

# 2HDM @ 100 TeV pp



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Talk based on work:

1404.1922, 1408.4119 (with Coleppa, Kling)

1504.04381 (with Tong Li)

1504.06624 (with Kling and Pyarelal)

Int. J. Mod. Phys. A30 (2015) (with Hajer et. al.)

1604.01406 (With Kling and Jose Miguel No)

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# Outline

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- Higgses in 2HDM
- Higgs production @ 100 TeV pp
- BSM Higgs searches: conventional modes
- BSM Higgs searches: exotic modes
  - 2HDM benchmark planes
  - Preliminary results for  $H/A \rightarrow AZ/HZ$  channel @ 100 TeV pp
- Conclusion
- 2HDM @ Higgs factory

# 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

# Introduction

- ◎ Search for extra Higgses
  - ➔ Precision Higgs study: couplings of the SM-like Higgs
  - ➔ Direct search of extra Higgses: direct evidence for BSM new physics
- ◎ Conventional search channel (even for non-SM Higgs):  
 $\gamma\gamma$ ,  $ZZ$ ,  $WW$ ,  $\tau\tau$ ,  $bb$
- ◎ Charged Higgs is challenge!
- ◎ New Higgs decay modes open for (non-)SM Higgs decay
  - ➔ relax the current search bounds
  - ➔ offer new discovery channels

# 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:  $h^0, H^0$ , CP-odd Higgs:  $A^0$ , Charged Higgses:  $H^\pm$**

# 2HDM Higgs Sector

- CP conserving
- Flavor limits: Type I, Type II, lepton-specific, flipped, ...  
Type II:  $\phi_1$ , down-type, leptons:  $\phi_2$ , up-type
- parameters (CP-conserving, flavor limit,  $Z_2$  symmetry)

$m_{11}^2, m_{22}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$



$v, \tan \beta, \alpha, m_h, m_H, m_A, m_{H^\pm}$

soft  $Z_2$  breaking:  $m_{12}^2$

# 2HDM Higgs Sector

## ● $h^0/H^0$ $VV$ coupling

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

## ● Higgs-Higgs-V coupling

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

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

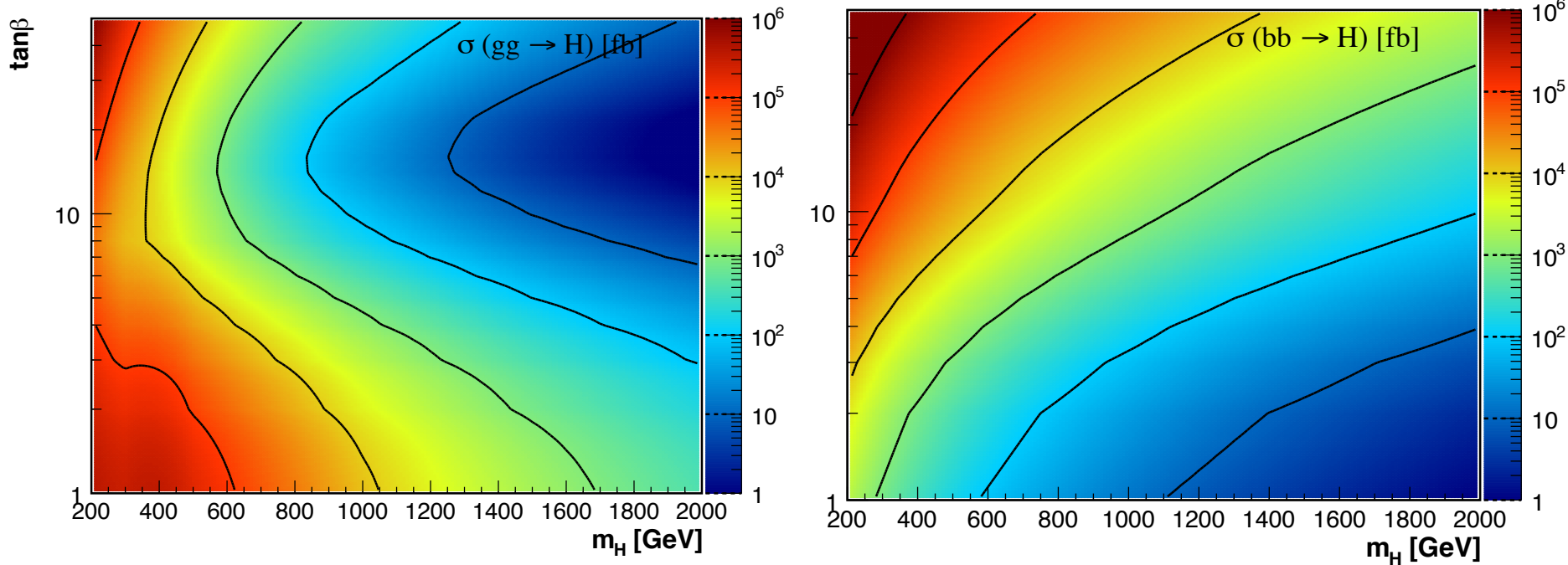
Alignment limit

- $h^0$  125 GeV,  $\cos(\beta - \alpha) \sim 0$
- $H^0$  125 GeV,  $\sin(\beta - \alpha) \sim 0$

