# The light charged Higgs and CP odd Higgs bosons at the LHC

*Seodong Shin*

Seoul National University / Indiana University

Work in progress with R. Dermisek, J.P. Hall, E. Lunghi

Phenomenology 2013 Symposium, May 6

# Outline

- Charged Higgs lighter than top quark
- Light CP odd Higgs from doublet/singlet
- Constraint from $H \to WW$ search
- Conclusions

# Charged Higgs lighter than *t* quark

*We may have more than one Higgs boson*

# The discovery of the SM Higgs-like particle

- An important quest of the LHC

5σ $h \to \gamma\gamma$ $h \to ZZ^* \to 4\ell$

+ $h \to WW \to 2\ell 2\nu$ $h \to 2\tau$

- The existence of a fundamental scalar in the nature
- Why do we have only one scalar? Extended Higgs sector

  (Talks in this session!)
- Additional SU(2) doublet as a minimal extension

Interesting phenomena by charged Higgs boson

# Charged Higgs lighter than top quark

$t \to H^+ b$

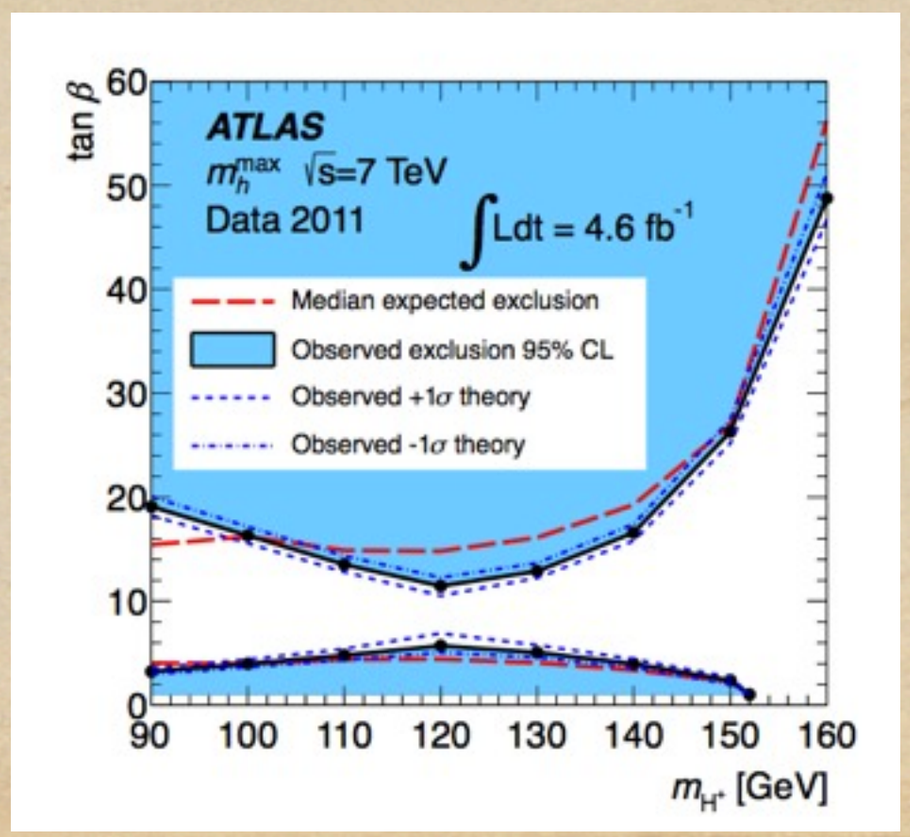
LHC : top factory

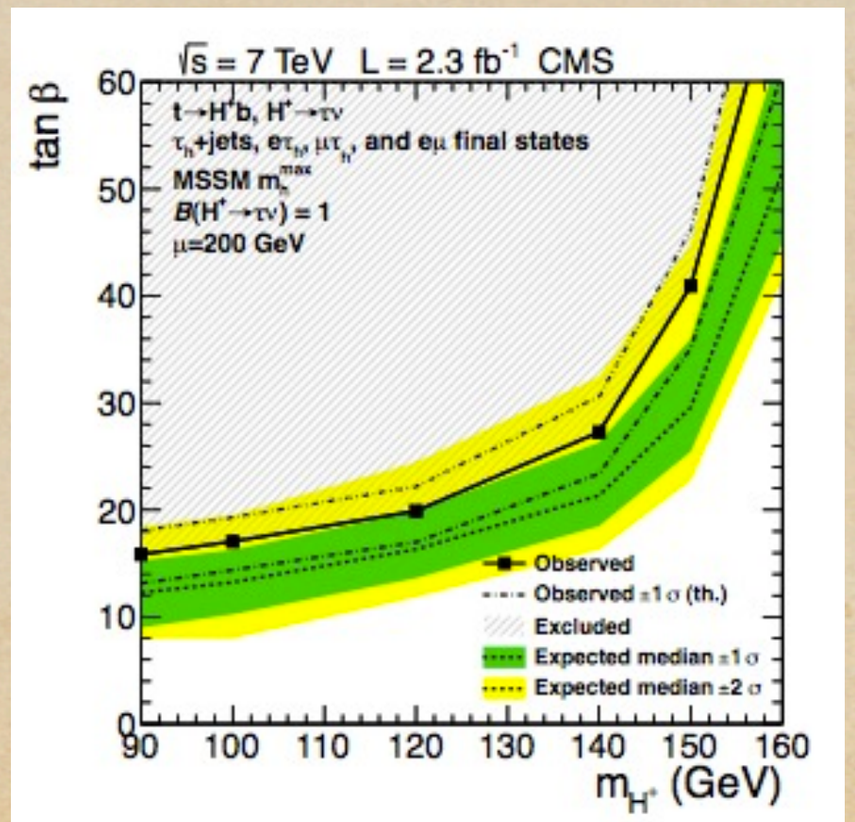
- quickly search it with the current data

Main consideration : MSSM $H^+ \to \bar{\tau}\nu$ or $c\bar{s}$

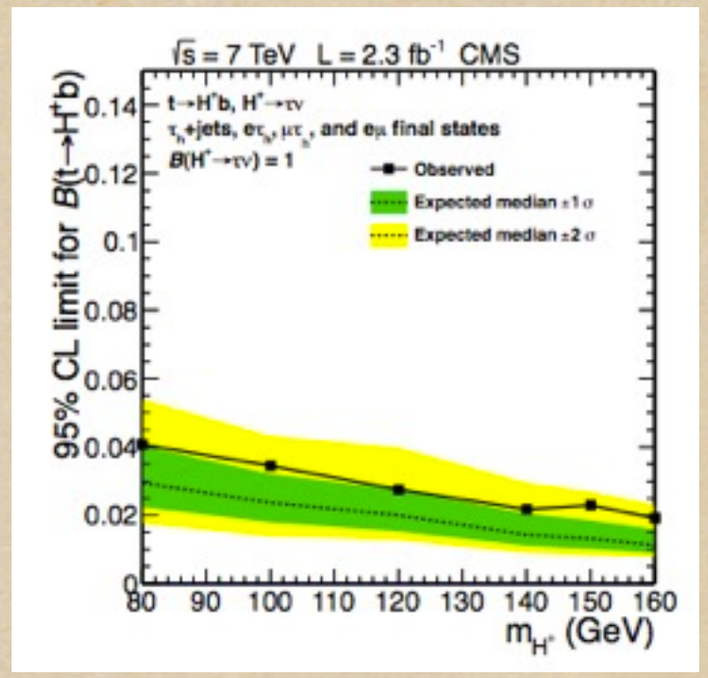
Good bounds!!

