

# HEAVY HIGGS BOSONS

## FROM LHC TO 100 TeV

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arXiv:1504.07617 J. Hajer, T. Liu and J.F.H. Shiu

arXiv:1512.xxxxx N. Craig, J. Hajer, T. Liu and H. Zhang

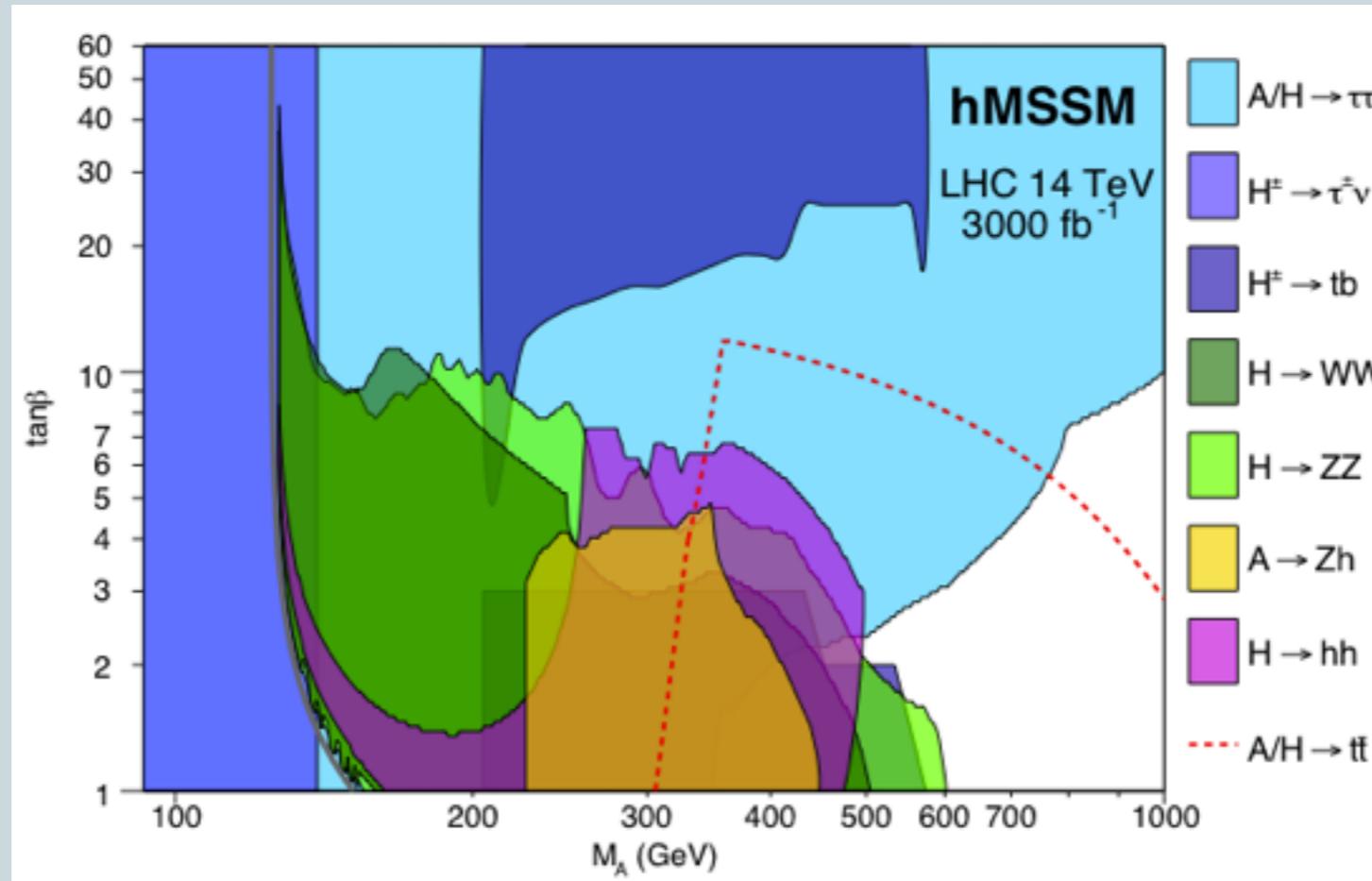


# BSM Higgs Bosons

- ¢ An extended Higgs sector extensively exists in NP
- ¢ We focus on the MSSM Higgs bosons (no CP-violation):  $H$ ,  $A$ ,  $H_c$ 
  - ¢ Higgs mass spectrum and couplings only depend on two parameters (in addition to the SM ones) at tree-level:  $\tan_{\beta}$ ,  $m_A/m_{H_c}$
  - ¢ So we can make a sensitivity projection on a plane expanded by these two parameters:  $m_A/m_{H_c} - \tan_{\beta}$
- ¢ It is straightforward to generalise the analyses to many other models, such as 2HDM, NMSSM, etc.



# MSSM Higgs Bosons at 14 TeV



[A. Djouadi et. al.'15]

See Marcela's talk

JianMing's talk

- ⌚ A sensitivity projected at the LHC, by rescaling the 7 and 8 TeV results to 14 TeV
- ⌚ The well-known wedge region still remains uncovered.
- ⌚ Potential difficulty for probing low  $\tan\beta$  region via  $gg \rightarrow H/A \rightarrow tt$ .



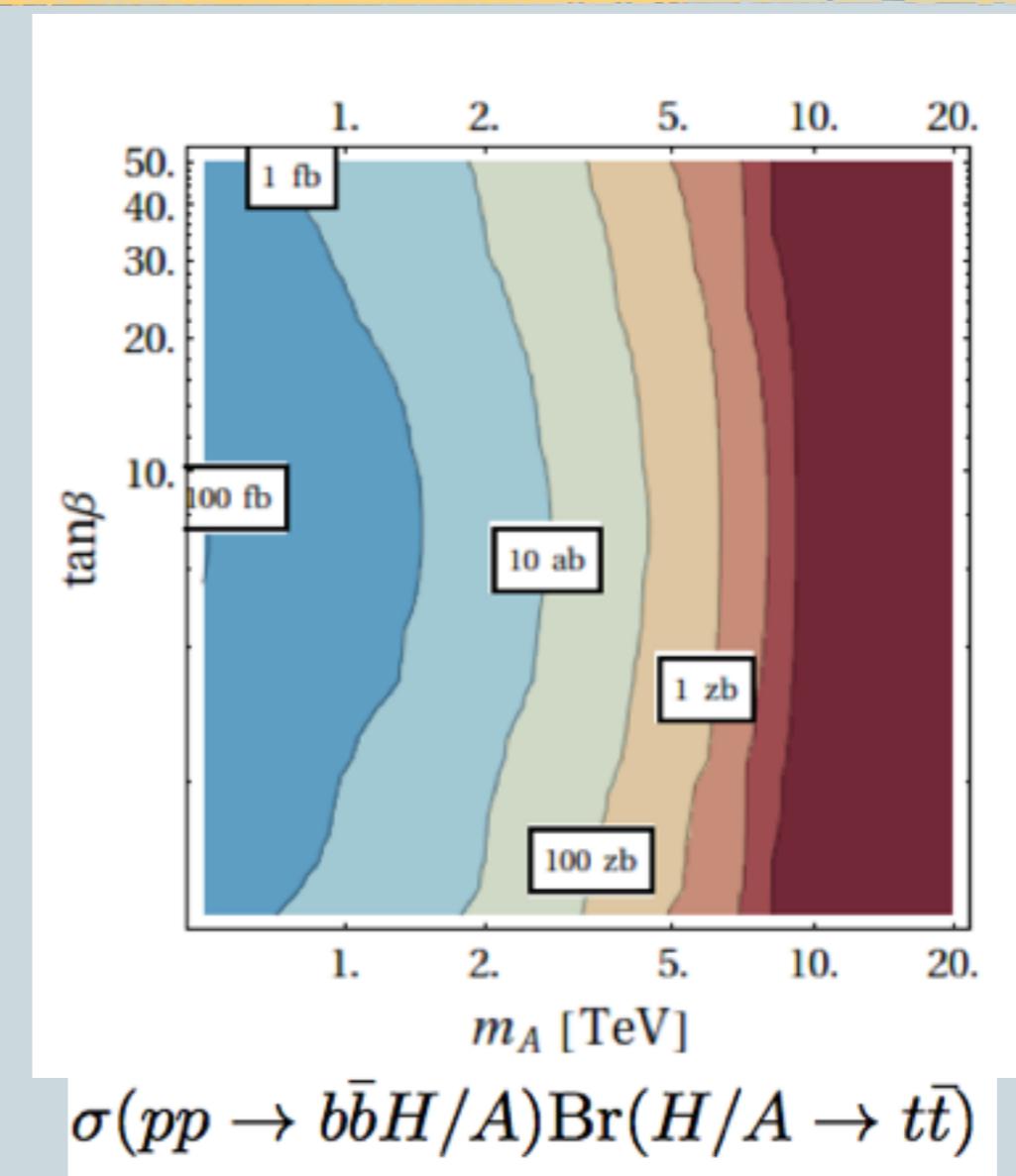
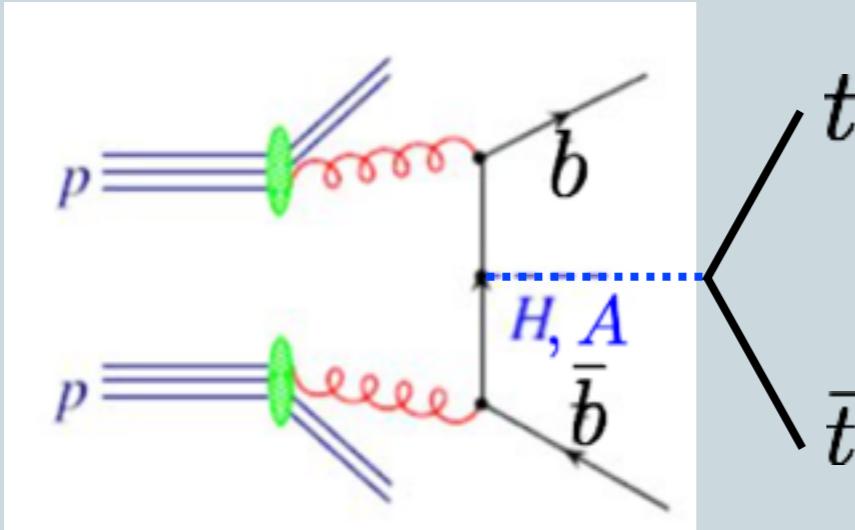
# Questions to Address

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- ¢ For neutral Higgs search, how to probe the uncovered wedge region?
- ¢ how to circumvent the difficulty of probing the low tan\_beta region via  $gg \rightarrow H/A \rightarrow tt$ ?
- ¢ What are the main contributing channels for charged Higgs search in the decoupling limit?
- ¢ What are the sensitivity reaches that might be achieved at the LHC and 100TeV Collider?