# BSM Higgs Production @ 100 TeV pp



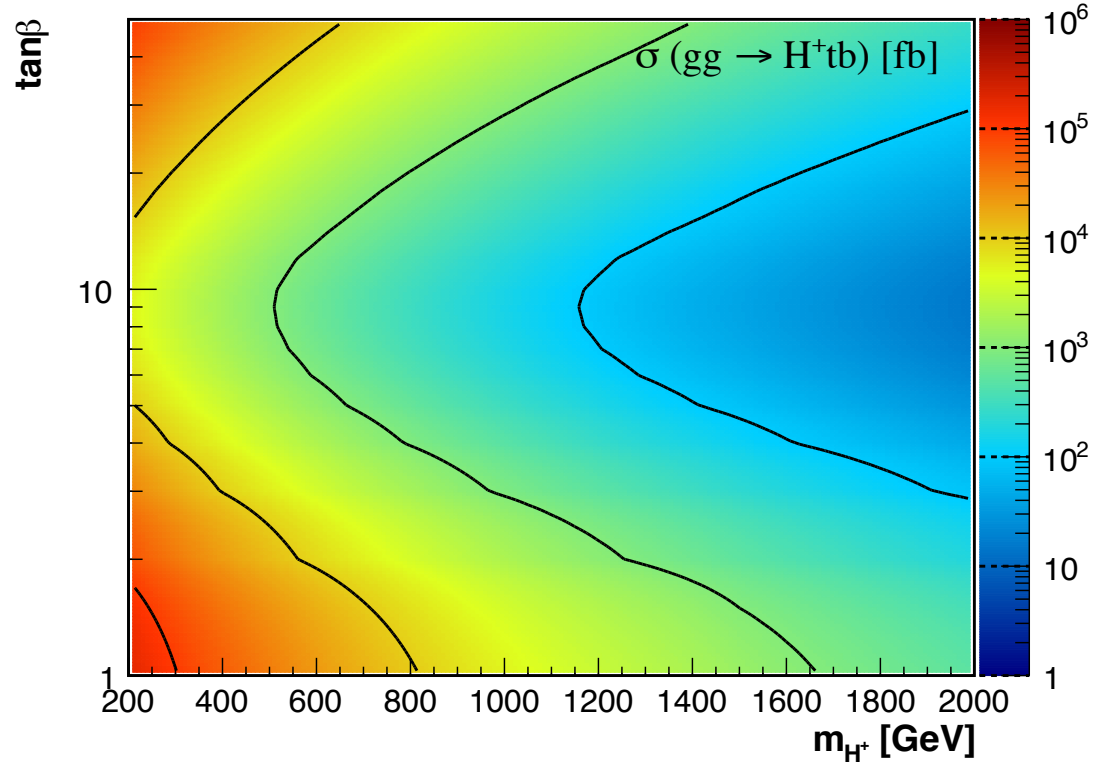
# Neutral Higgses



**30-50 times more than 14 TeV for 500 GeV Higgs**

**VBF, VH production highly suppressed for non-SM Higgses.**

# Charged Higgses



90 times more than 14 TeV for 500 GeV Higgs

# BSM Higgs Searches: Conventional Modes

$\gamma\gamma$ ,  $ZZ$ ,  $WW$ ,  $\tau\tau$ ,  $bb$

# BSM Higgs Searches: Conventional Modes


$\gamma\gamma, ZZ, WW, \tau\tau, bb$

  
small Br

# BSM Higgs Searches: Conventional Modes

$\gamma\gamma, ZZ, WW, \tau\tau, bb$

  
small Br

  
absent or  
suppressed

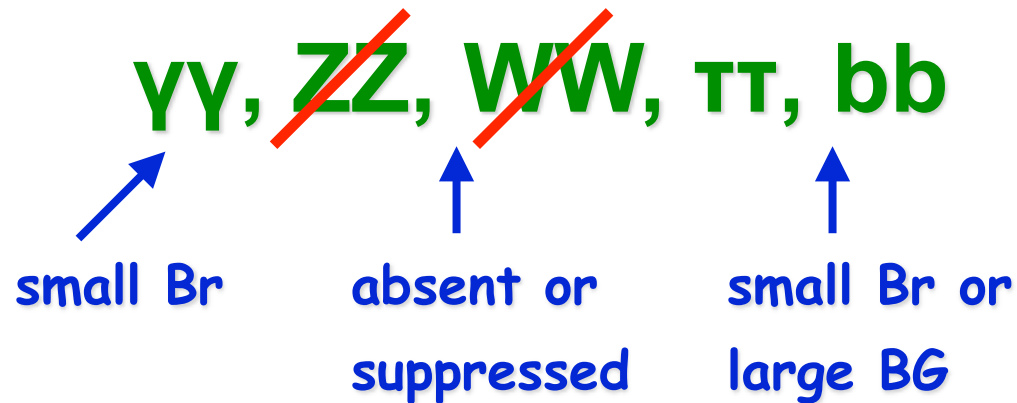
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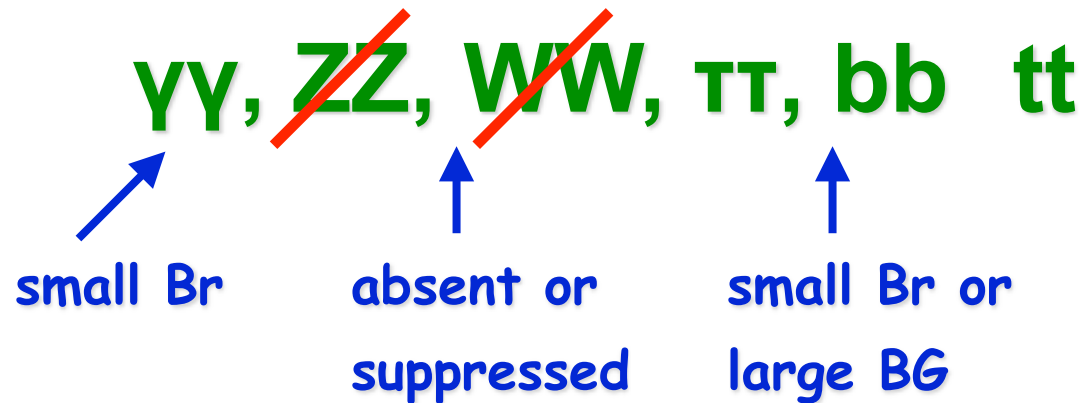
small Br

absent or suppressed

# BSM Higgs Searches: Conventional Modes



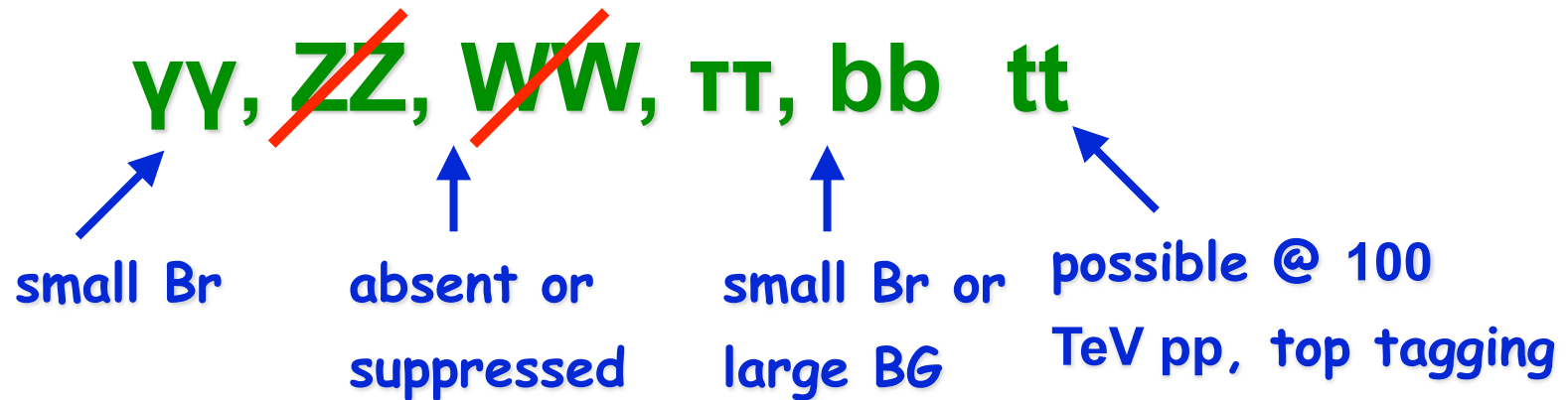
# BSM Higgs Searches: Conventional Modes





# BSM Higgs Searches:

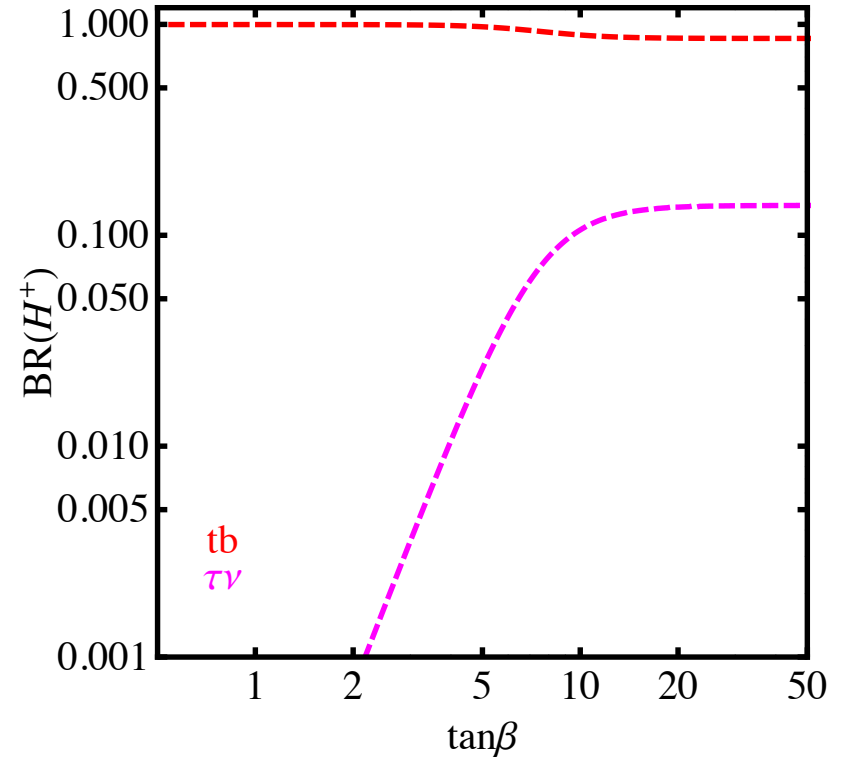
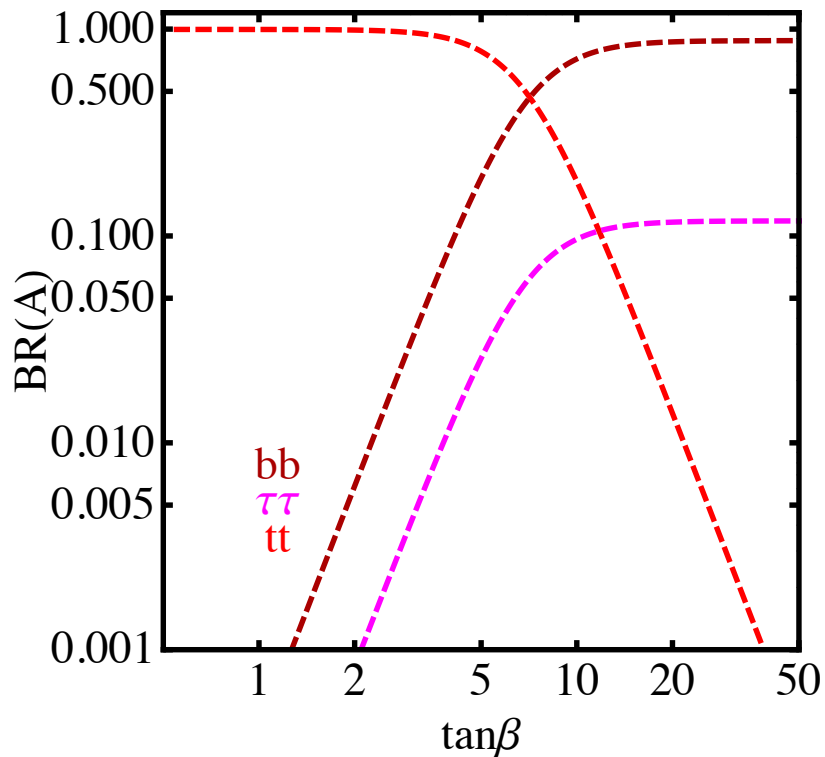
## Conventional Modes