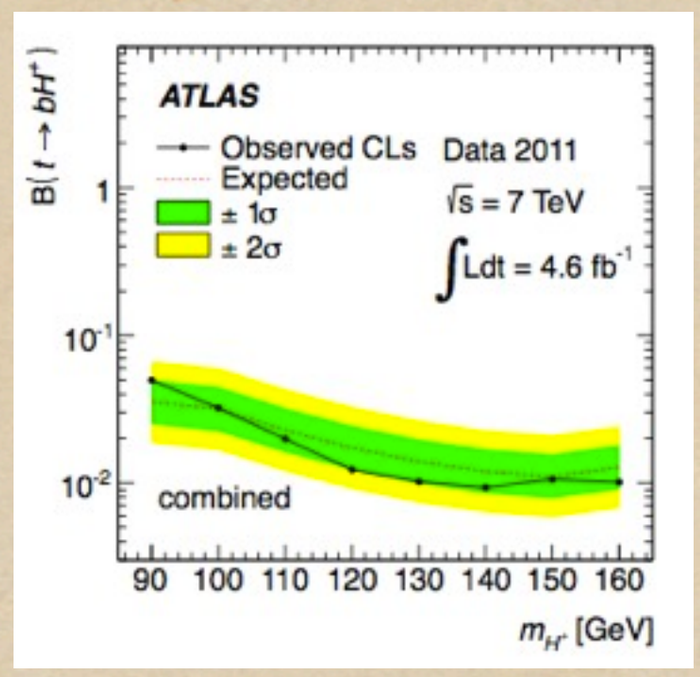
$$\mathrm{Br}(H^+ \to \bar{\tau}\nu) = 1$$



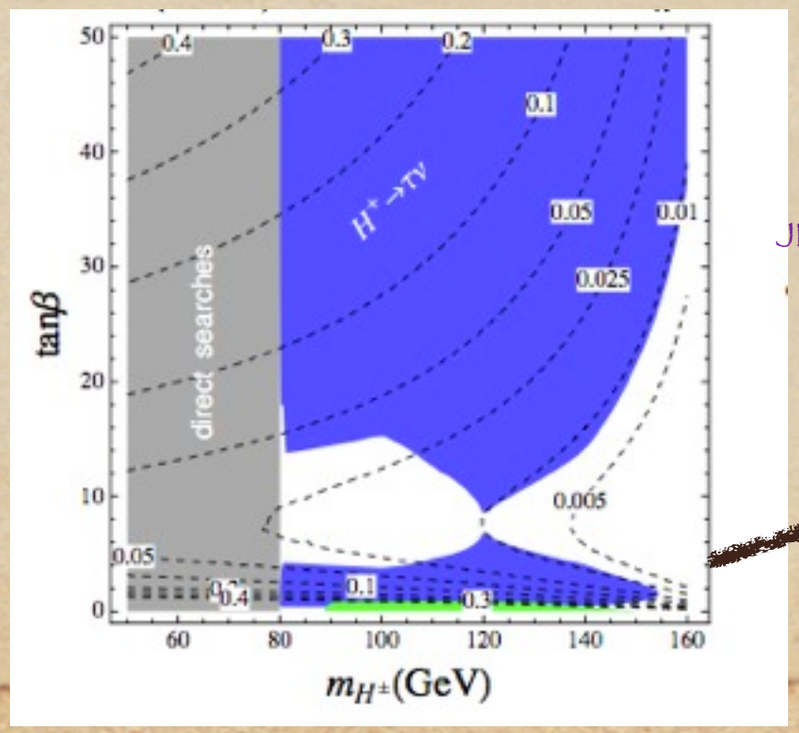



$\mathrm{Br}(t \to H^+ b)$ Constrained below 5% in this case

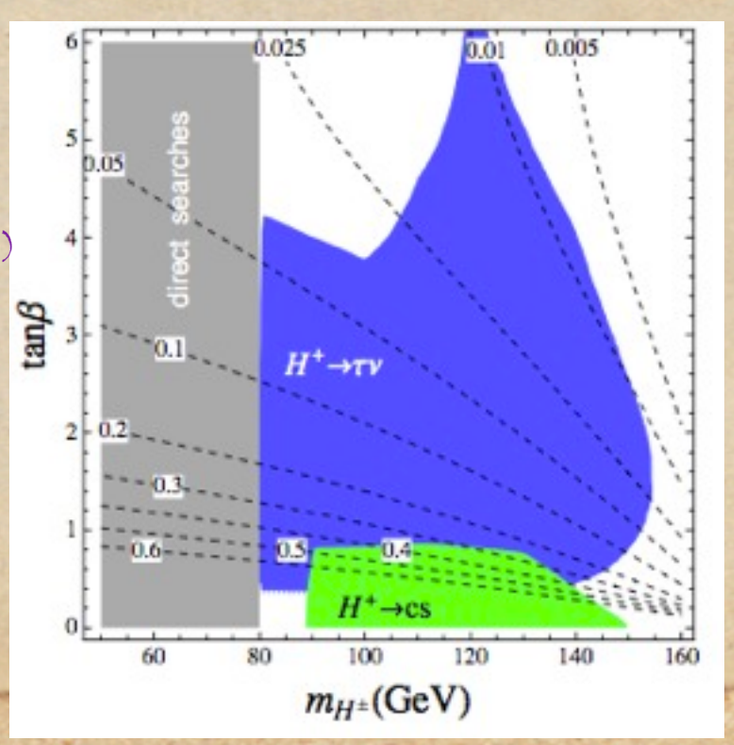



Considering the decay $H^+ \to c\bar{s}$




Dermisek et al., JHEP 04, 063 (2013)




Enhanced in a small region

below 5% for tan$\beta$>1

# Not a full search of light charged Higgs

What if additional decay channel with sizable Br ?

- New matter particles? (Constrained by the LHC data)
- Particles within the extended Higgs sector

  Dermisek & Gunion, Phys. Rev. D 79, 055014 (2009), .....

  Bae et al. , 1001.0623
- .....etc

# Not a full search of light charged Higgs

What if additional decay channel with sizable Br ?

- New matter particles? (Constrained by the LHC data)
- Particles within the extended Higgs sector

Dermisek & Gunion, Phys. Rev. D 79, 055014 (2009), .....

Bae et al. , 1001.0623

- .....etc

$H^+ \rightarrow W^+ A$ light Higgs CP even CP odd

The existence of light Higgses : interesting in light WIMP suspected from CDMSII-Si, CoGeNT, DAMA, CRESST

annihilation, SI cross section

Bae, Kim, Shin, Phys. Rev. D82, 115014 (2010)

Kim, Shin, JHEP 05, 036 (2009)

Shin, arXiv:1011.6377

Gunion et al. , Phys. Rev. D73, 015011 (2006)

etc.....

# Not a full search of light charged Higgs

What if additional decay channel with sizable Br ?

- New matter particles? (Constrained by the LHC data)
- Particles within the extended Higgs sector
- .....etc

Dermisek & Gunion, Phys. Rev. D 79, 055014 (2009), .....

Bae et al. , 1001.0623

$H^+ \rightarrow W^+ A$ light Higgs CP even / CP odd ✓ NOT MSSM

The existence of light Higgses : interesting in light WIMP suspected from CDMSII-Si, CoGeNT, DAMA, CRESST

annihilation, SI cross section

Bae, Kim, Shin, Phys. Rev. D82, 115014 (2010)

Kim, Shin, JHEP 05, 036 (2009)

Shin, arXiv:1011.6377

Gunion et al. , Phys. Rev. D73, 015011 (2006)

etc.....

