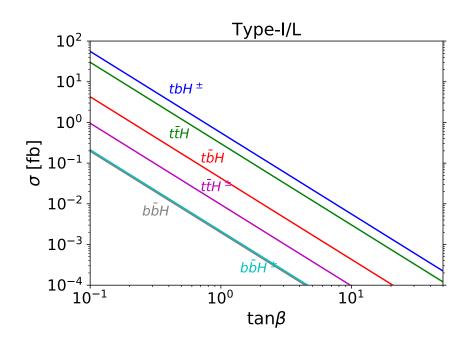


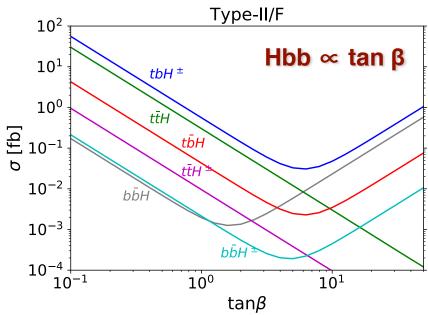


### Annihilation vs. VBF









	production	Type-I	Type-II	Type-F	Type-L			
amall tan B < 5	$tbH^{\pm}$	tb,tb						
small $\tan \beta < 5$	$t ar{t} H/A$	$tar{t},tar{t}$						
	(tbH/A)		(	$tb, tar{t})$				
	$tbH^{\pm}$		tb,tb	$tb, tb; tb,  au u_{ au}$				
intermediate $\tan \beta$	$t ar{t} H/A$	$t \bar{t}, t \bar{t}$	$tar{t},tar{t};tar{t},bar{b}$		$t\bar{t}, t\bar{t}; t\bar{t}, \tau^+\tau^-$			
	$b ar{b} H/A$	$H/A$ $ bar{b}, tar{t}; bar{b}, bar{b}$		$b,bar{b}$	_			
	(tbH/A)	$(tb,tar{t})$	$(tb, tar{t}; tb$	$\left  (tb, t\bar{t}; tb, \tau^+\tau^-) \right $				
	$tbH^{\pm}$	tb, tb	$tb, tb( au u_{ au})$	tb, tb	$tb,  au u_{ au}$			
large $\tan \beta > 10$	t ar t H/A	$tar{t},tar{t}$	_		$t\bar{t},  au^+ au^-$			
	$bar{b}H/A$	_	$b\bar{b}, b\bar{b}(\tau^+\tau^-)$ $b\bar{b}, b\bar{b}$		_			
	(tbH/A)	$(tb, tar{t})$ $(tb, bar{b})$		$(tb, \tau^+\tau^-)$				
$\frac{1}{1}$	$\tau^+\tau^-H/A$				$\tau^+\tau^-, \tau^+\tau^-$			
very large $\tan \beta > 50$	$ au u_ au H^\pm$		_	$ au u_{ au},  au u_{ au}$				

### 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!