# Neutral Higgs-14TeV

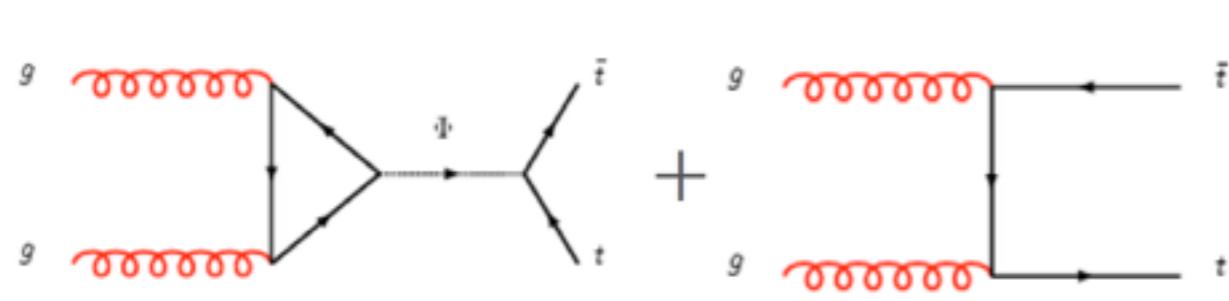


- ⌚ moderate  $\tan_\beta$  enhanced !
- ⌚ expected to yield a larger sensitivity for probing moderate  $\tan_\beta \Rightarrow$  the wedge region might be covered !

$$g_{HVV} = g_{hZA} = g_{hW^\mp H^\pm} \propto \cos(\beta - \alpha) \rightarrow 0$$



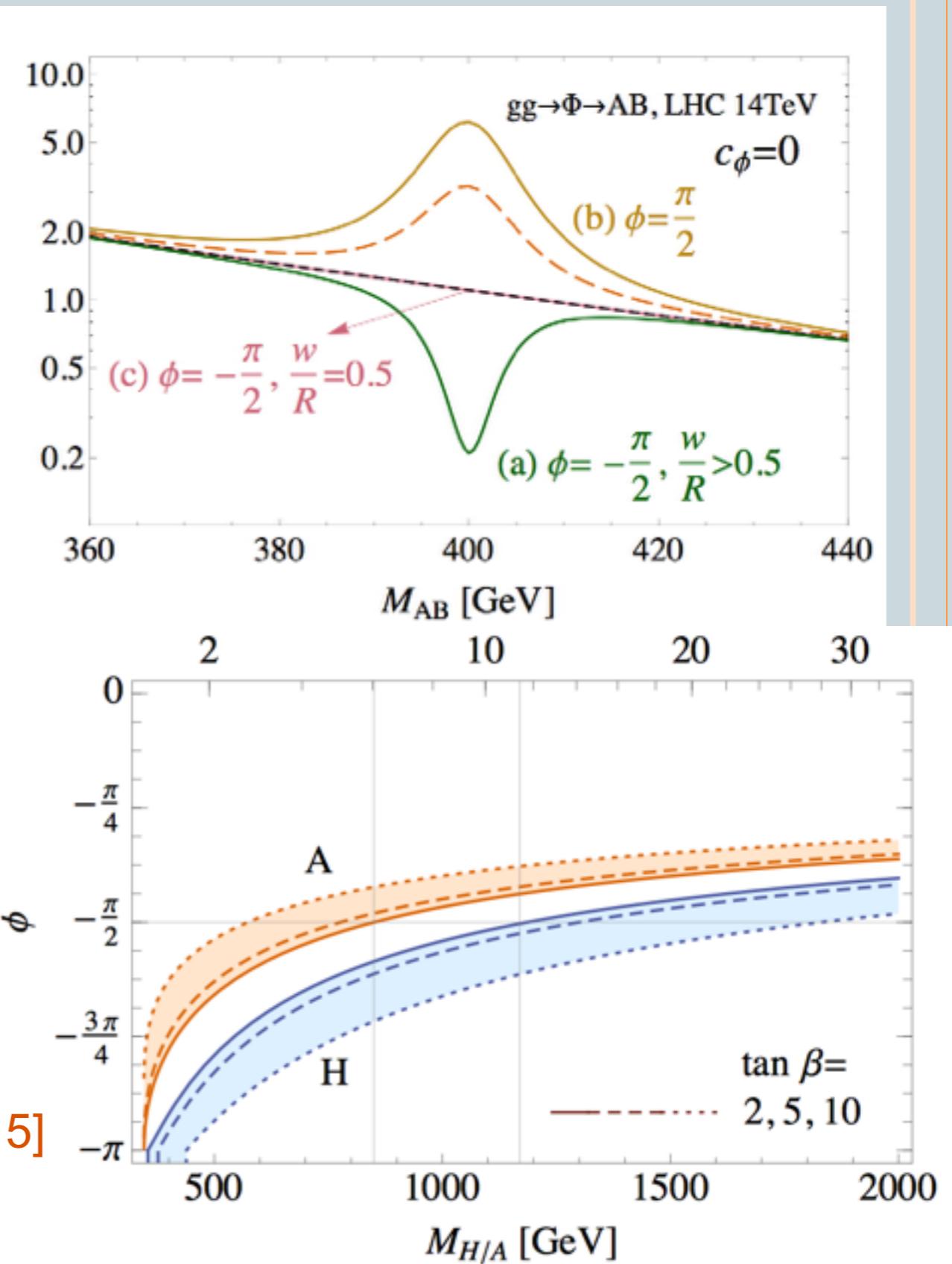
# Neutral Higgs-14TeV



$$\hat{\sigma} = \hat{\sigma}_{\text{bg}} + \frac{M^4}{(\hat{s} - M^2)^2 + M^4 w^2} \times \left[ \frac{2(\hat{s} - M^2)}{M^2} \hat{\sigma}_{\text{int}} c_\phi + \hat{\sigma}_{\text{res}} \left( 1 + \frac{2w}{R} s_\phi \right) \right]$$

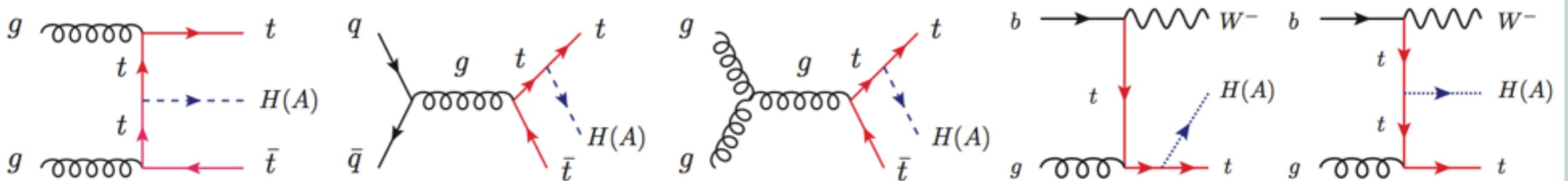
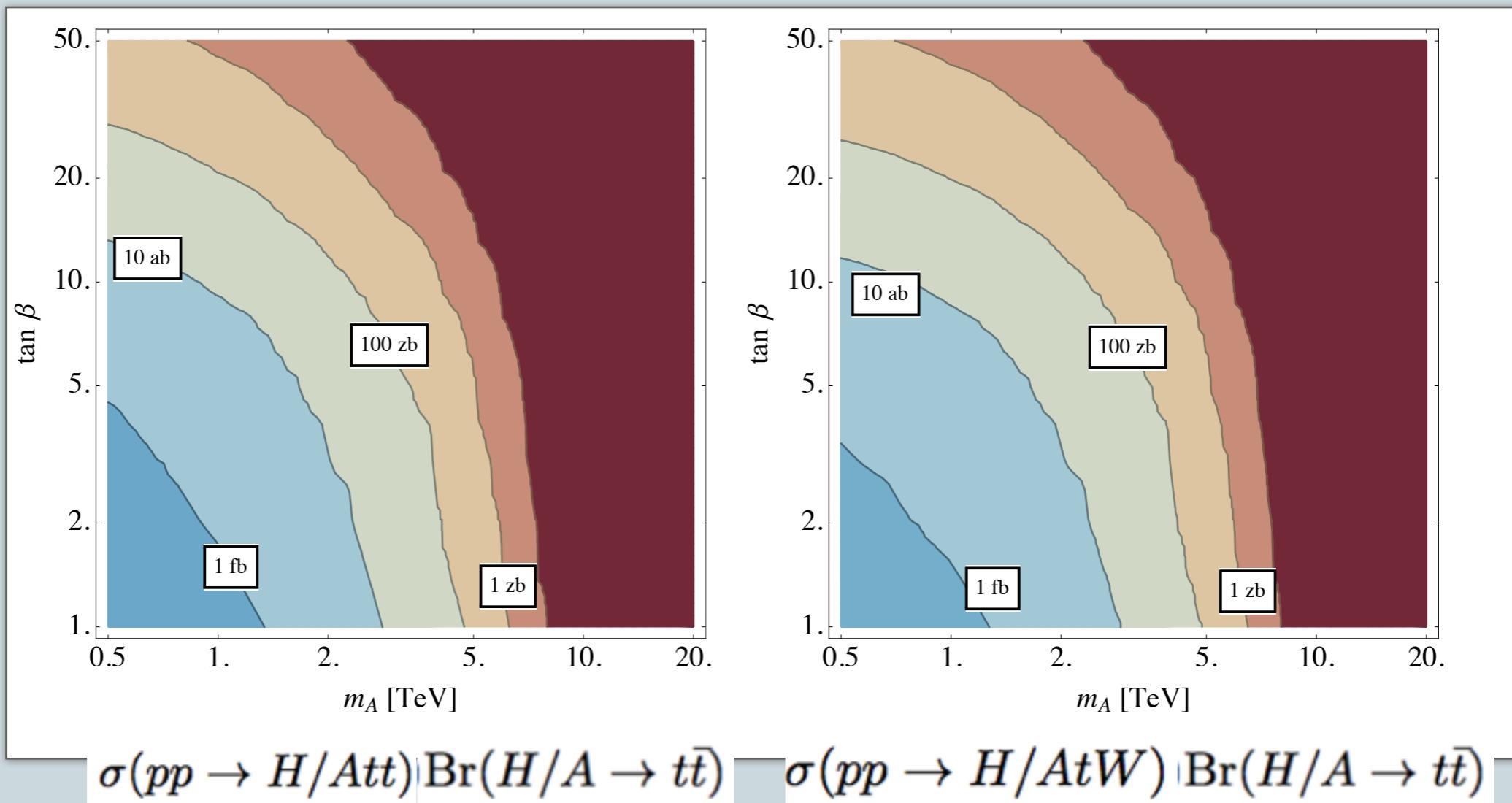
$$\begin{aligned} \hat{\sigma}_{\text{bg,res}} &= \frac{1}{32\pi\hat{s}} \int dz \sum \mathcal{A}_{\text{bg,res}}^2, \\ \hat{\sigma}_{\text{int}} e^{i\phi} &= \frac{1}{32\pi\hat{s}} \int dz \sum \mathcal{A}_{\text{bg}} \mathcal{A}_{\text{res}} e^{i(\phi_{\text{res}} - \phi_{\text{bg}})} \\ R &= \frac{\hat{\sigma}_{\text{res}}}{\hat{\sigma}_{\text{int}}} , \quad w \equiv \frac{\Gamma}{M}. \end{aligned}$$

[J. Sunghoon et. al.'15]