# Light CP odd Higgs from doublet/singlet

# Basic assumptions of the analysis

- The extended Higgs sector is SU(2) doublet (+ singlet)
  : Minimal consideration, 2HDM (+ singlet)

- The discovered particle at the LHC (say $H_{LHC}$) has the SM Higgs gauge interaction

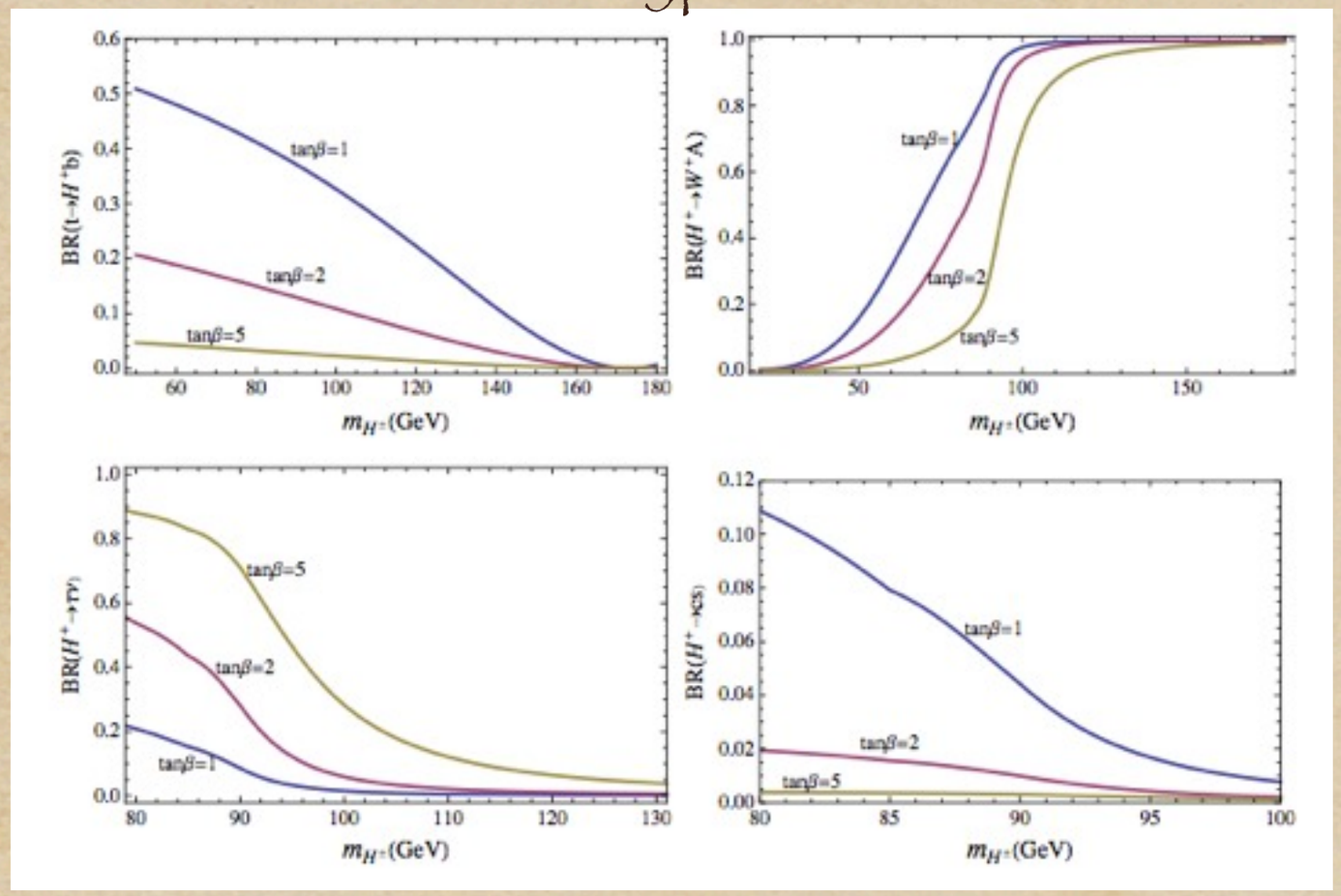
- There is another neutral Higgs $\Phi$ which can decay into $H^{\pm}W^{\mp}$

- No additional CP violation & No discussion on Flavor violation
  : Model dependent

- In this talk : Analysis is shown when A is CP odd Higgs

# When A is doublet

$m_A$ = 8 GeV Type II




Dermisek, Lunghi, Raval, JHEP 04, 063 (2013)