# Searching for Other Higgses

⊙  $A/H$  decay

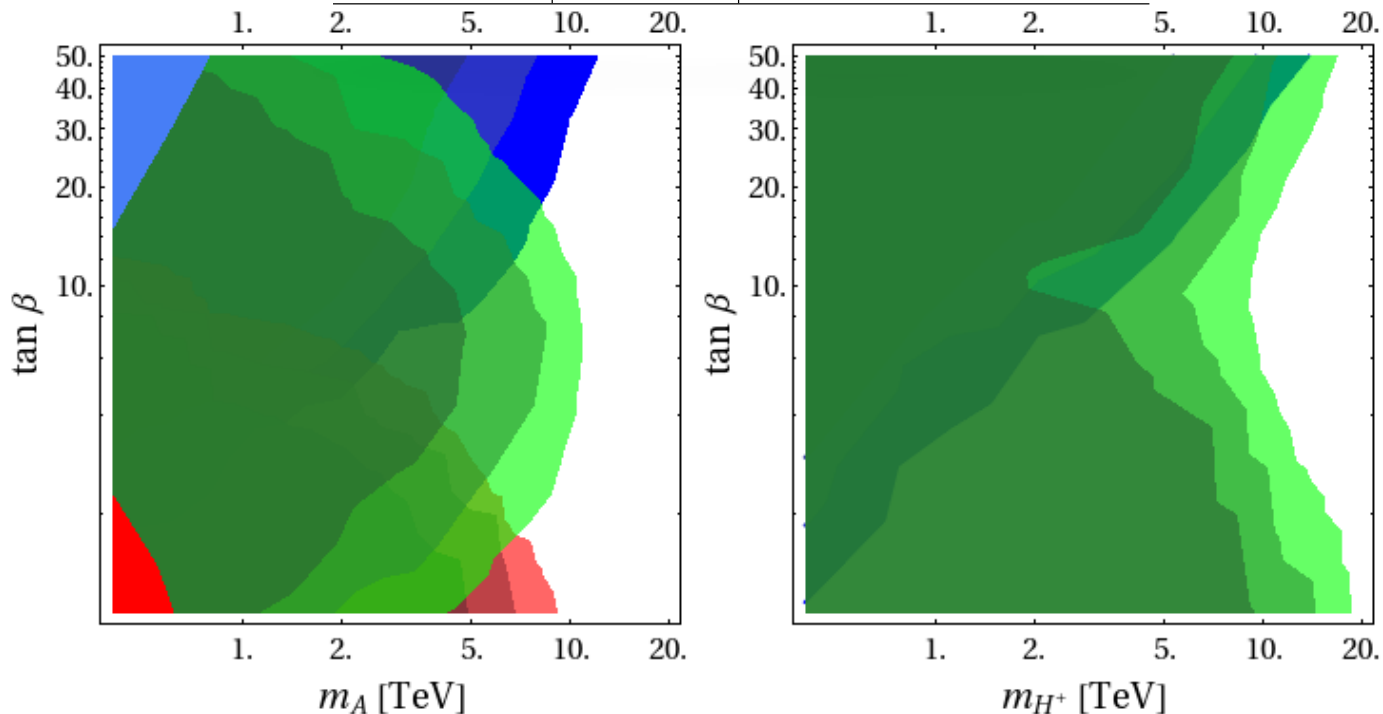
⊙  $H^\pm$  decay



500 GeV parent particle

# Conventional Search Channel for BSM Higgses

	$\tan \beta$	Channels
Neutral Higgs $H^0, A$	High	$pp \rightarrow bbH^0/A \rightarrow bb\tau\tau, bbbb$
	Intermediate	$pp \rightarrow bbH^0/A \rightarrow bbtt$
	Low	$pp \rightarrow H^0/A \rightarrow tt$
Charged Higgs $H^\pm$	High	$pp \rightarrow tbH^\pm \rightarrow tbtb, tb\tau\nu_\tau$
	Low	$pp \rightarrow tbH^\pm \rightarrow tbtb$



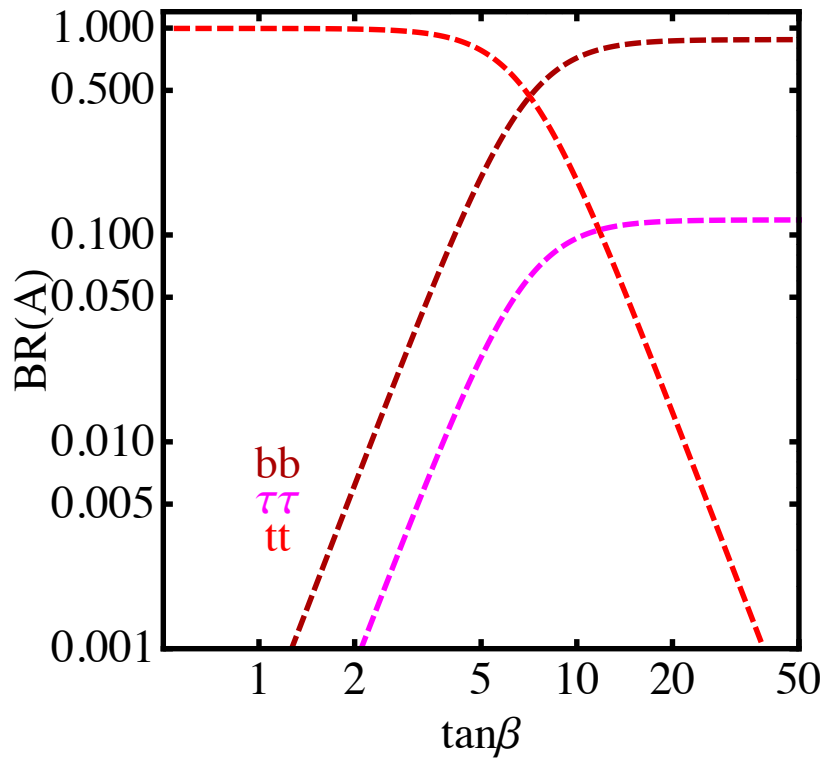
S. Su

Hajer, Ismail, Kling, Li, Liu, Su, Int. J. Mod. Phys. A30 (2015)