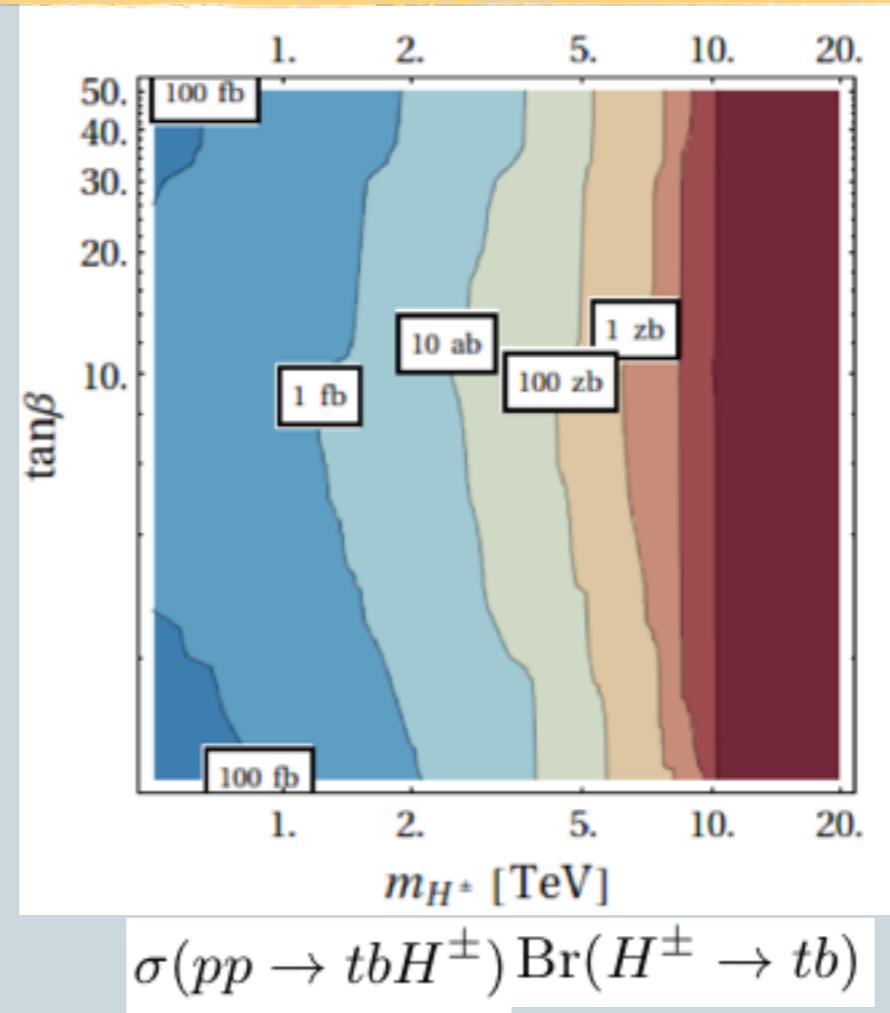


# Neutral Higgs-14TeV





# Charged Higgs-14TeV



- Production: tb Hc is dominant, enhanced by both low and high  $\tan\beta$
- Decay: dominated by Hc  $\rightarrow$  bt (particularly for low  $\tan\beta$ )  
can not neglect Hc  $\rightarrow$  tau+vt for high  $\tan\beta$  region

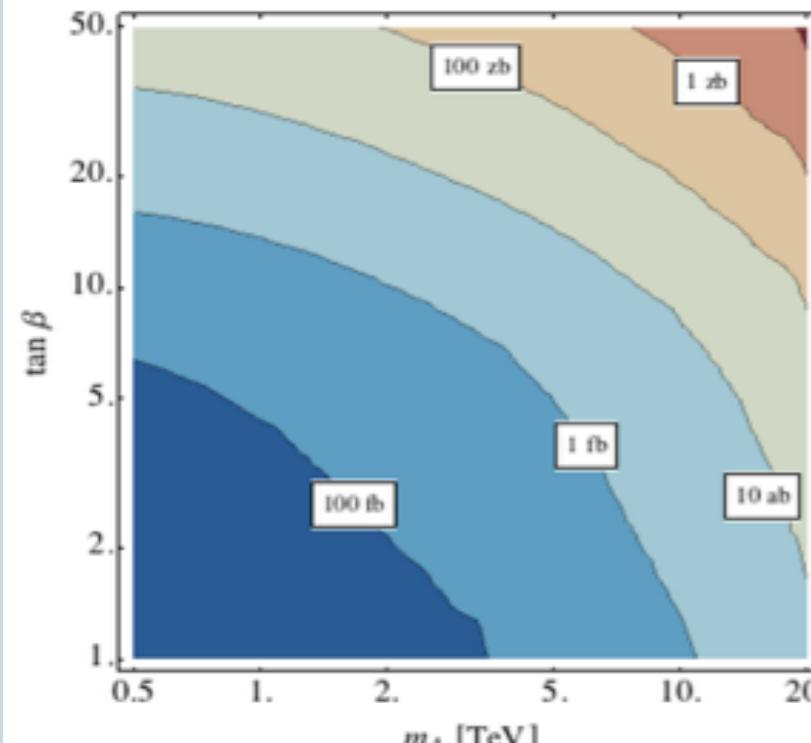
$$g_{H^+\bar{u}d} = \frac{1}{\sqrt{2}v} V_{ud}^* [m_d \tan\beta (1 + \gamma_5) + m_u \cot\beta (1 - \gamma_5)]$$



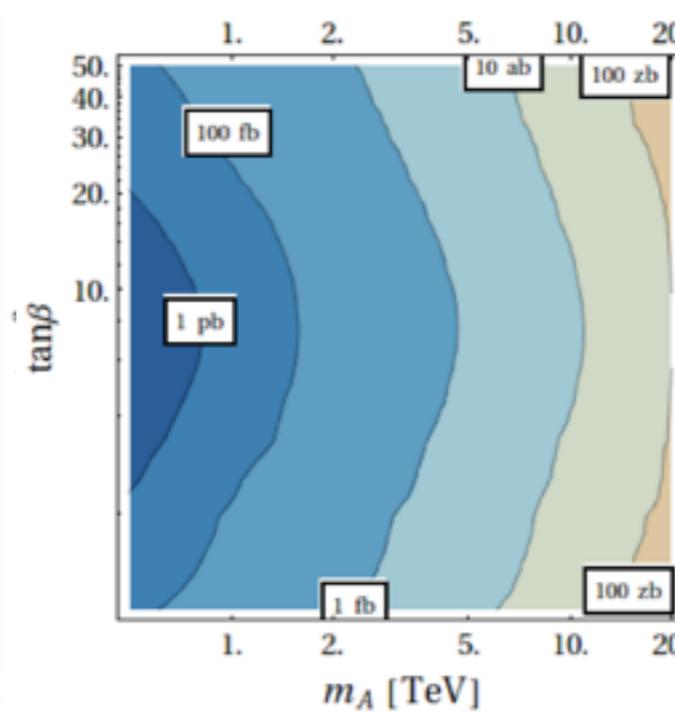
# Expectation

	$\tan \beta$	Channels
Neutral Higgs ( $H/A$ )	High	$pp \rightarrow bbH/A \rightarrow bb\tau\tau, bbbb$
	moderate	$pp \rightarrow bbH/A \rightarrow bbtt$
	Low	$pp \rightarrow H/A \rightarrow tttt$
Charged Higgs ( $H^\pm$ )	High	$pp \rightarrow tbH^\pm \rightarrow tbtb, tb\tau\nu_\tau$
	Low	$pp \rightarrow tbH^\pm \rightarrow tbtb$