$$\Gamma(H^+ \to \bar{\tau}\nu) \propto m_{H^+} m_\tau^2 \tan^2\beta$$

Yukawa coupling

$$\Gamma(H^+ \to W^+ A) \propto m_{H^+}^3$$

gauge coupling

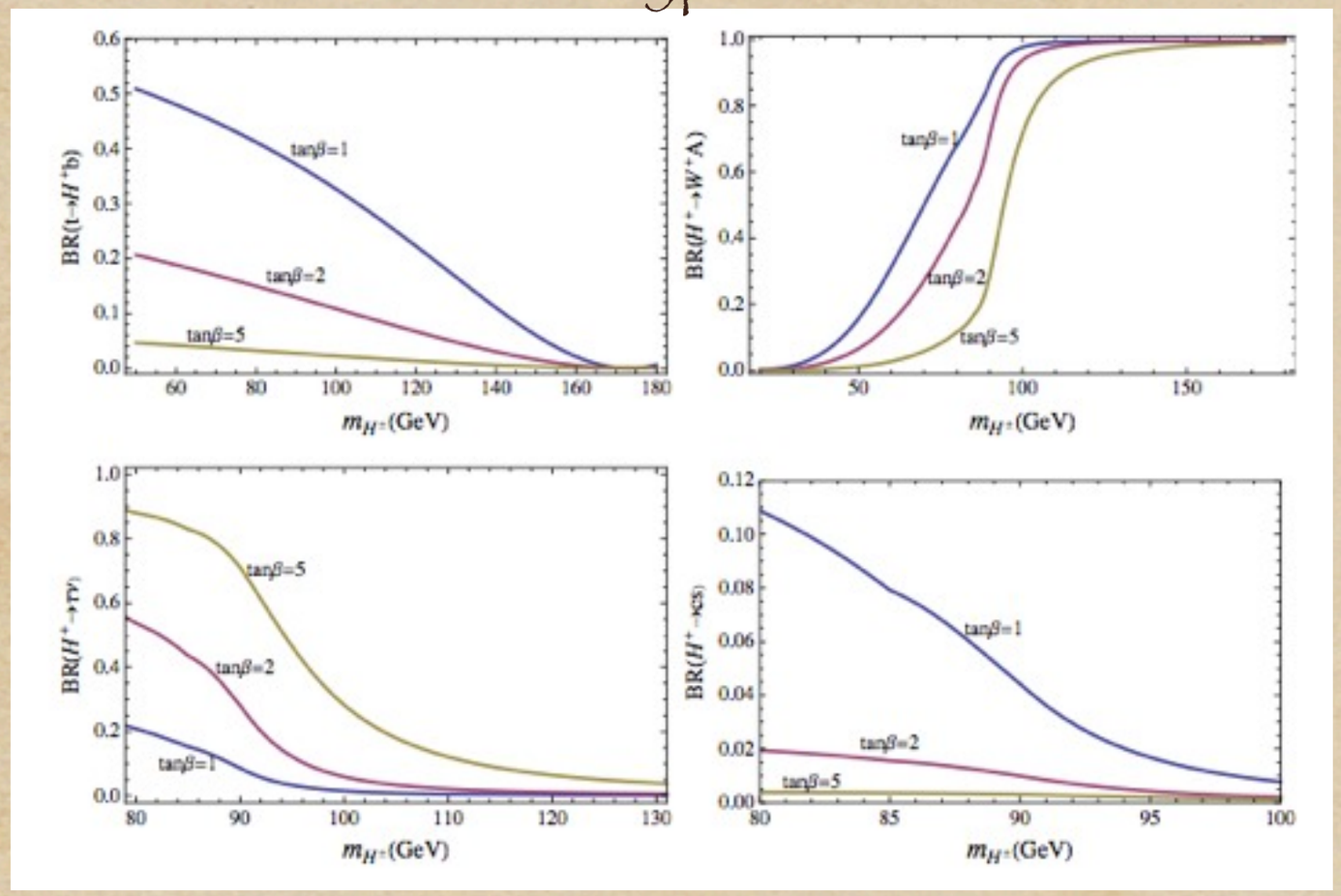
$Br(H^+ \to W^+A)$ can be large for

Low tan$\beta$ and heavy $H^+$

$Br(t \to H^+b)$ is NOT strongly constrained as before

# When A is doublet

$m_A$ = 8 GeV Type II




Dermisek, Lunghi, Raval, JHEP 04, 063 (2013)

$$\Gamma(H^+ \to \bar{\tau}\nu) \propto m_{H^+} m_\tau^2 \tan^2\beta$$

Yukawa coupling

$$\Gamma(H^+ \to W^+ A) \propto m_{H^+}^3$$

gauge coupling

$Br(H^+ \to W^+A)$ can be large for

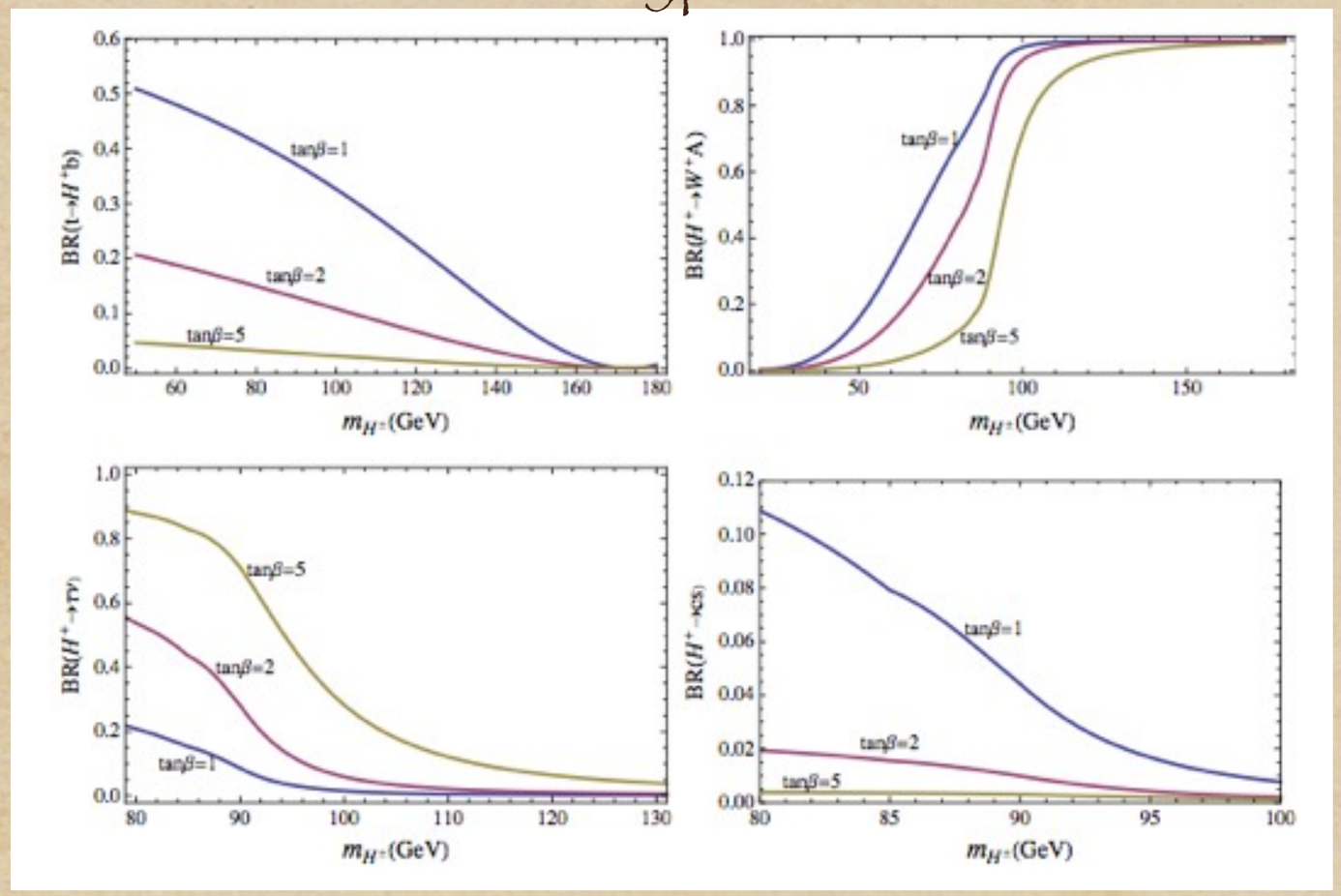
Low $\tan\beta$ and heavy $H^+$

$Br(t \to H^+b)$ is NOT strongly constrained as before

- $m_A < 2m_b$ is strongly constrained by the $\Upsilon \to A\gamma$ decay, $A \to \mu\,\mu$
- Model dependent bounds from $H_{LHC} \to AA$

# When A is doublet

$m_A$ = 8 GeV Type II




Dermisek, Lunghi, Raval, JHEP 04, 063 (2013)

$$\Gamma(H^+ \to \bar{\tau}\nu) \propto m_{H^+} m_\tau^2 \tan^2\beta$$

Yukawa coupling

$$\Gamma(H^+ \to W^+ A) \propto m_{H^+}^3$$

gauge coupling

$Br(H^+ \to W^+A)$ can be large for

Low $\tan\beta$ and heavy $H^+$

$Br(t \to H^+b)$ is NOT strongly constrained as before

- $m_A < 2m_b$ is strongly constrained by the $\Upsilon \to A\gamma$ decay, $A \to \mu\,\mu$

$m_A > 2m_b$

- Model dependent bounds from $H_{LHC} \to AA$

# When A has a singlet fraction (Not 100% singlet)

$H^+ \rightarrow W^+A$

# When A has a singlet fraction (Not 100% singlet)

$H^+ \to W^+A$

- There is remained parameter space from the $\Upsilon \to A\gamma$ and $A \to \mu\,\mu$ decays even for $m_A < 2m_b$

  : There can be trilepton signal at the LHC for $L > 20\ fb^{-1}$

  Dermisek, Lunghi, Raval, JHEP 04, 063 (2013)