# BSM Higgs Searches: Exotic Modes

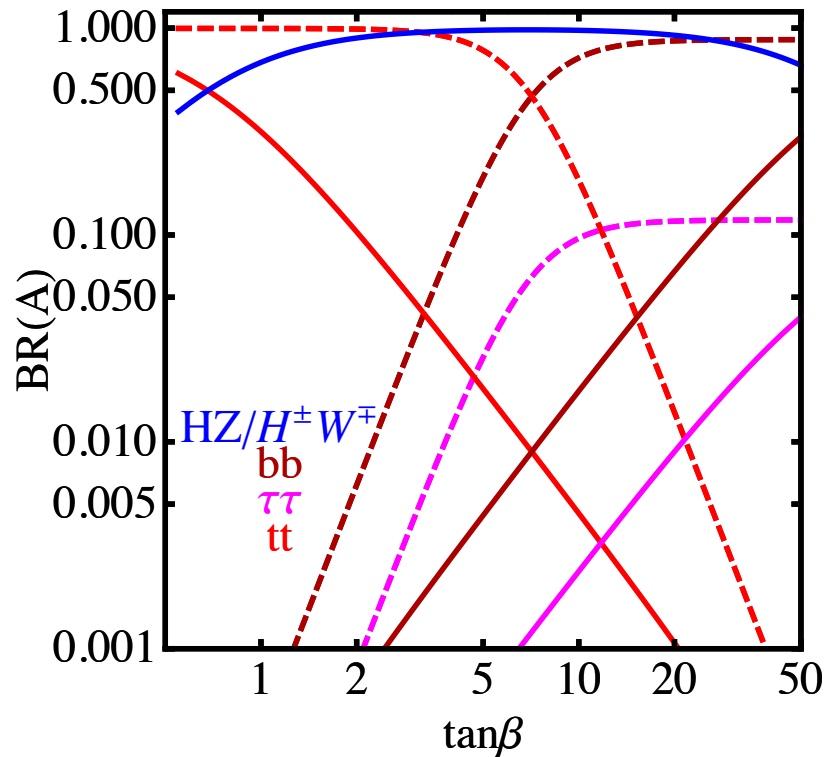
# Searching for Other Higgses

⊙ **A decay**



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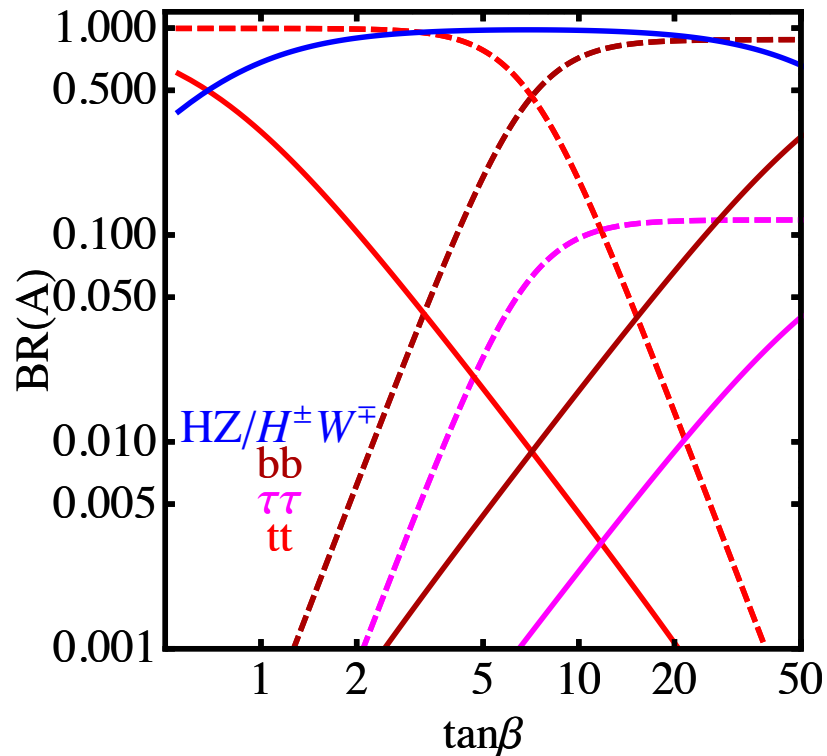