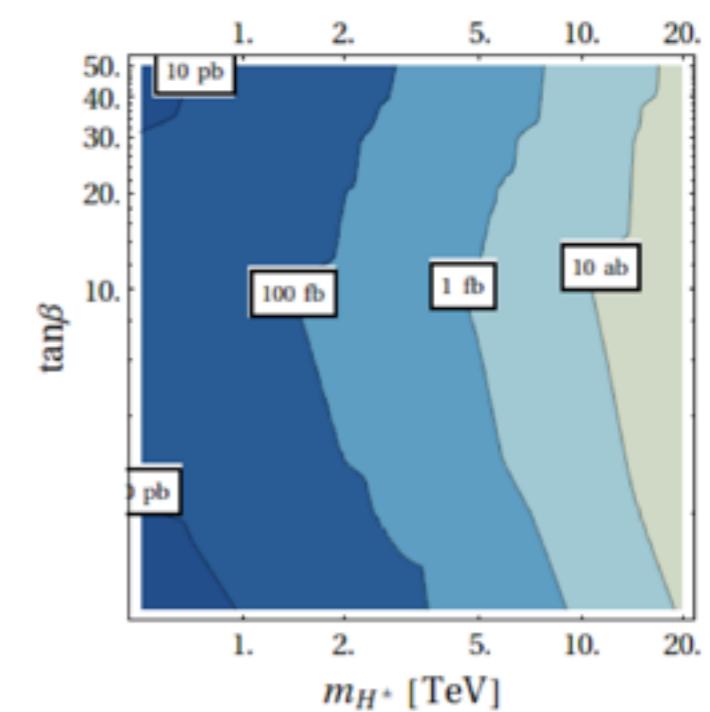
100TeV



(a)  $pp \rightarrow tH(A) + X \rightarrow ttt + X$



(b)  $\sigma(pp \rightarrow b\bar{b}H/A)\text{Br}(H/A \rightarrow t\bar{t})$



(c)  $\sigma(pp \rightarrow tbH^\pm)\text{Br}(H^\pm \rightarrow tb)$



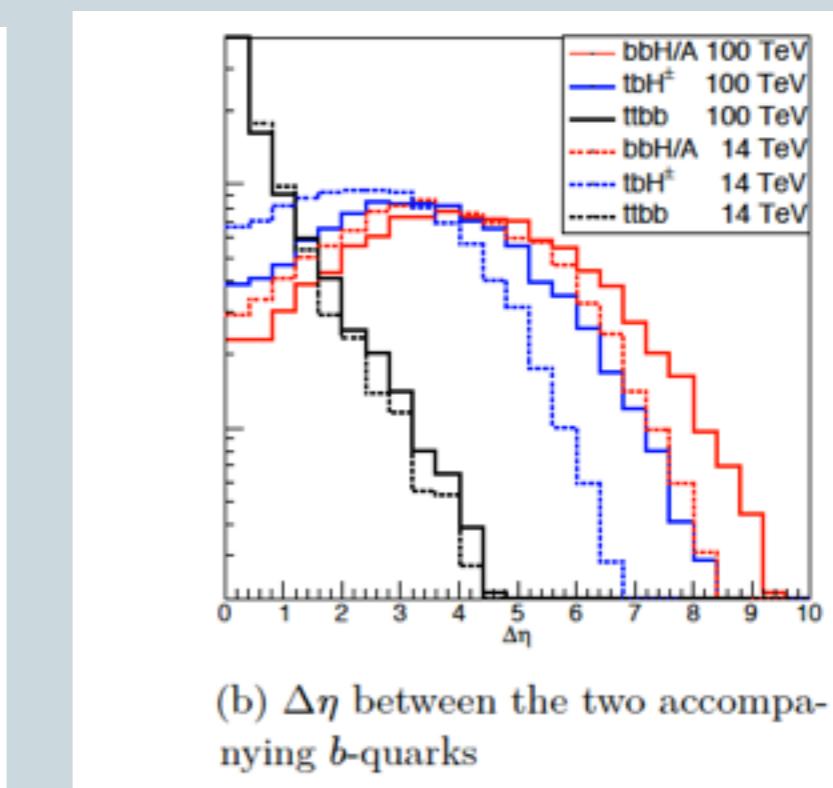
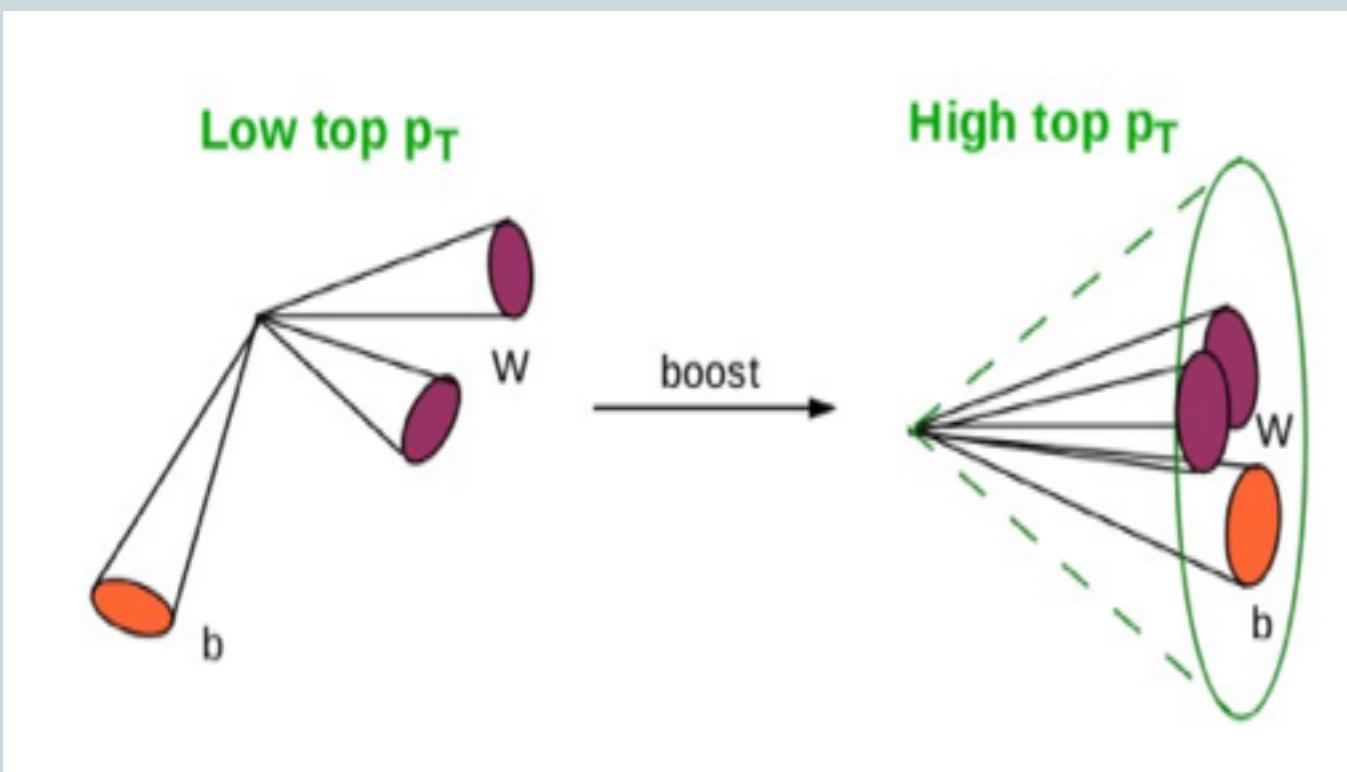
# Kinematics

## Heavy Higgs resonance

related to the heaviness of Higgs bosons in the decoupling limits, boosted top.

## Forwardness/Backwardness of accompanying particles

the accompanying particles are less boosted, but tend to have a large rapidity.

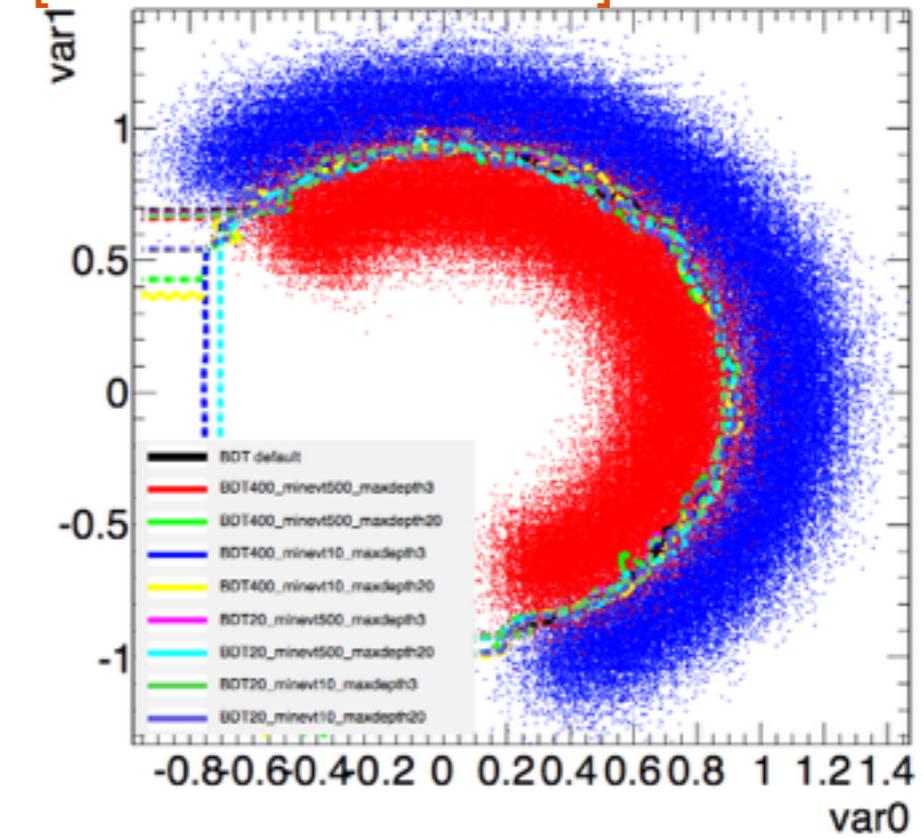




# BDT

BDT: Non-linear combination of variables.  
optimise the analysis.

[Yann COADOU '13]

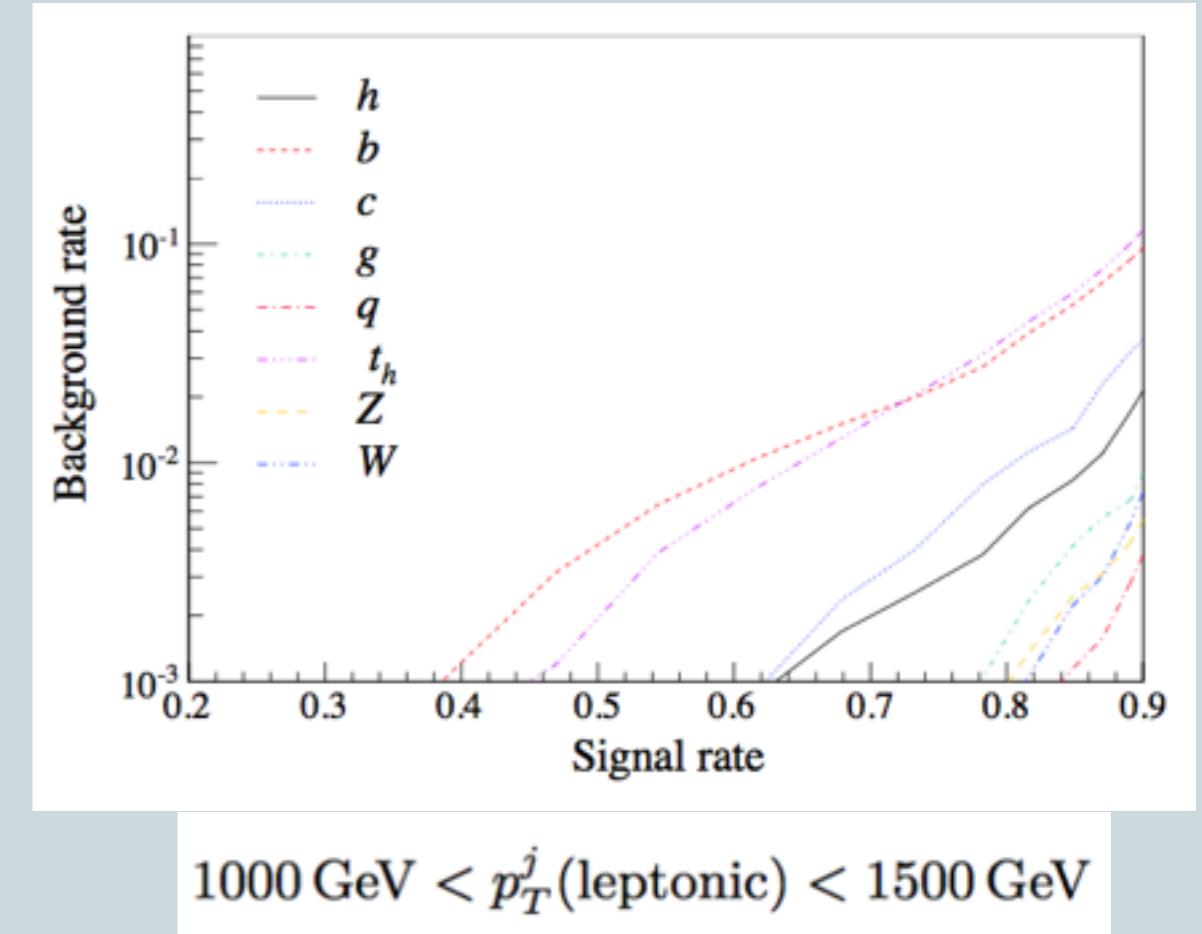
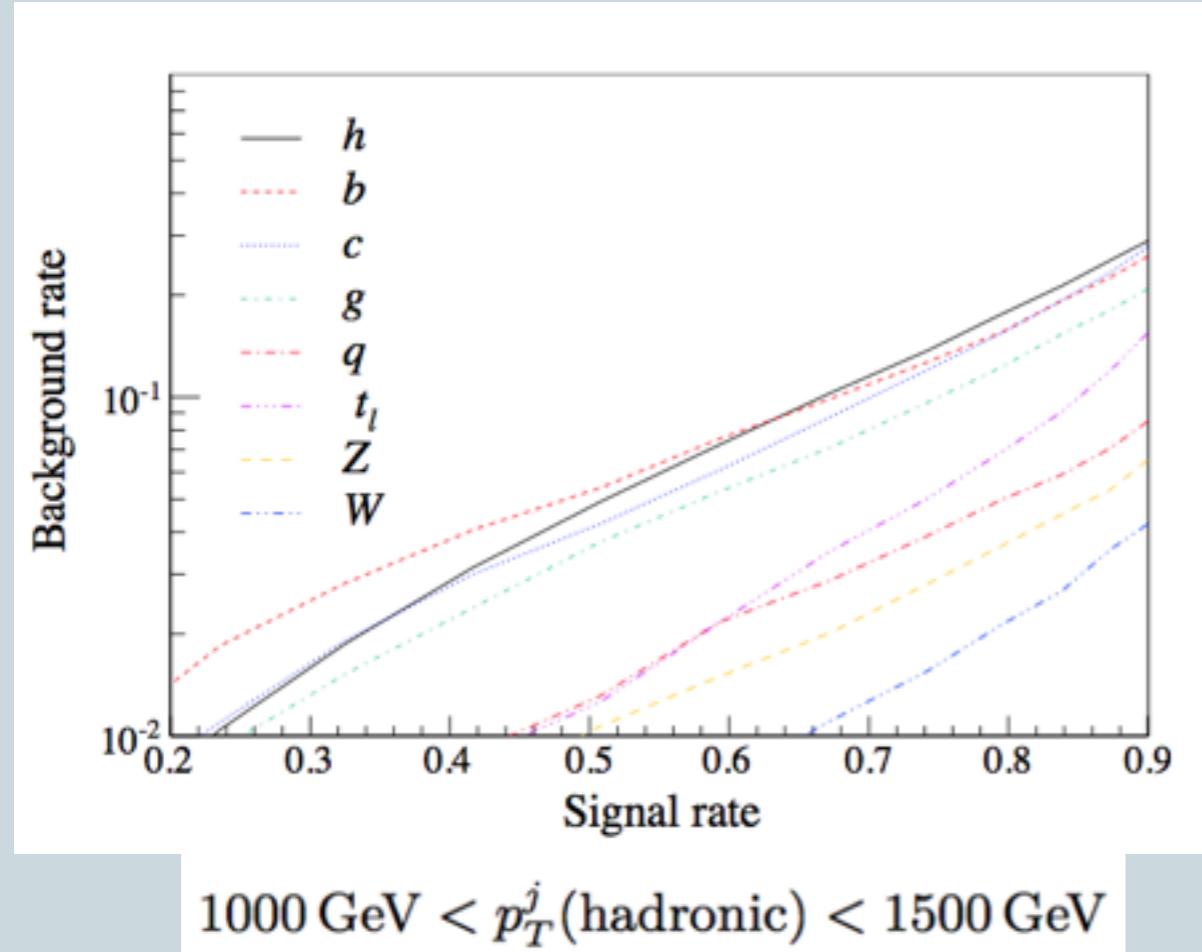