- Model dependent bounds from $H_{LHC} \to AA$

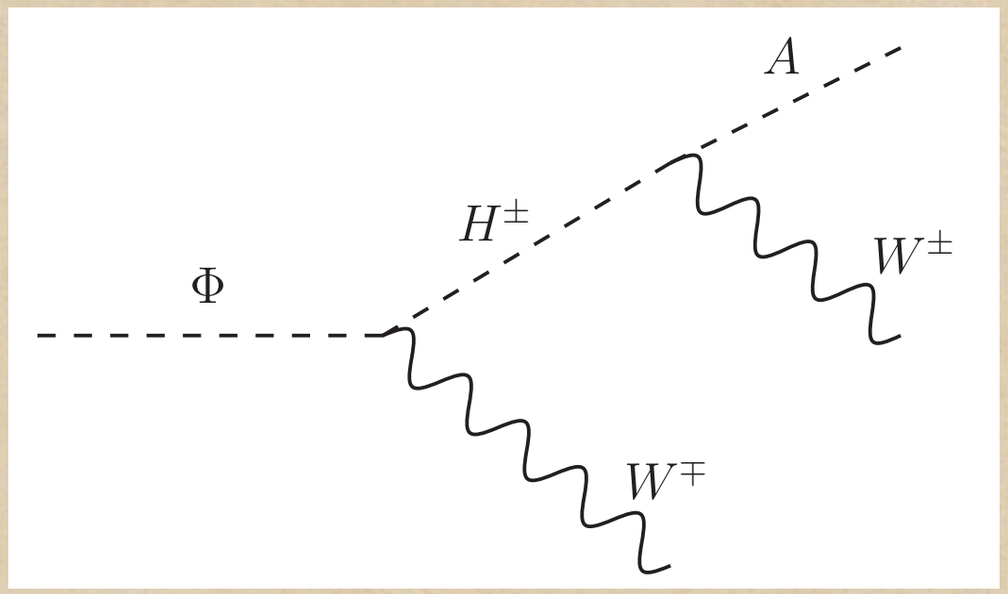
  : Still we need to have $m_A > 2m_\tau$ (at least $A \to \tau\tau$ or bb dominant)

  CMS search on 4 $\mu$ (arXiv:1210.7619), Cerdeno, Ghosh, Park, arXiv:1301.1325

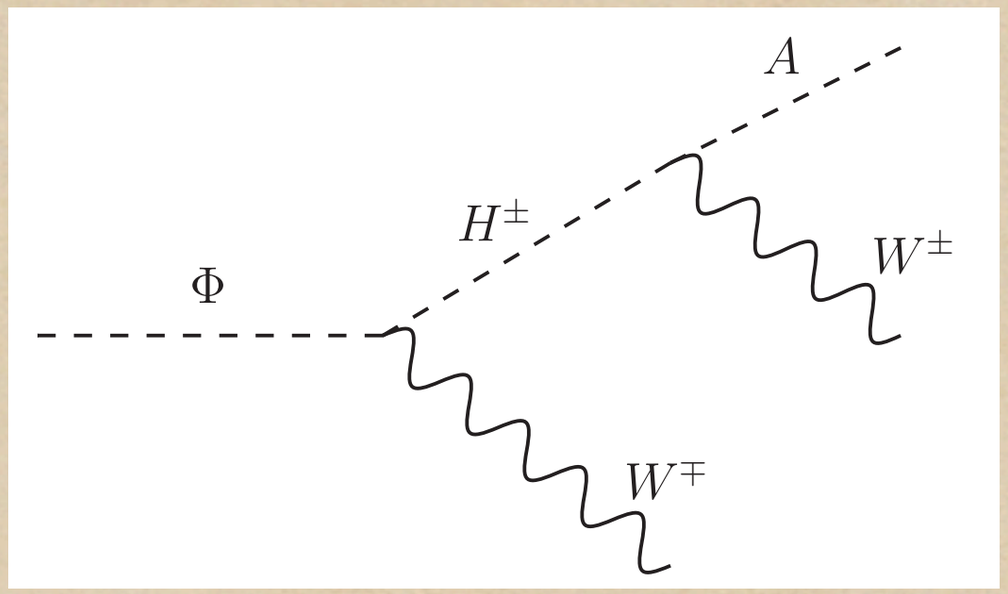
- Define the mixing angle as $A = A_D \cos\theta_A + A_S \sin\theta_A$

# Constraint from H→WW search

# Heavy neutral Higgs $\Phi$ which can decay into $H^+W^-$

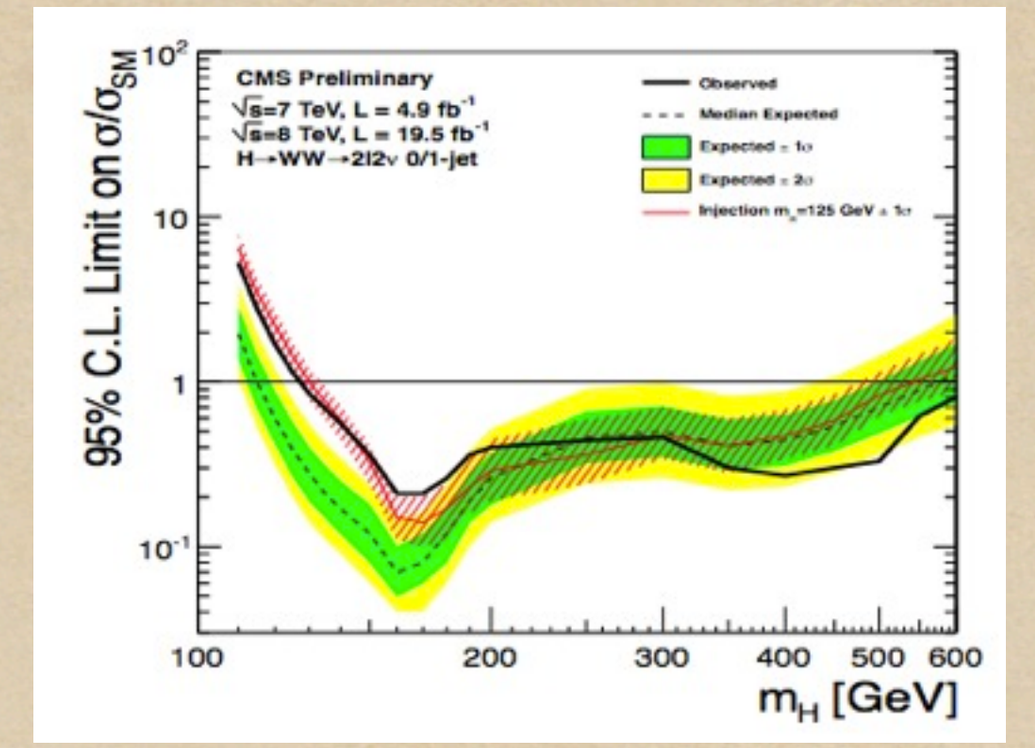


# Heavy neutral Higgs $\Phi$ which can decay into $H^+W^-$




- Contribute to the Higgs search through $H \to WW$ (max $\sigma_{prod.} \times Br$)
- Constrain the general parameters : $\tan\beta$, $\theta_A$, Higgs masses
  although $Br(\Phi \to H^+W^-)$ $\Phi \to H_{LHC}A$, $H'Z$,... (model dependent)
- If the charged Higgs were much heavier than the neutral Higgses, the Higgs dedicated search $H \to WW$ does not give strong constraint (No tree $\Phi \to WW$)

# CMS result : strong upper bound on max $\sigma_{prod.}$xBr




Cuts to discriminate the background is also strong

- Analyzed $2\ell 2\nu$ (+ 0/1 -jet events)
- Cut based analysis : using the direct kinematic cuts s.t. lepton $p_T$'s, $m_{\ell\ell}$, $m_T$, $\Delta\phi_{\ell\ell}$
- Shape based analysis : 2 dim. distribution of $m_{\ell\ell}$, $m_T$ at each Higgs mass