**500 GeV parent particle**  
**200 GeV daughter particle**

# Searching for Other Higgses

⊙ A decay

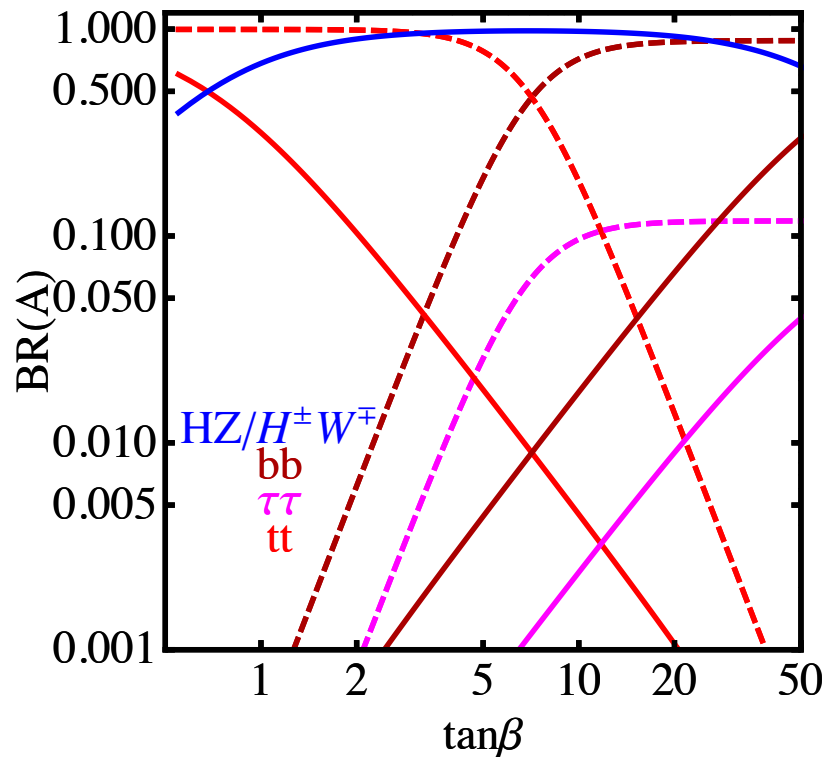
⊙ H<sup>0</sup> decay



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200 GeV daughter particle

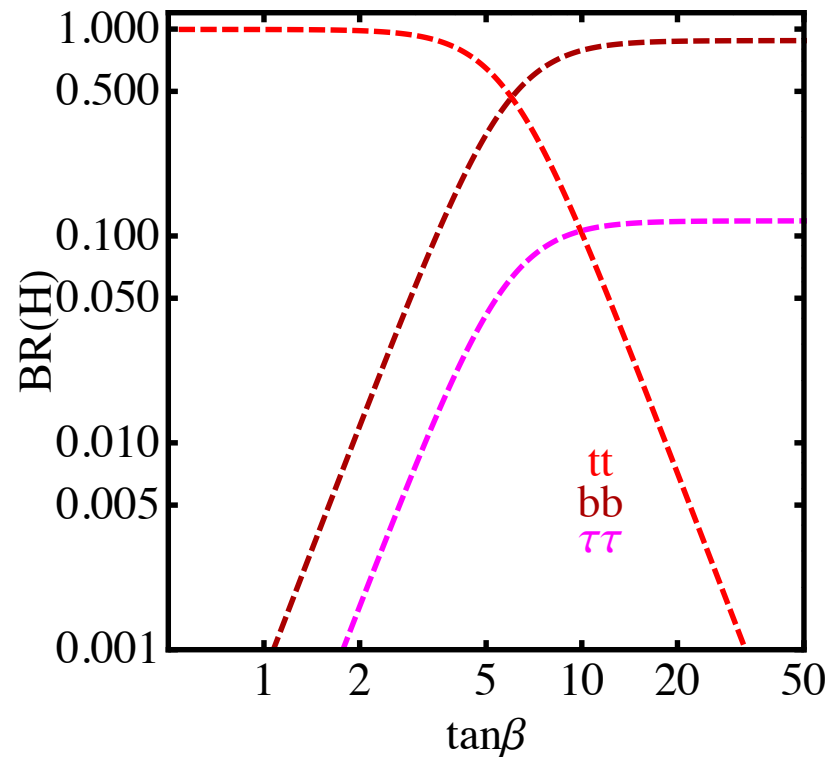
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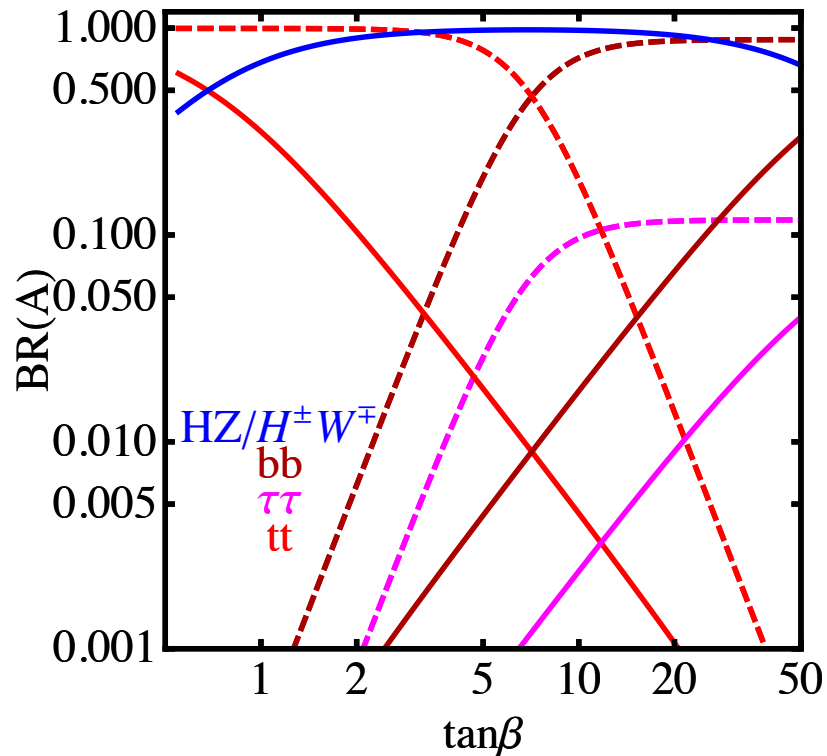
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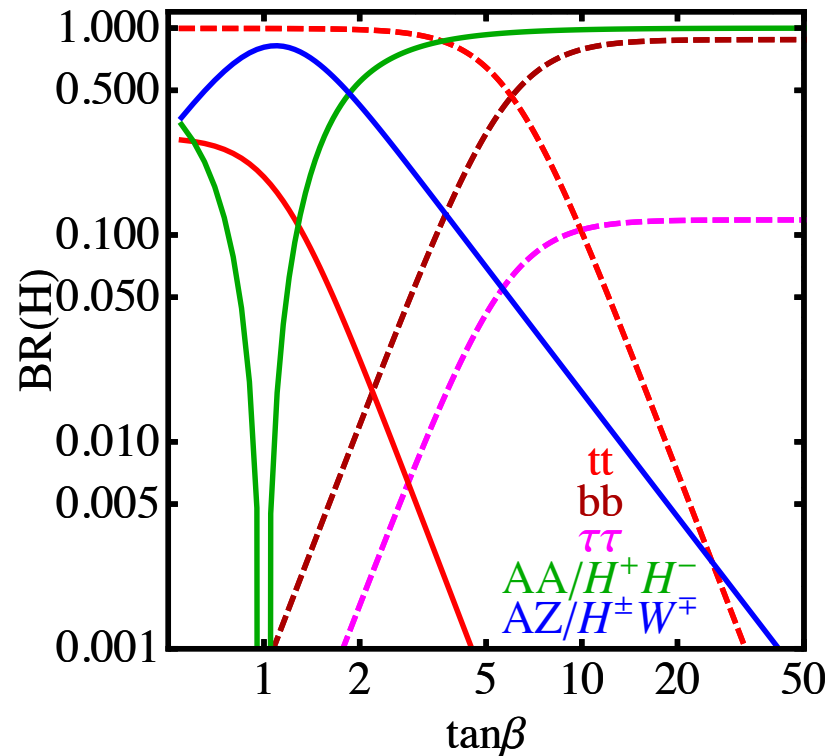
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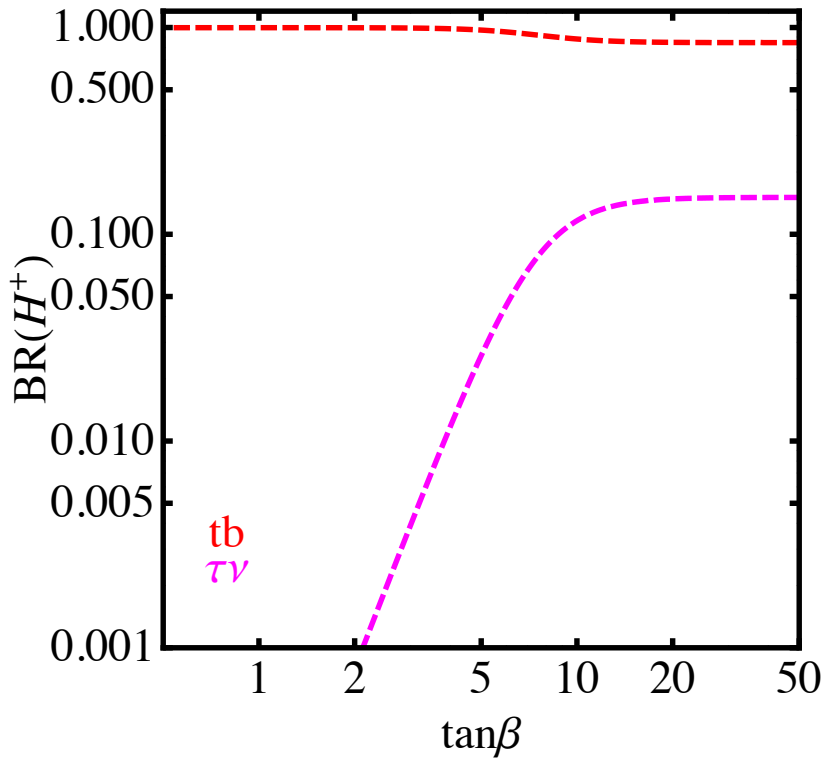
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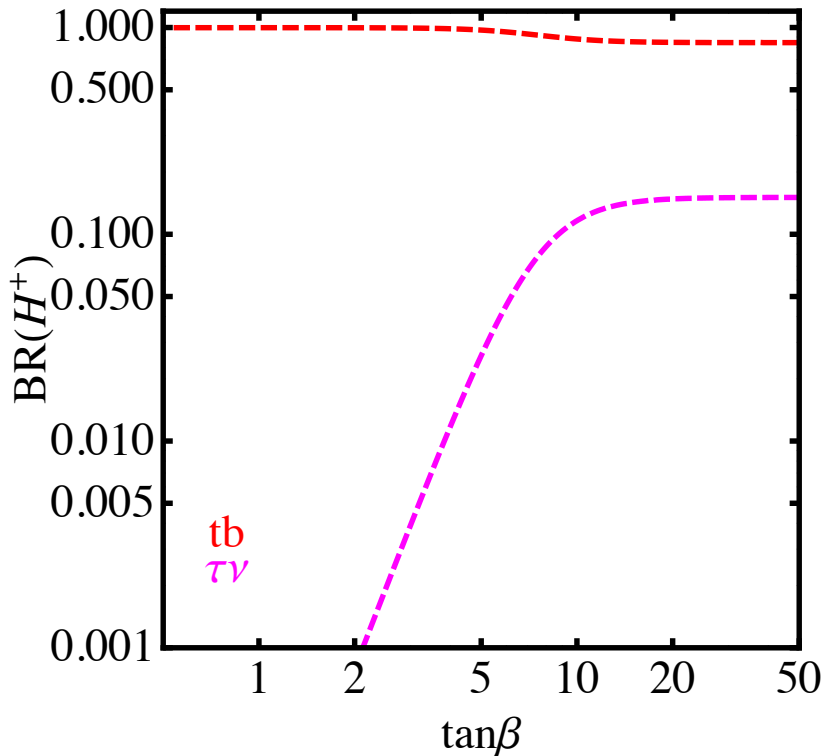
# Charged Higgs Challenge

## ⊙ $H^\pm$ decay



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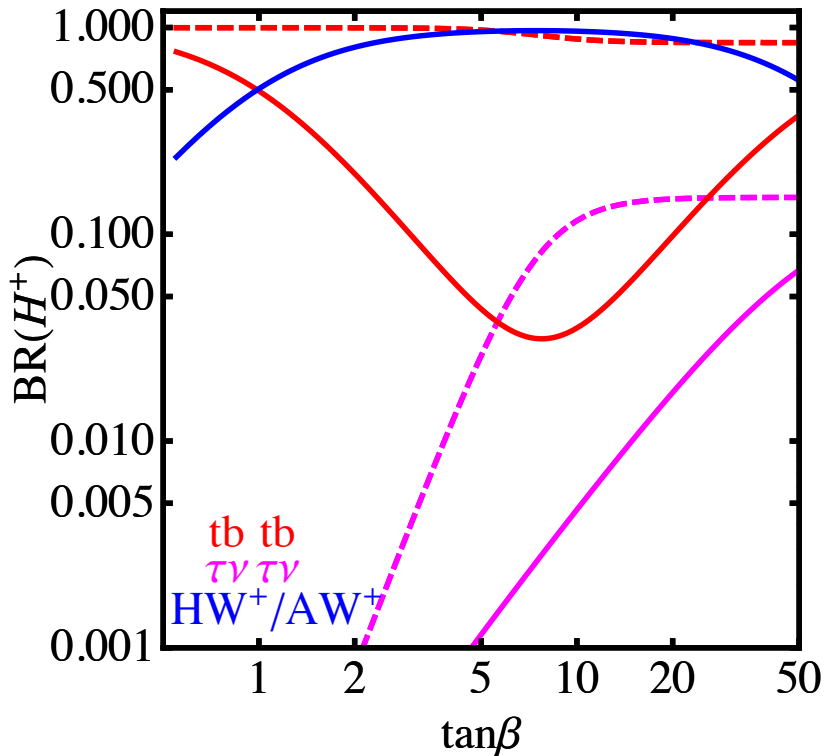


## ⊙ New decay mode for $H^\pm$ : $H^\pm \rightarrow AW/HW$

$$g_{H^\pm h^0 W^\mp} = \frac{g \cos(\beta - \alpha)}{2} (p_{h^0} - p_{H^\pm})^\mu,$$
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# Searching for Other Higgses