(a) Circular correlation example

- ⌚ Construct top BDT: one is hadronic, another one is leptonic.
- ⌚ Construct Bottom Fusion BDT: demand two b-like jets with large delta eta



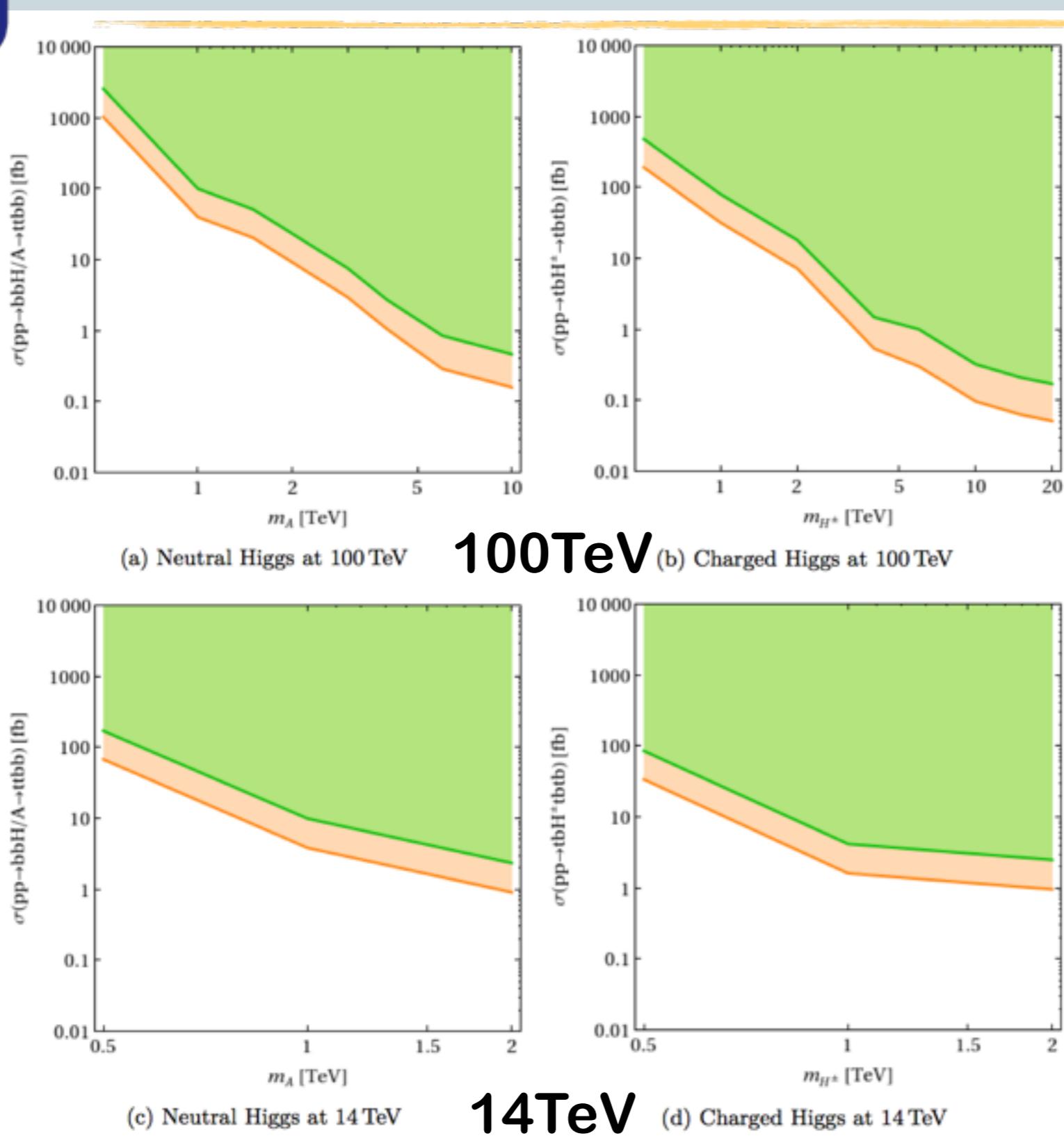
# Top Tagger BDT



- hadronic top tagger: b secondary vertex and jet mass information, also veto hard lepton.
- leptonic top tagger: b secondary vertex and lepton information, as well as jet mass requirement.



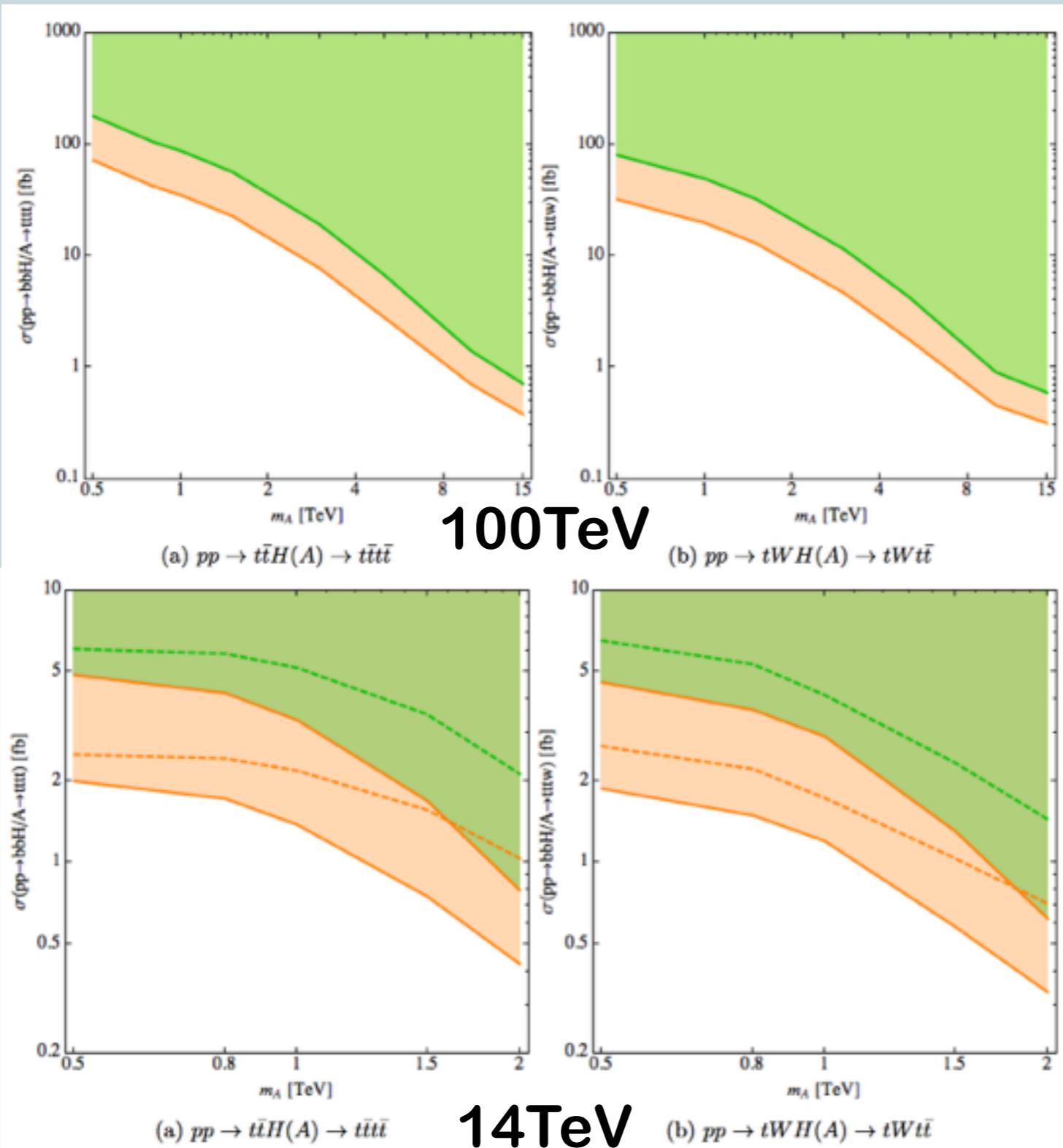
# Model-independent Exclusion limit



- ⌚ As mass increases, the constraints becomes stronger.
- ⌚ Constraints are weaker at 100TeV.