  Huge difference between the signal and background

# The upper bound of σ can be loosen in our process

In the cut based analysis, we can define (due to difference in the kinematics)

$$\text{acceptance} = \frac{(\#\text{of events passed the cut/total \# of events without cut})_{\text{New}}}{(\#\text{of events passed the cut/total \# of events without cut})_{\text{SM}}}$$

- If the acceptance is small : upper bound of σ from $H \rightarrow WW$ can be loosen
- We need a detail shape based analysis in our process to apply the proper cut
  (For each $m_\Phi$, can we apply the cut for $m_\Phi = m_H$ ?)
- The current CMS notes provide only 8 cuts
  ($m_H$ = 120, 125, 130, 160, 200, 250, 300, 400 GeV)
- If A produces 2 jets (∋ complete doublet case), our process can produce $2\ell 2\nu$ + 2 jets where the kinematic cuts by the CMS are not directly applied

# When $\Phi$ is the heavy CP odd Higgs in the type II 2HDM + singlet

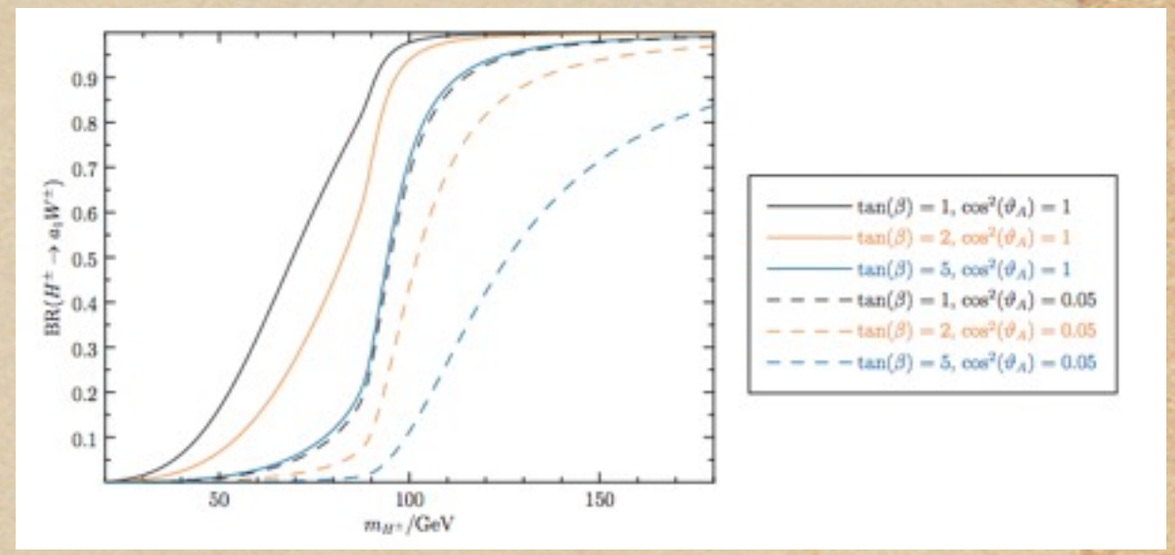
$\Gamma(H^+ \to \bar{\tau}\nu) \propto m_{H^+} m_\tau^2 \tan^2\beta$ $\sigma$ (p p → $\Phi$) is large for small tan$\beta$

The H → WW search constrain the low tan$\beta$ region

Assumption

i) No new particles lighter than $H^+$

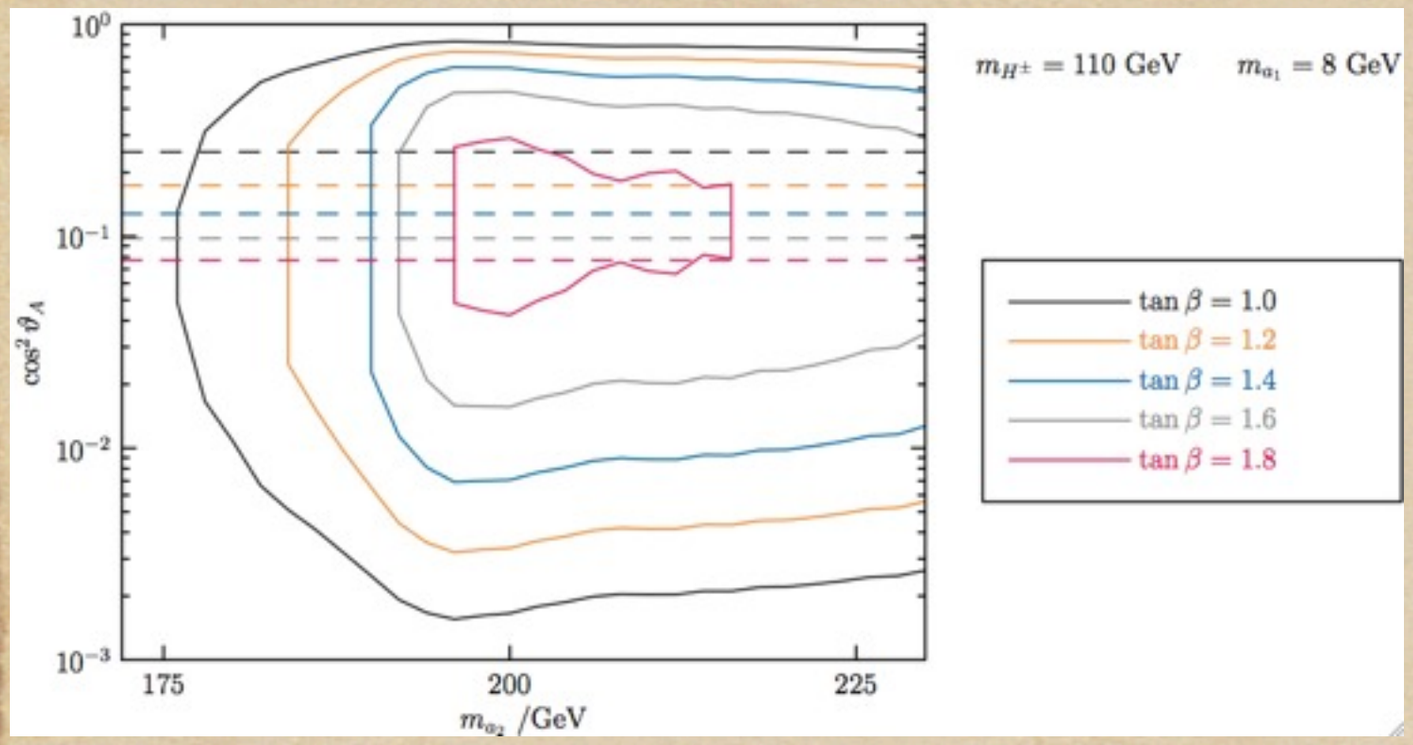
ii) No effect on Br($\Phi \to H^+W^-$) by the model dependent $\Phi \to H_{LHC}A$, H'Z,...




Then, we can obtain the limit of the parameters

$$\Gamma(H^+ \to W^+ A) \propto m_{H^+}^3 \cos^2\theta_A$$

# When $\Phi$ is the heavy CP odd Higgs in the type II 2HDM + singlet




Apply the cut : stronger constraint on $\sigma_{prod.}$xBr. between the cuts of $H \to WW$ for $m_H \approx 160$, 200 GeV.