New channels open up for non-SM Higgs decay

neutral Higgs	HH type	$(bb/\tau\tau/WW/ZZ/\gamma\gamma)(bb/\tau\tau/WW/ZZ/\gamma\gamma)$	$h_{SM} \rightarrow AA,$ $H \rightarrow h_{SM} h_{SM},$ $H \rightarrow AA,$
	$H^+H^-$ type	$(\tau\nu/tb)(\tau\nu/tb)$	$H \rightarrow H^+H^-$
	$WH^\pm$ type	$(l\nu/qq')(\tau\nu/tb)$	$H/A \rightarrow WH^\pm$
	ZH type	$(ll/qq/\nu\nu)(bb/\tau\tau/WW/ZZ/\gamma\gamma)$	$H \rightarrow ZA,$ $A \rightarrow ZH, Zh$
charge Higgs	WH type	$(l\nu/qq')(bb/\tau\tau)$	$tH^\pm$ production, $H^\pm \rightarrow WH$ $H^\pm \rightarrow WA$

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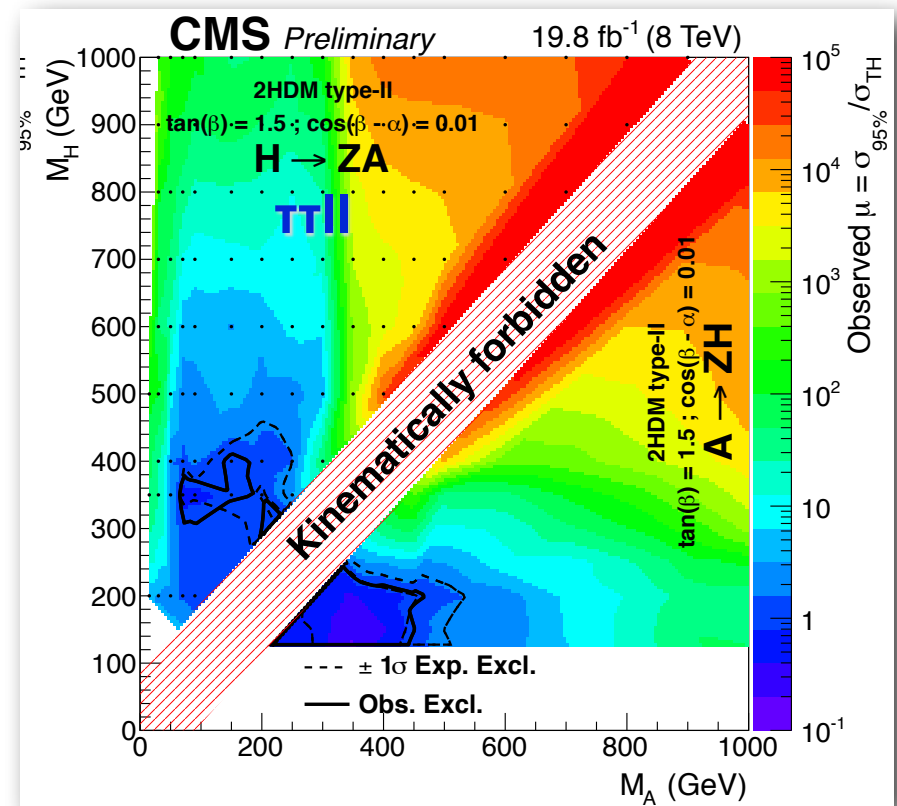
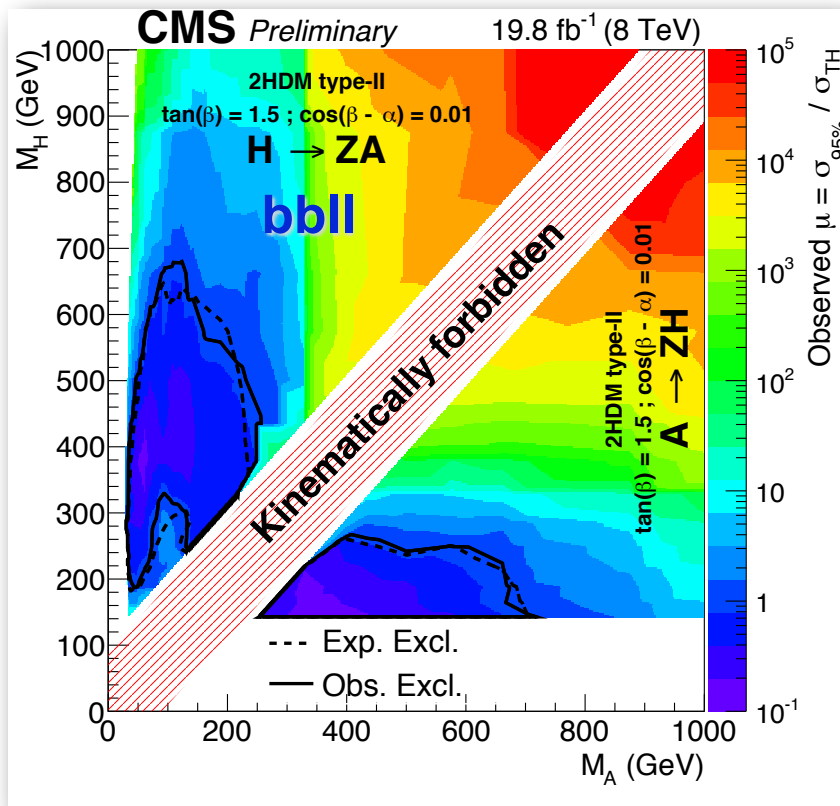
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charge Higgs	WH type	$(l\nu/qq')(bb/\tau\tau)$	$tH^\pm$ production, $H^\pm \rightarrow WH$ $H^\pm \rightarrow WA$

# CMS A/H → H/AZ Limits

CMS:  $gg \rightarrow A/H \rightarrow H/AZ$  for non-SM daughter H/A in  $bbll$ ,  $\tau\tau ll$  channel

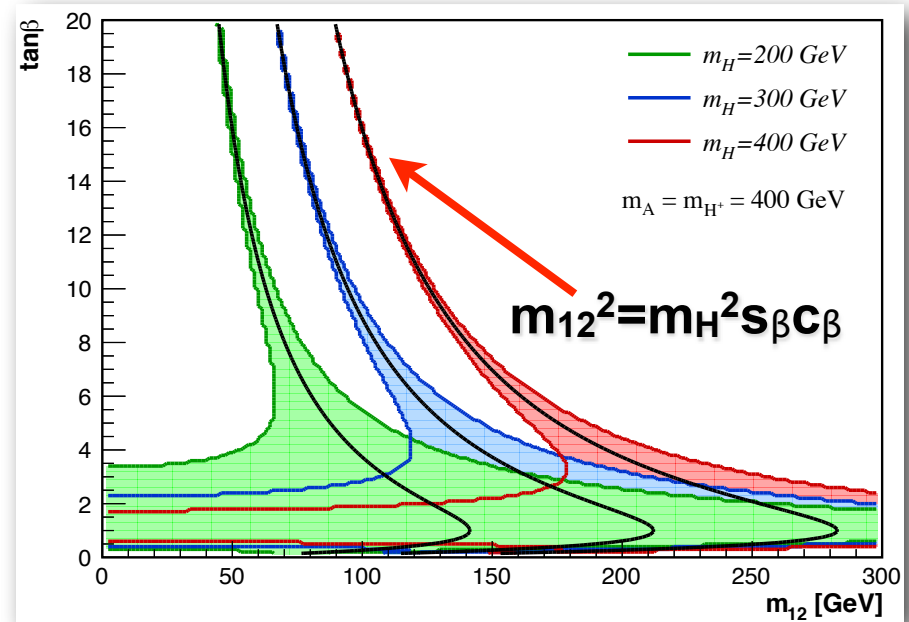
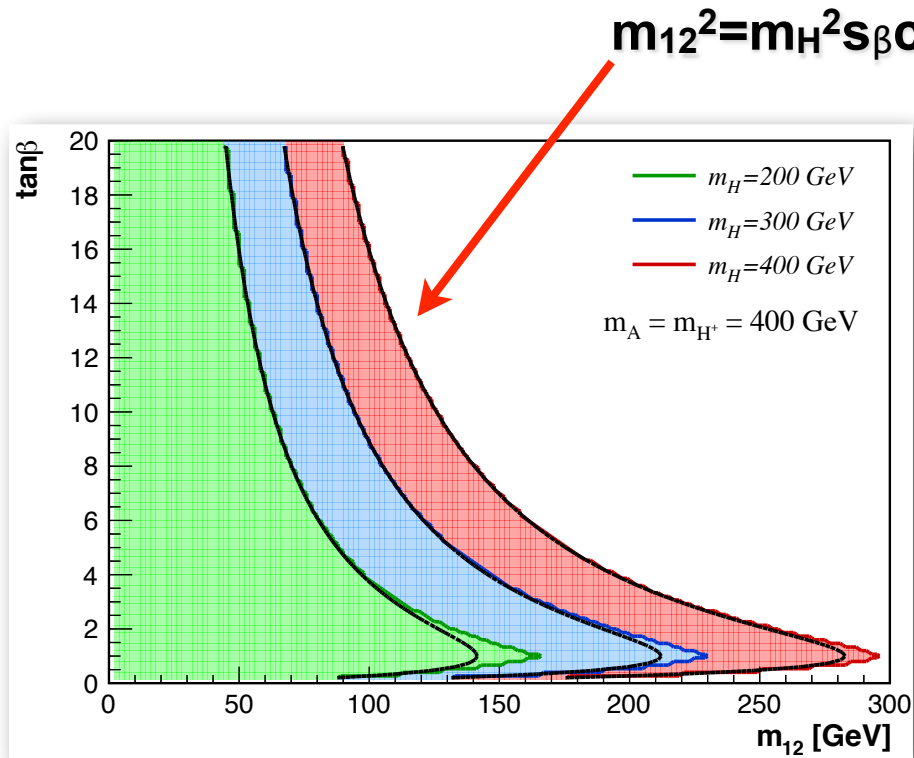
CMS-HIG-15-001