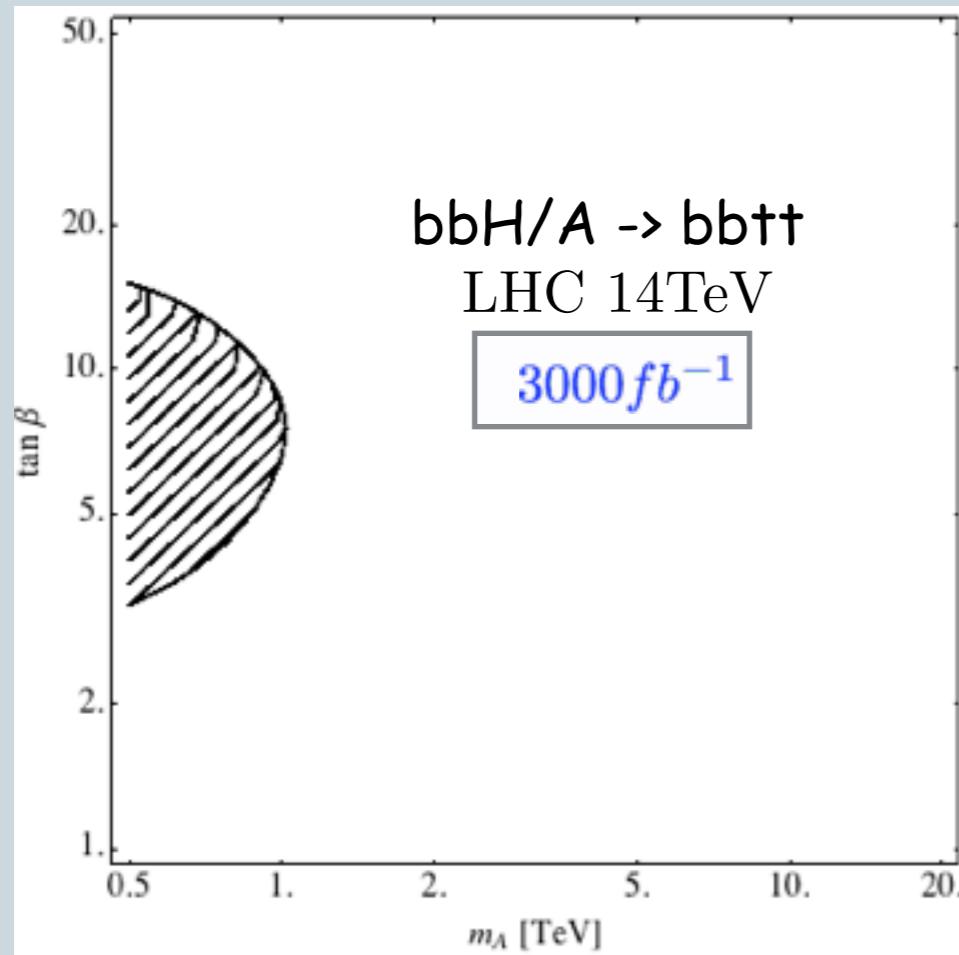
# Model-independent Exclusion limit



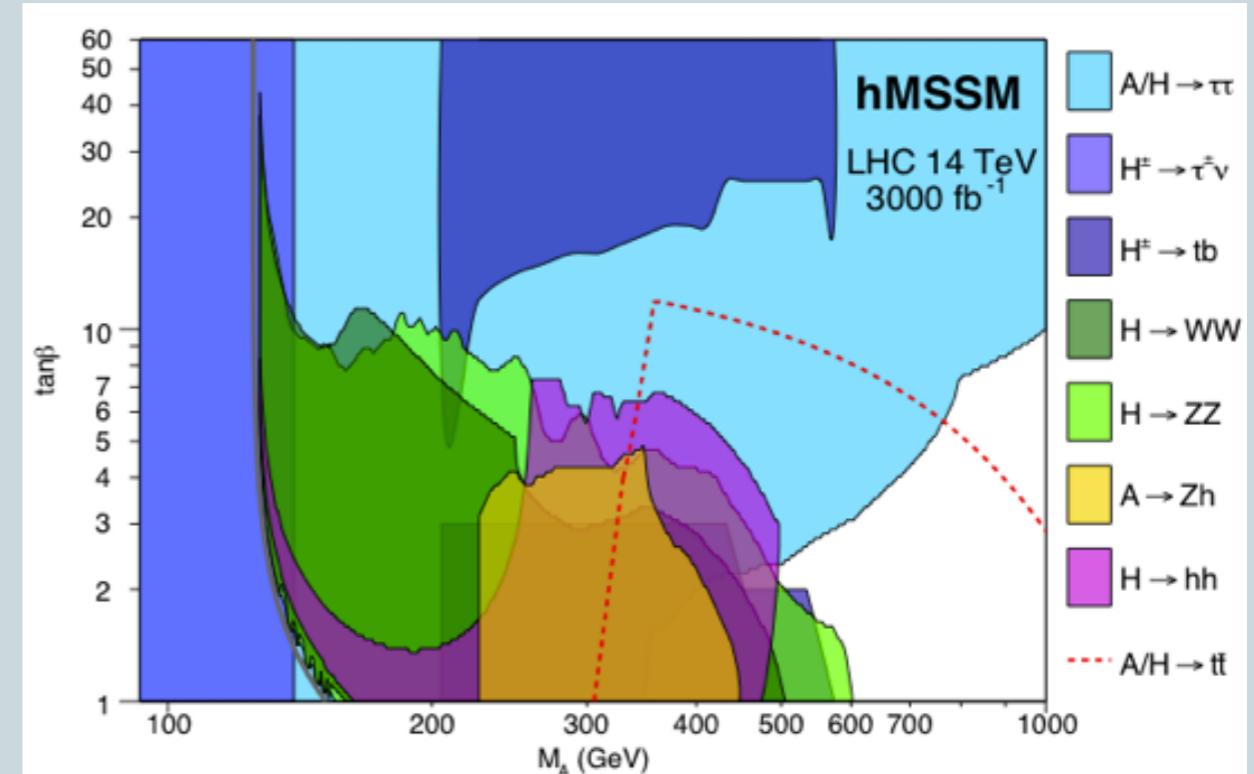
- ⌚ As mass increases, the constraints becomes stronger.
- ⌚ Constraints are weaker at 100TeV.



# Neutral Higgs Exclusion Limit-14TeV



(a) Exclusion limit

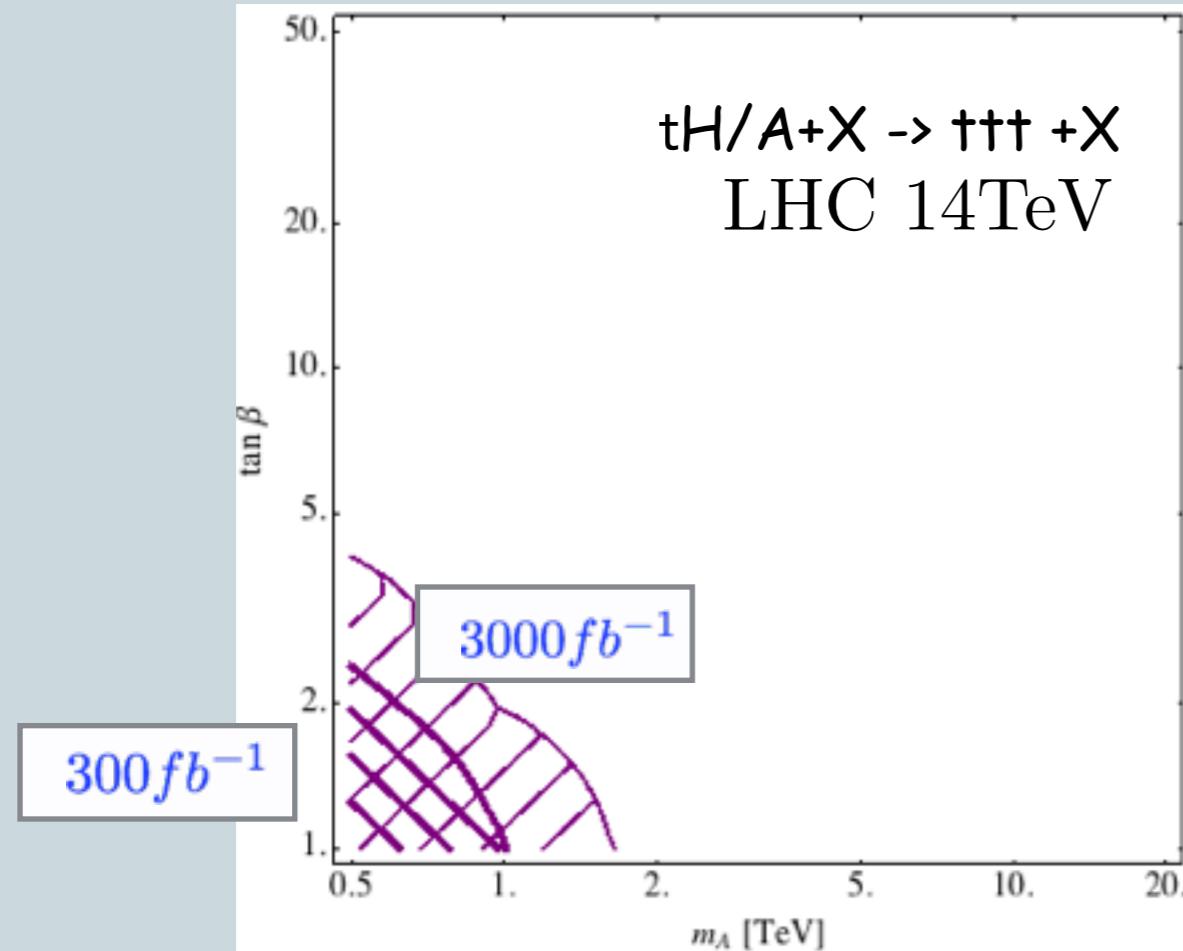


[A. Djouadi et. al.'15]

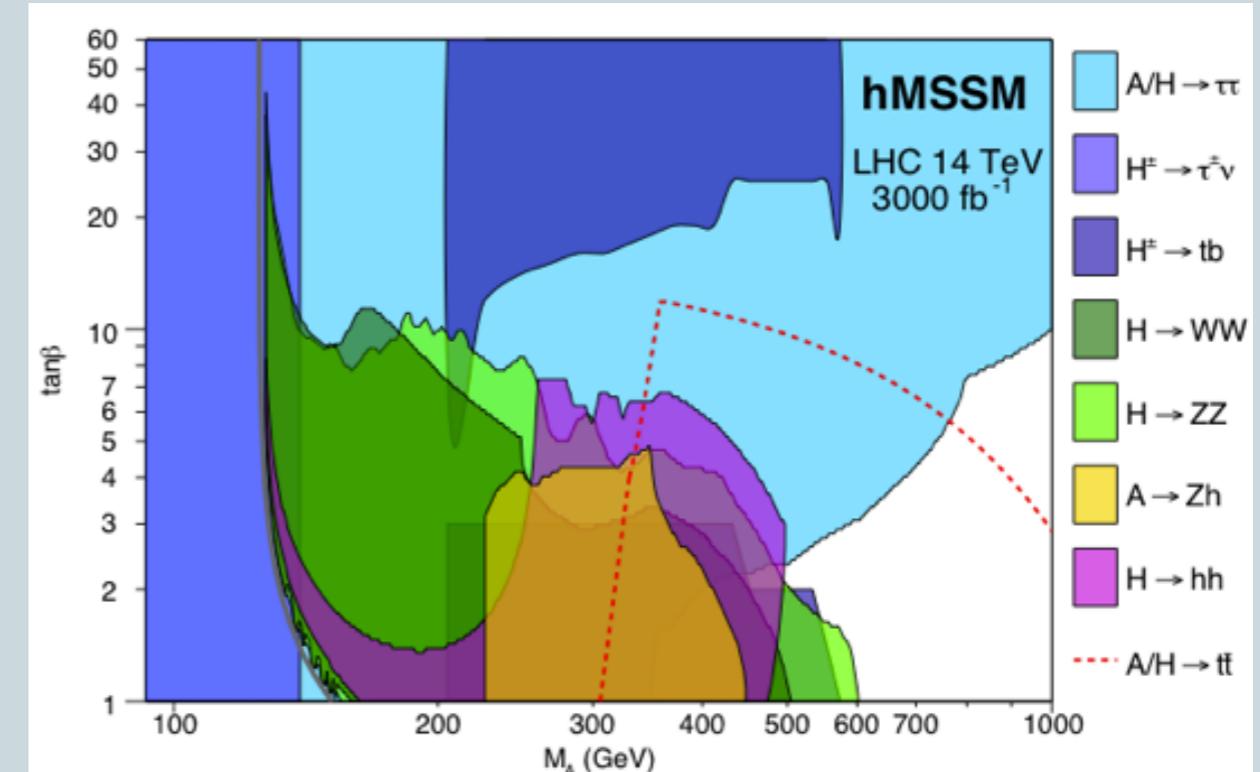
- ¢ The wedge region centered on moderate  $\tan \beta$  is covered(3/ab).
- ¢ A potentially to exclude  $m_A/m_H$  up to 1 TeV via  $bbH/A \rightarrow bb\tau\tau$ , with  $\tau\tau$  decaying semi-leptonically.