- Between the solid line : Not allowed by the $H \to WW$ for our choice of acceptance
- Above the dashed line : Not allowed by the $\Upsilon \to A\gamma$ and $A \to \mu\,\mu$ decay

i) Shrink for large $\tan\beta$ : $\sigma$ ($p\,p \to \Phi$) & Br($H^+ \to W^+A$) decreases as $\tan\beta$ increases

ii) large $\tan\beta$ increases the $\Upsilon \to A\gamma$ and $A \to \mu\,\mu$ decay bound as $\tan\beta$ increases

# Conclusions

- The search of charged Higgs lighter than the top quark is rather easily obtained due to the top decay $t \to bH^+$.
  Current limit : $H^+$ decays dominantly into $\tau\nu$ ( + cs for low $\tan\beta$).

- Additional search required for $H^+ \to W^+A$ can be dominant.

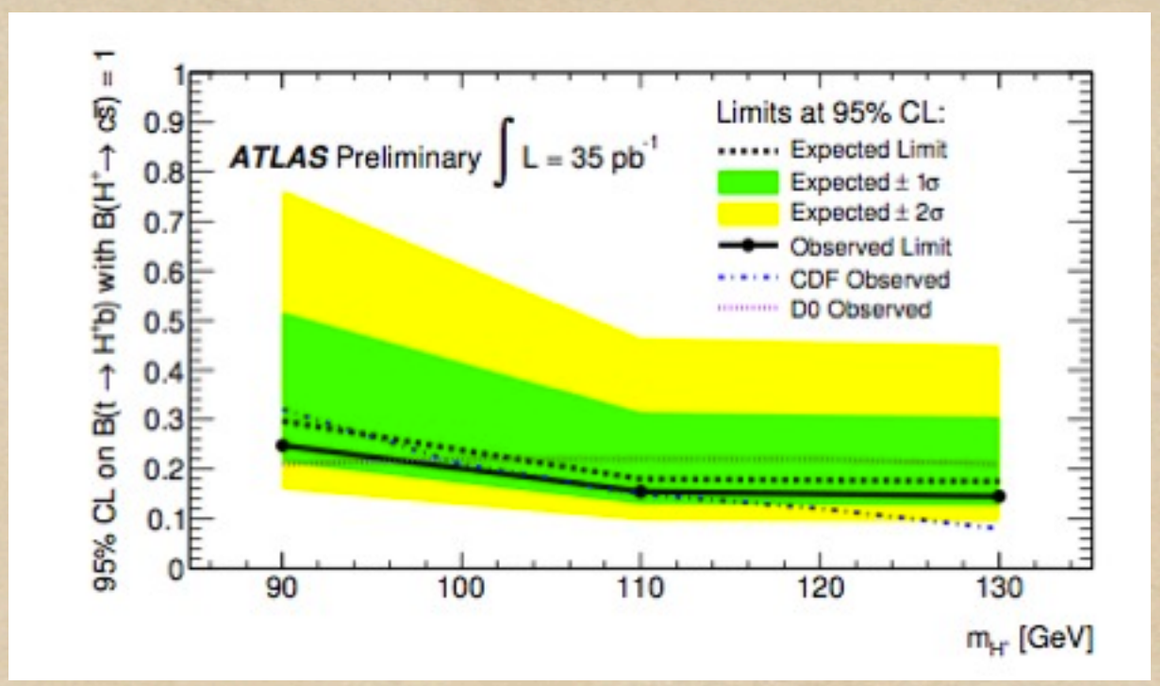
- A neutral heavy Higgs $\Phi$ produces WWA through the charged Higgs decay. Constrained by the Higgs dedicated search $H \to WW$.

- The different kinematics of $\Phi \to WWA$ from $H \to WW$ requires the shape based analysis as well as the cut based analysis. The number of opened cut is small, so the LHC group can provide more reference cuts or consider this possibility to search the light charged Higgs.

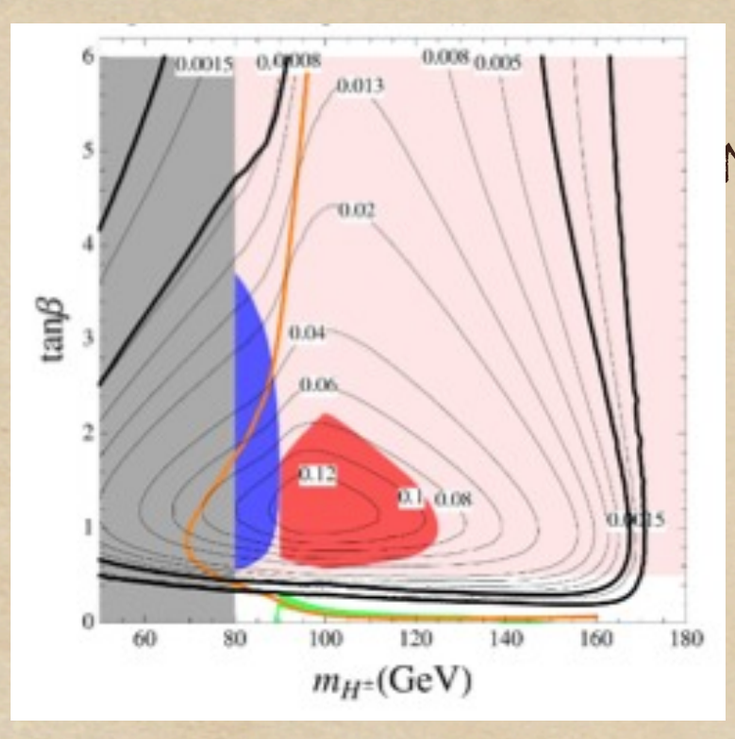
- With the given cuts, we can obtain the LHC search bound for this case in terms of $\theta_A$, masses of the Higgses, and $\tan\beta$.

# Back up slides

Considering the decay $H^+ \to c\bar{s}$



# Bound of 100% doublet A < 2b




Dermisek, Lunghi, Raval, JHEP 04, 063 (2013)

Numbers : Br($t \to H^+ b$) X Br($H^+ \to W^+ A$) X Br($A \to \tau\tau$)