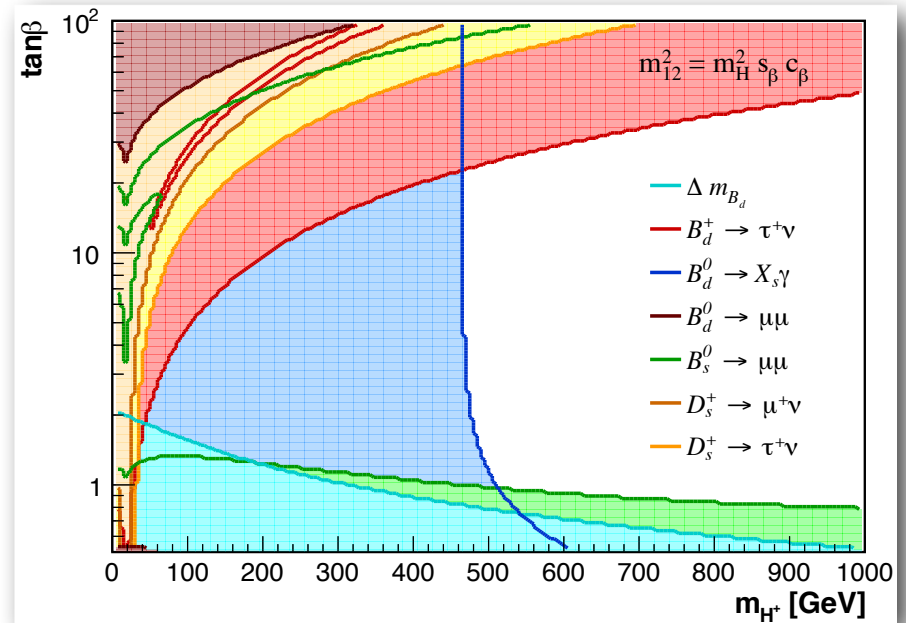
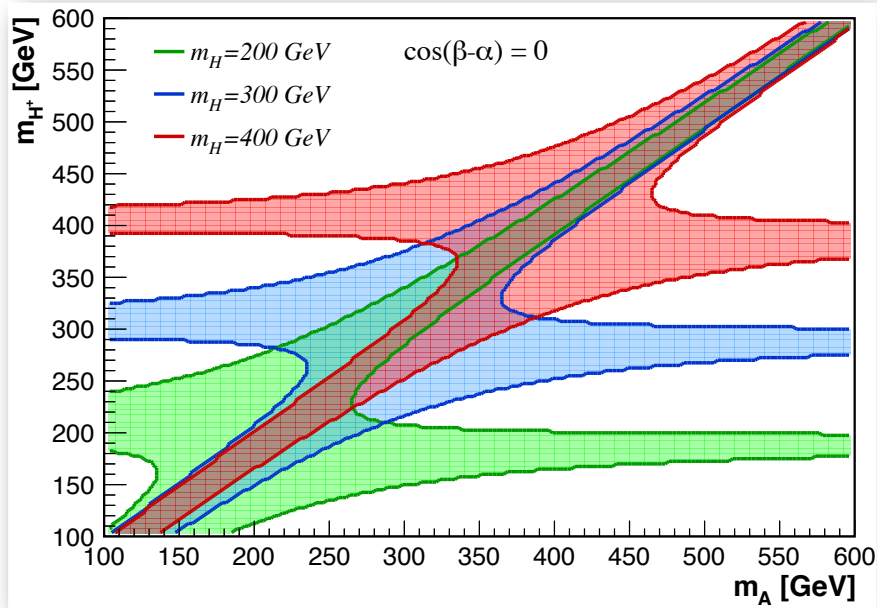


# 2HDM benchmark planes

# Vacuum Stability/Pert./Unitarity



# Precision/Flavor



$m_{H^\pm} \sim m_H$  or  $m_{H^\pm} \sim m_A$

# Benchmark Planes

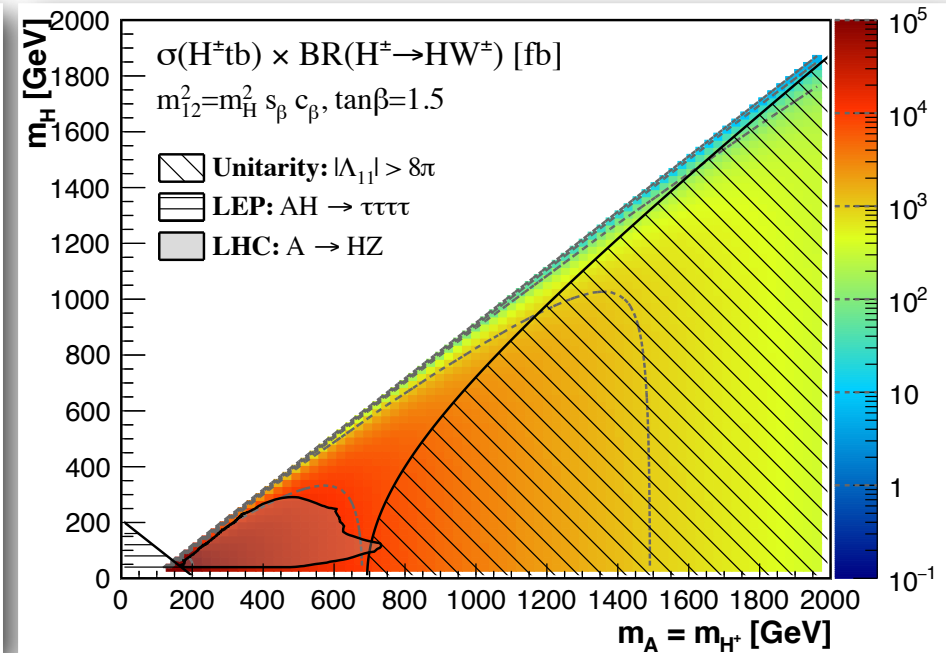
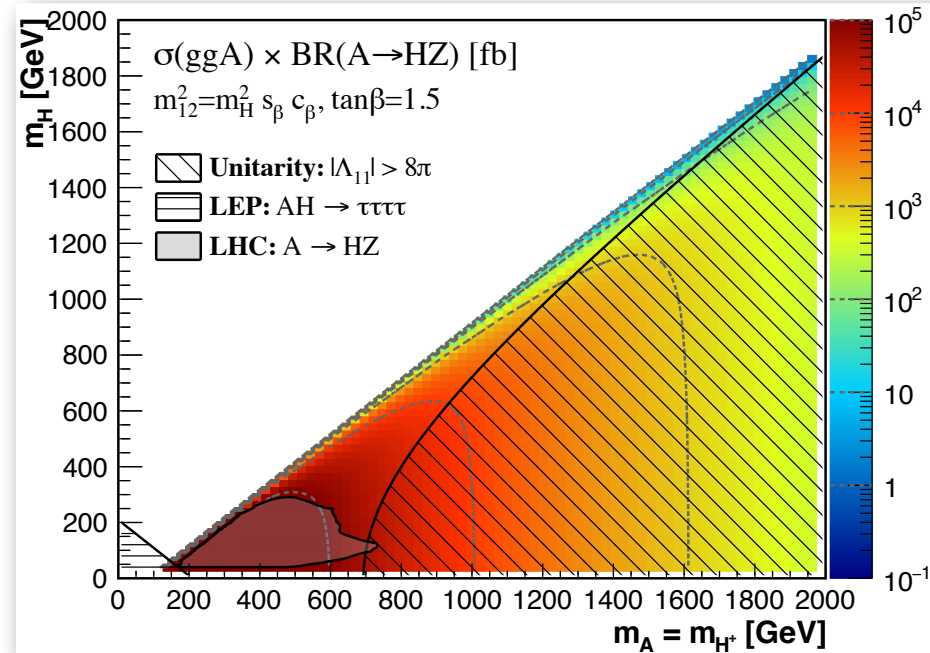
1604.01406 (With Kling and Jose Miguel No)