# Neutral Higgs Exclusion Limit-14TeV



(a) Exclusion limit

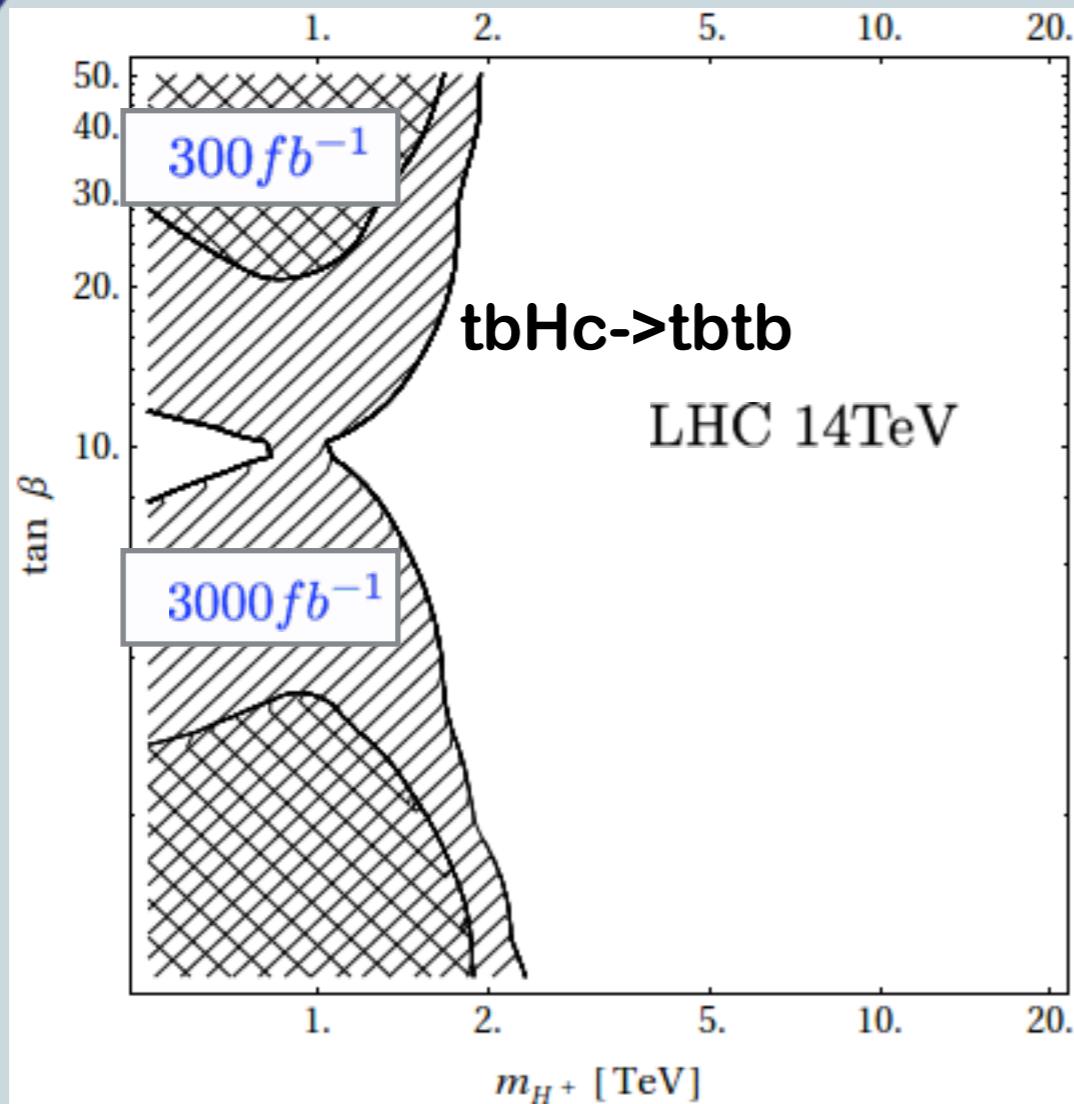


[A. Djouadi et. al.'15]

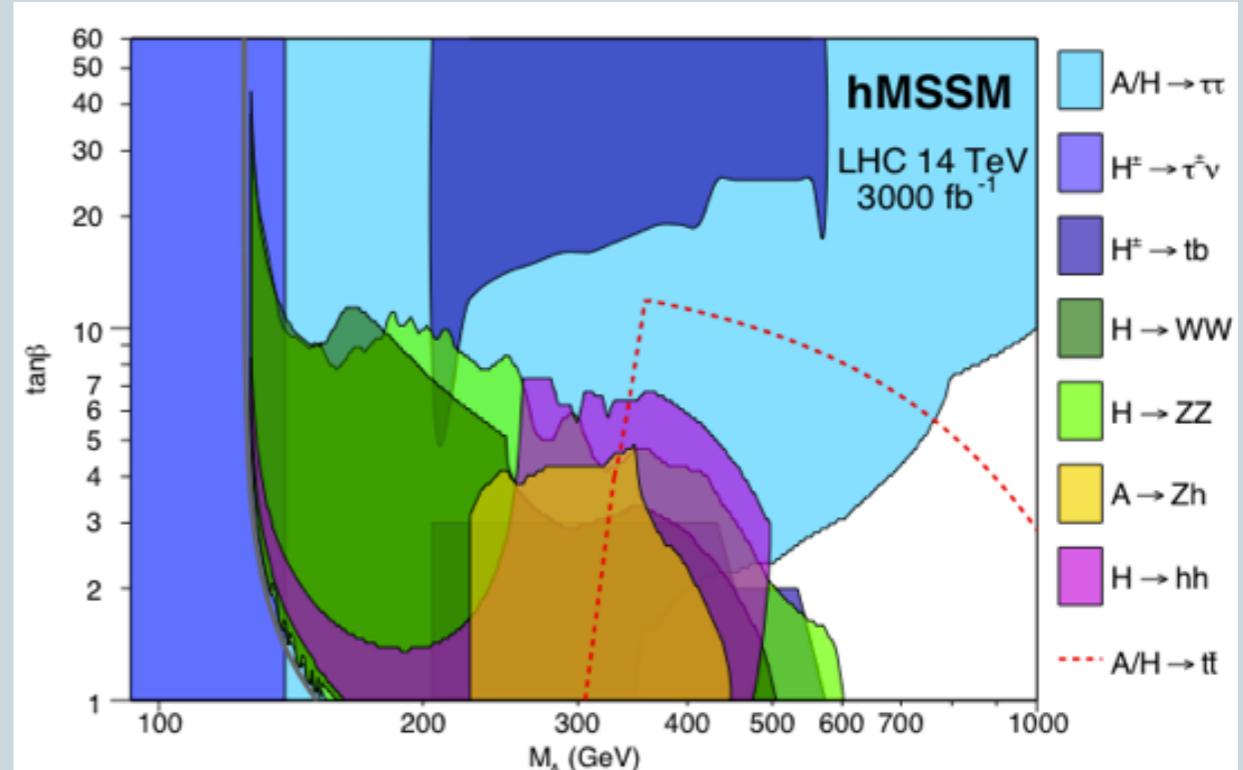
- ¢ The red dotted line for low  $\tan\beta$  region is covered to  $\sim 1$  TeV for  $(0.3/\text{ab})$  and to  $\sim 1.5$  TeV for  $(3/\text{ab})$ .
- ¢ Associated production help to probe the low  $\tan\beta$  region.



# Charged Higgs Exclusion Limit-14TeV



(a) Exclusion limit

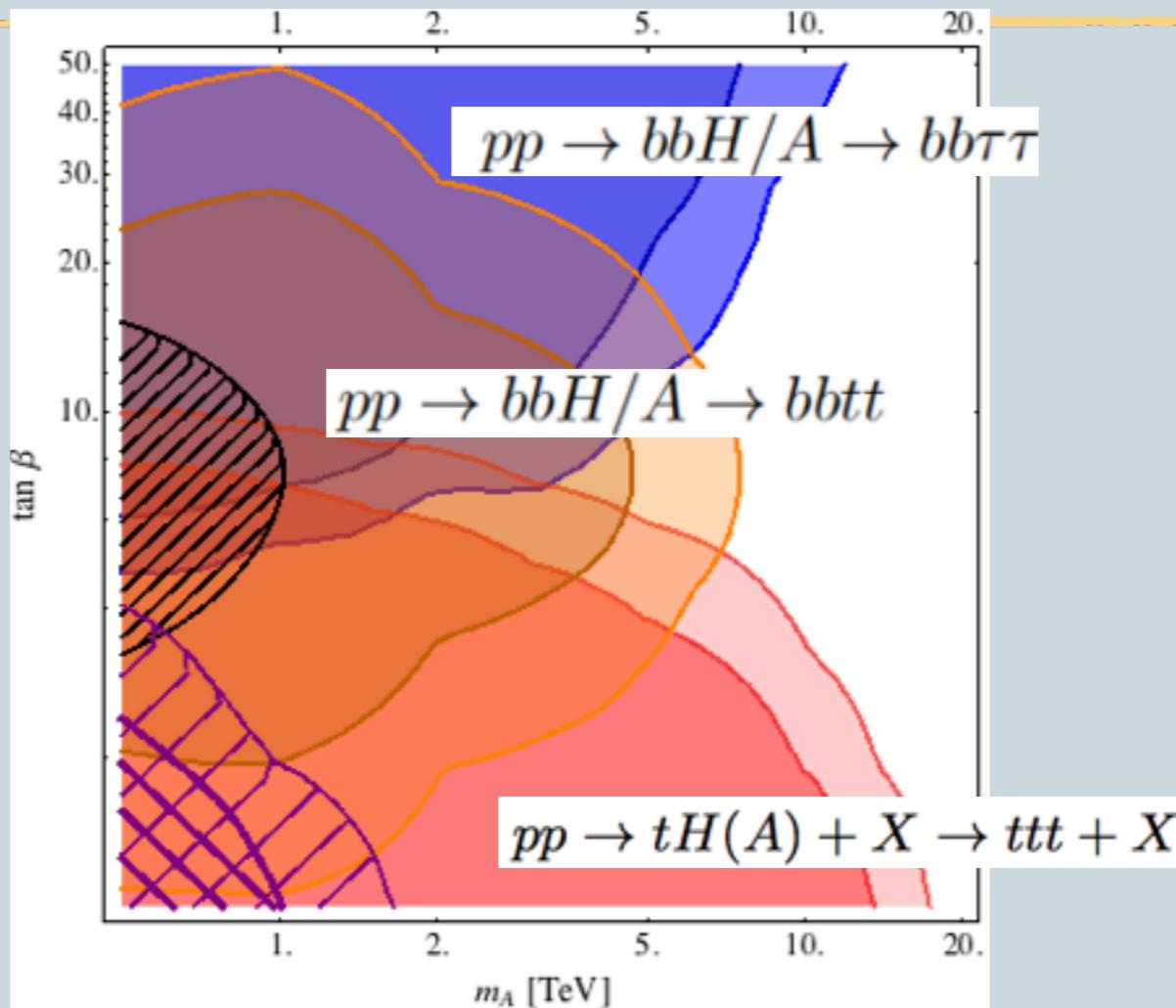


[A. Djouadi et. al.'15]