Pink : $r \to A\gamma$ decay

Red : CDF bound $t \to H^+ b \to W^+ A b \to W^+ b \tau\tau$

Blue (Green) : LHC $t \to H^+ b \to \tau\nu(cs)b$

Right of Orange line : Br($H^+ \to W^+ A$) > 50%

Inner thick contour : 20 $fb^{-1}$ of 8 TeV LHC

Outer thick contour : 40 $fb^{-1}$ of 14 TeV LHC

# CMS cut

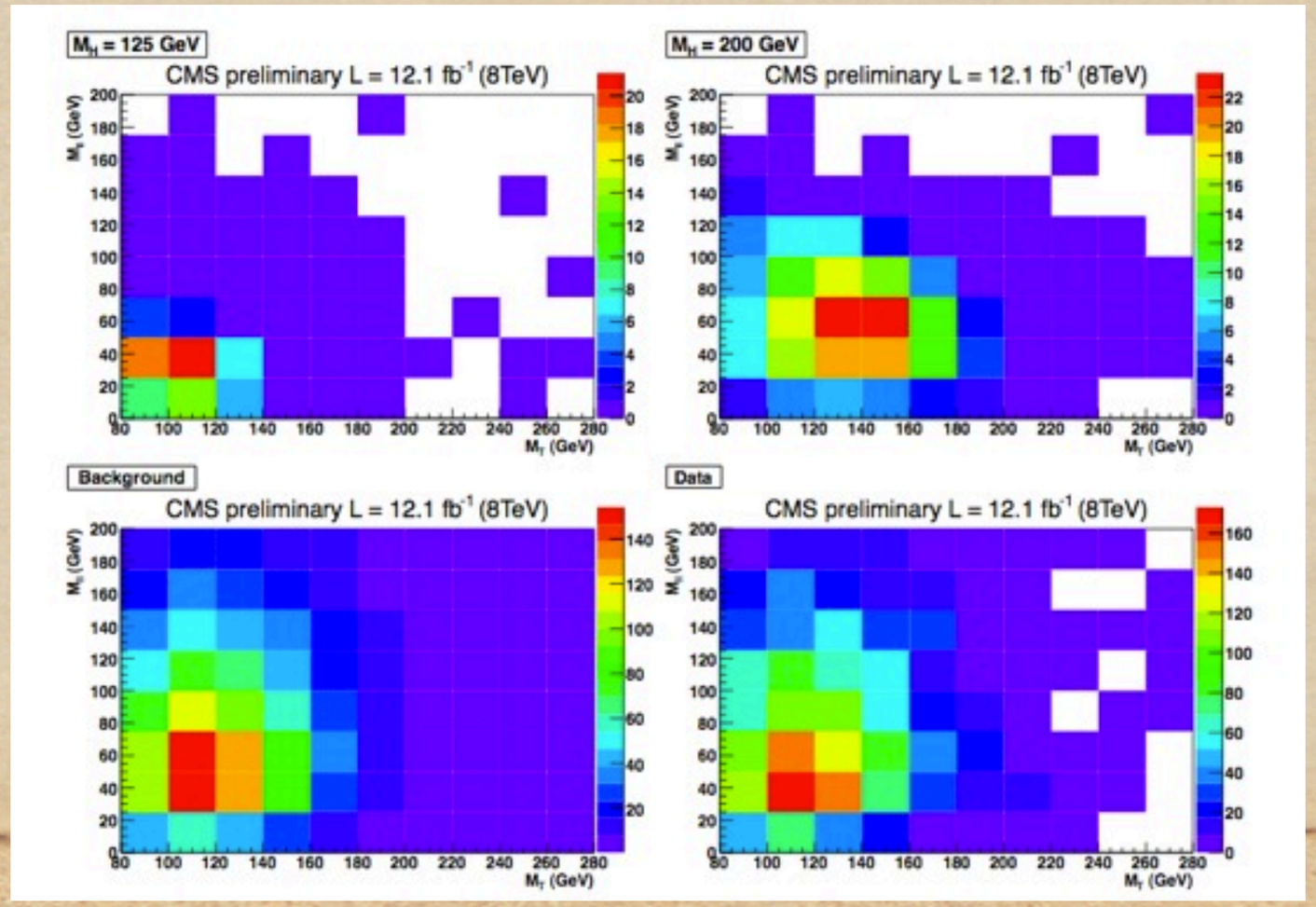
CMS PAS HIG-12-042

Table 1: Final event selection requirements for the cut-based analysis in the 0-jet and 1-jet samples. Values for other mass hypotheses follow a smooth behavior with respect to the report values.

| $m_H$ [GeV] | $p_T^{\ell,max}$ [GeV] | $p_T^{\ell,min}$ [GeV] | $m_{\ell\ell}$ [GeV] | $\Delta\phi_{\ell\ell}$ [°] | $m_T$ [GeV] |
|---|---|---|---|---|---|
| | > | > | < | < | [,] |
| 120 | 20 | 10 | 40 | 115 | [80,120] |
| 125 | 23 | 10 | 43 | 100 | [80,123] |
| 130 | 25 | 10 | 45 | 90 | [80,125] |
| 160 | 30 | 25 | 50 | 60 | [90,160] |
| 200 | 40 | 25 | 90 | 100 | [120,200] |
| 250 | 55 | 25 | 150 | 140 | [120,250] |
| 300 | 70 | 25 | 200 | 175 | [120,300] |
| 400 | 90 | 25 | 300 | 175 | [120,400] |

$$m_T = \sqrt{2 p_T^{\ell\ell} E_T^{\rm miss} (1 - \cos \Delta\phi_{E_T^{\rm miss}\ell\ell})}$$

$\Delta\phi_{E_T^{\rm miss}\ell\ell}$ : difference in azimuth between $E_T^{\rm miss}$ , $p_T^{\ell\ell}$

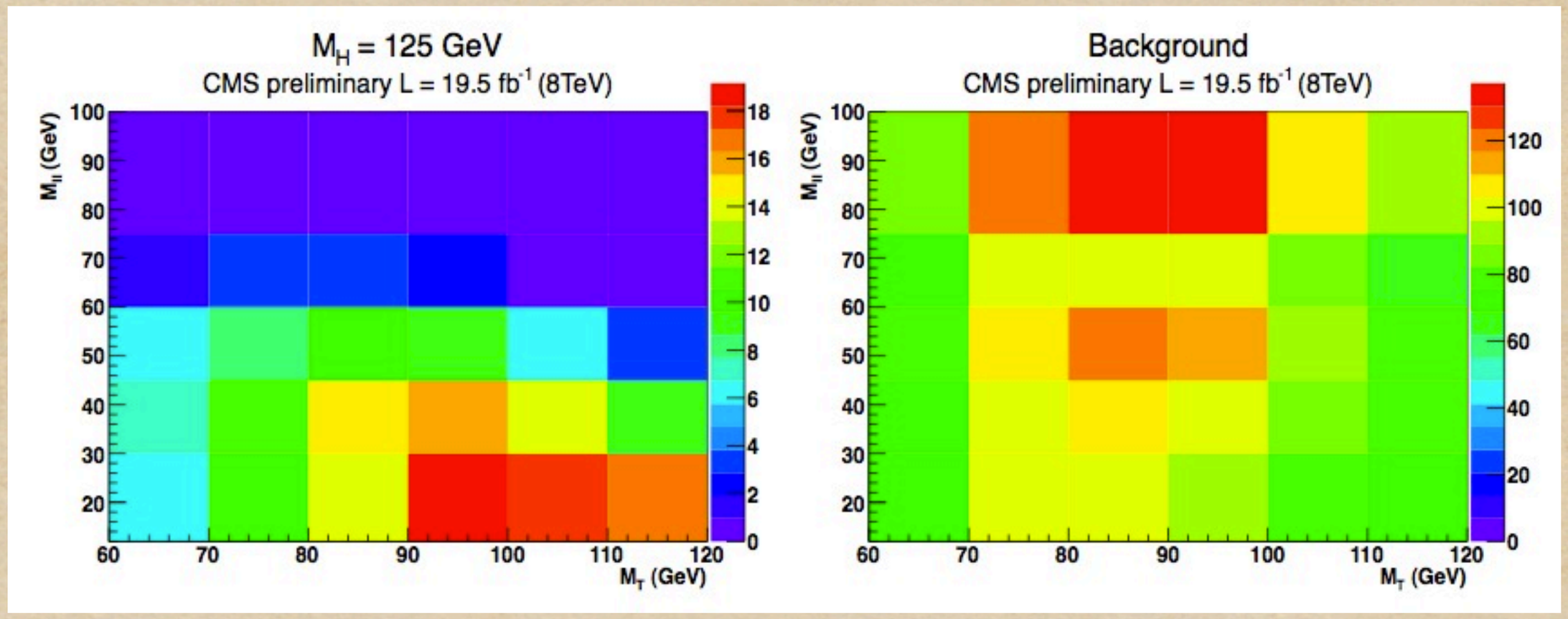



0-jet

# CMS cut

CMS CR-2013/068

0-jet



# A CMS result

CMS CR-2013/102