	Mass Planes	decays	$m_{12}^2$	$\tan \beta$	Figures
BP IA	$m_A > m_{H^+} = m_H$	$A \rightarrow H^\pm W^\mp$ $A \rightarrow HZ$	$m_H^2 s_\beta c_\beta$	1.5, 7, 30	5, 6
			0	1.5	
BP IB	$m_A < m_{H^+} = m_H$	$H \rightarrow AZ, H \rightarrow AA$ $H^\pm \rightarrow AW^\pm$	0	1.5	9
BP IIA	$m_H > m_{H^+} = m_A$	$H \rightarrow AZ, H \rightarrow AA$ $H \rightarrow H^+ H^-, H \rightarrow H^\pm W^\mp$	0	1.5	10
BP IIB	$m_H < m_{H^+} = m_A$	$A \rightarrow HZ$ $H^\pm \rightarrow HW^\pm$	$m_H^2 s_\beta c_\beta$	1.5, 7, 30	7, 8
			0	1.5	
BP III	$m_A = m_H = m_{H^+}$ vs. $c_{\beta-\alpha}$	$A \rightarrow hZ, H^\pm \rightarrow hW^\pm$ $H \rightarrow hh$	$m_H^2 s_\beta c_\beta$	1.5, 7, 30	11, 12, 13
			0	1.5	

$m_{H^\pm}$  vs.  $m_H = m_A$ : electroweak precision require  $m_{H^\pm} \sim m_A, m_H$ ,  
close exotic decay mass window.

# BPIIB

**BPIIB:  $m_H < m_{H^\pm} = m_A$     $A \rightarrow HZ$ ,  $H^\pm \rightarrow HW^\pm$**

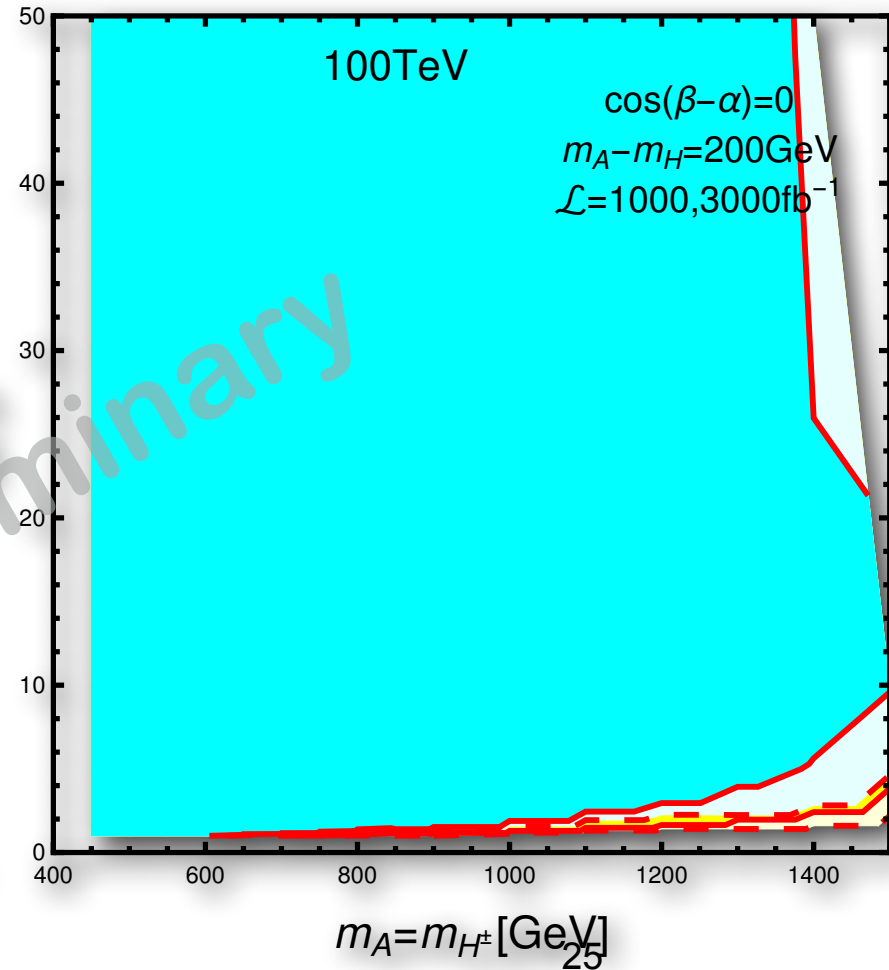
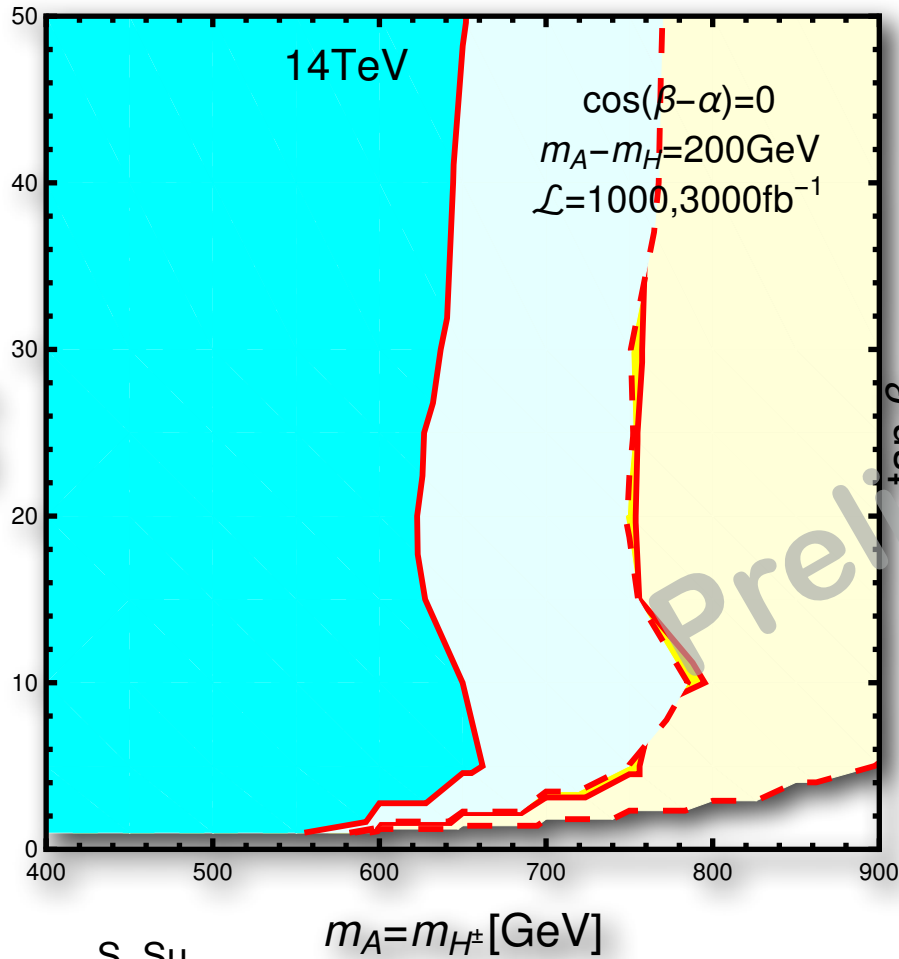


**100 TeV  $A \rightarrow HZ$**

# BPIIB

**BPIIB:  $m_H < m_{H^\pm} = m_A$   $A \rightarrow HZ$**

Kling, Li, Pyarelal, Song, SS,  
work in progress



# Conclusion

- ⦿ non-SM Higgs @ Extended Higgs sector
- ⦿ BSM Higgs search via conventional channel: top tagging
- ⦿ BSM Higgs search via exotic modes
  - ➔ Higgs → light Higgs + gauge boson
  - ➔ Higgs → two light Higgses

Complementary to conventional channels

An exciting journey ahead of us!



# 2HDM: Higgs Precision

Gu, Li, Liu, SS, Su, work in progress