- Combine with  $bbH/A \rightarrow bbtt$ ,  $\text{tbHc} \rightarrow \text{tbtb}$  can push the exclusion limit up to  $\sim 2$  TeV



# Conclusion-Neutral Higgs at 100 TeV

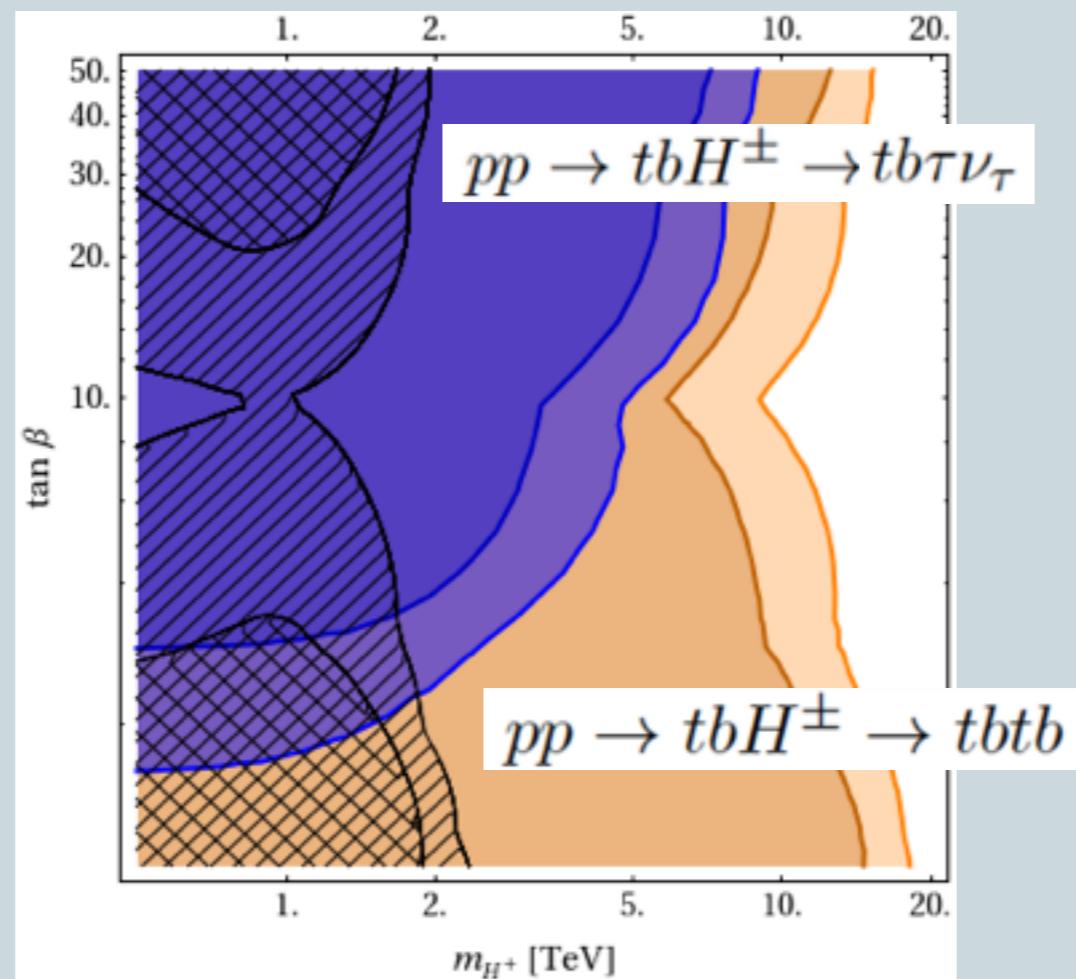


(a) Exclusion limit

- ⌚ Different transparency represents different luminosity, 30/ab and 3/ab.
- ⌚ Large  $\tan \beta$ :  $bbH \rightarrow bbt\tau\tau$  continues to play a significant role.
- ⌚ A potential to exclude  $m_A/m_H$  up to 10TeV via  $bbH/A \rightarrow bbtt$  (30/ab), with  $tt$  decaying semi-leptonically, except for low  $\tan \beta$  region.



# Conclusion-Charged Higgs at 100 TeV



(a) Exclusion limit

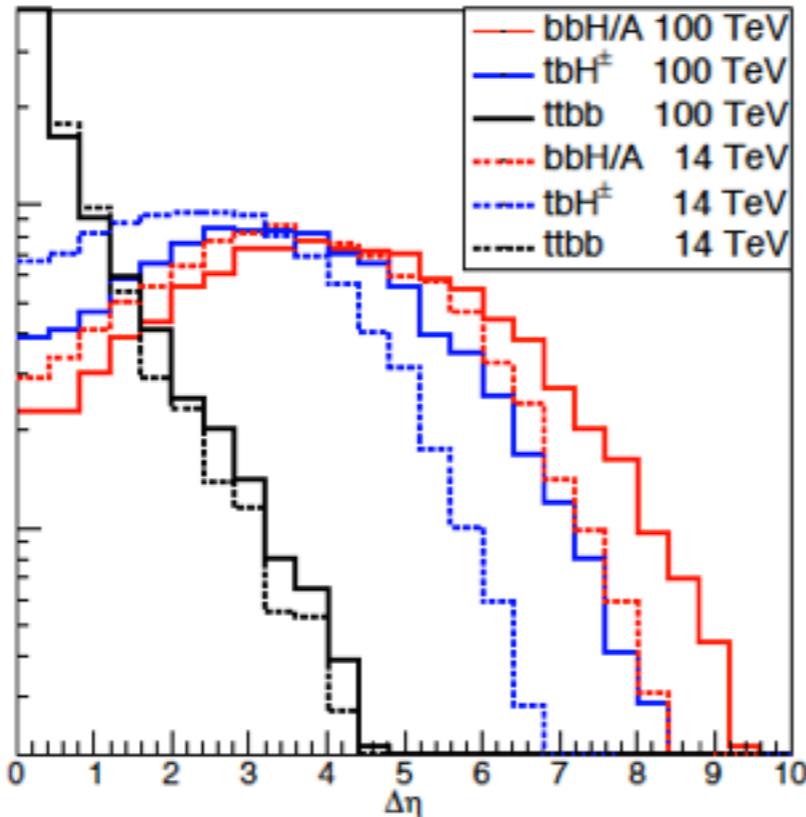
- ⌚ Different transparency represents different luminosity, 30/ab and 3/ab.
- ⌚ A potential to exclude mHc up to 10 TeV via tbHc  $\rightarrow$  tbtb (30/ab) for the whole tan\_beta region, with tt decaying semi-leptonically
- ⌚ Cover up to 20TeV (30/ab) for both high and low tan\_beta region.



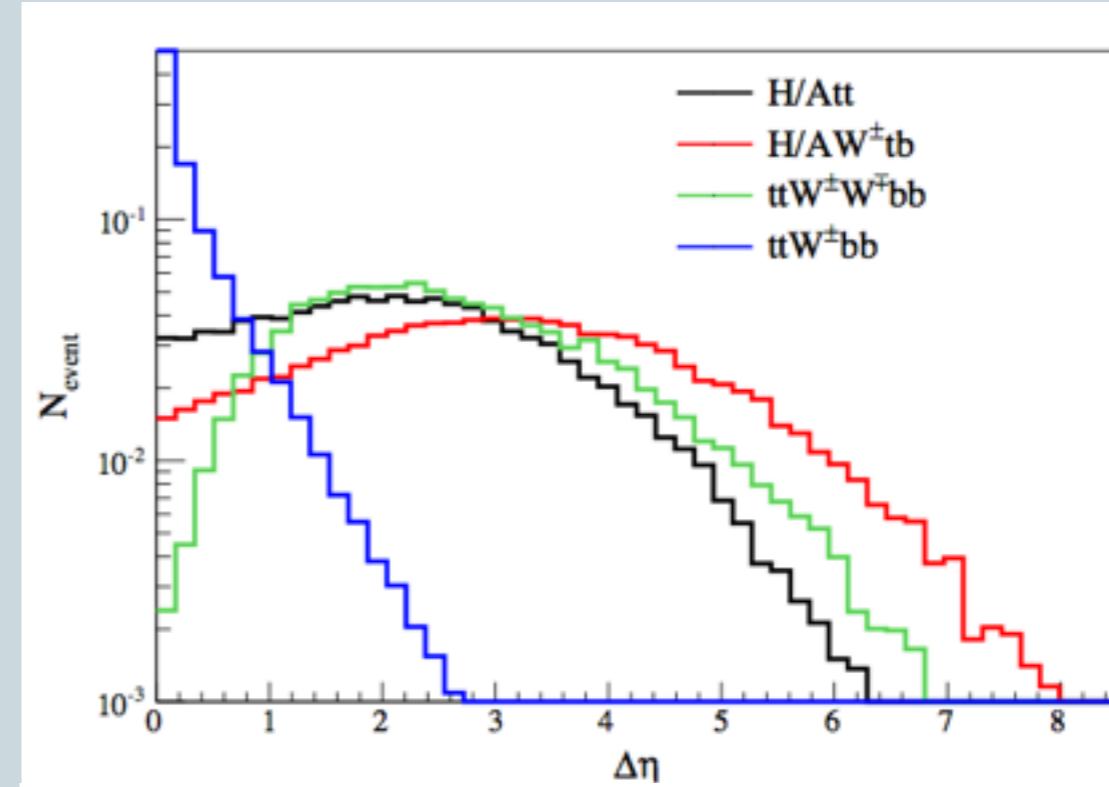
**Thank you**



# Kinematics - Particles Accompanying Higgs Production



$\Delta\eta$  between the two accompanying  $b$ -quarks



$\Delta\eta$  between two accompanying  $b$ -quarks

- ⌚ All  $b$  quarks are required to have  $p_T > 40$  GeV for 100TeV, and  $p_T > 20$  GeV for 14TeV.
- ⌚ The  $b$ -quarks accompanying Higgs production tend to be forward and backward => large delta eta

