

Sheldon: “Research Lab” is more than a game:  
The physics is theoretical, but the fun is real!

# Review of Status of Theory Predictions for Charged Higgs Cross Sections and Branching Ratios

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1. Motivation and Theory
2. Charged Higgs Production Cross Section
3. Charged Higgs Branching Ratios
4. Conclusions

## 1. Motivation and theory

Higgs mechanism in the SM case:

$$\mathcal{L}_{\text{SM}} = \underbrace{m_d \bar{Q}_L \Phi d_R}_{\text{d-quark mass}} + \underbrace{m_u \bar{Q}_L \Phi_c u_R}_{\text{u-quark mass}}$$

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L, \quad \Phi_c = i\sigma_2 \Phi^*, \quad \Phi \rightarrow \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \Phi_c \rightarrow \begin{pmatrix} v \\ 0 \end{pmatrix}$$

In SUSY: term  $\bar{Q}_L \Phi^*$  not allowed

Superpotential is holomorphic function of chiral superfields, i.e. depends only on  $\varphi_i$ , not on  $\varphi_i^*$

$\Rightarrow H_d (\equiv H_1)$  and  $H_u (\equiv H_2)$  needed to give masses  
to down- and up-type fermions

In general: two Higgs doublets appear (to me) ‘more natural’ than only one

## Models with charged Higgs bosons:

1. Two Higgs Doublet Model (**THDM**)
2. Minimal Supersymmetric Standard Model (**MSSM**)
3. MSSM with extra singlet (**NMSSM**)
4. MSSM with more extra singlets
5. SM/MSSM with Higgs triplets
6. ...

⇒ common and different features?

## Common and different features of Models with Charged Higgs Bosons

To my knowledge the following point have only **partially** been answered:

### Common features:

- what are the common features of all (or most) models?
- how can the charged Higgs be discovered at the LHC?
  - only through  $H^\pm \rightarrow \tau\nu_\tau$  (!?)
- what about  $H^\pm \rightarrow tb$ ?  $H^\pm \rightarrow cs$ ?
- which models would be missed?
- what can be done about them?

### Different features:

- once we have discovered 'a' charged Higgs, how can we distinguish them?
- what are the relevant LHC capabilities?
- are we prepared for all possibilities?

⇒ concentrate on the MSSM from now on!

⇒ THDM type II:  $g_{tbH^\pm} \sim m_t \cot\beta + m_b \tan\beta$ ,    $g_{\tau\nu H^\pm} \sim m_\tau \tan\beta$

## MSSM Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}}_{\text{gauge couplings, in contrast to SM}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{\text{gauge couplings, in contrast to SM}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

physical states:  $h^0, H^0, A^0, H^\pm$

Goldstone bosons:  $G^0, G^\pm$

Input parameters: (to be determined experimentally)

$$\tan \beta = \frac{v_2}{v_1}, \quad M_A^2 = -m_{12}^2(\tan \beta + \cot \beta)$$

In lowest order:

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$$\tan \beta = \frac{v_2}{v_1}, \quad M_A^2 = -m_{12}^2(\tan \beta + \cot \beta)$$

⇒  $m_h$ ,  $m_H$ , mixing angle  $\alpha$ ,  $m_{H^\pm}$ : no free parameters, can be predicted

In lowest order:

$$m_{H^\pm}^2 = M_A^2 + M_W^2$$

Keep in mind: higher-order corrections

⇒ Test of the model!

Necessary:

- discover the charged Higgs at the LHC and measure its mass
- compare with theory prediction for  $M_{H^\pm}$  and XS
- derive MSSM parameters ...

## 2. Production Cross Sections of the Charged Higgs

Light charged Higgs:  $M_{H^\pm} < m_t$

Main production channel:  $pp \rightarrow t\bar{t} \rightarrow t H^- \bar{b}$  or  $H^+ b \bar{t}$

Heavy charged Higgs:  $M_{H^\pm} > m_t$

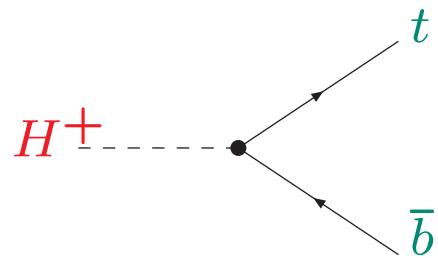
Main production channel:  $gb \rightarrow H^- t$  or  $g\bar{b} \rightarrow H^+ \bar{t}$

Same relevant decay channel:  $H^\pm \rightarrow \tau\nu_\tau$

⇒ in principle the same couplings are relevant for light and heavy charged Higgs

⇒ situation may change in other models . . .

## Effects of $\Delta_b$ :



$$y_b \frac{\tan \beta}{1 + \Delta_b}$$

$$\Delta_b = \frac{2\alpha_s}{3\pi} m_{\tilde{g}} \mu \tan \beta \times I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) + \frac{\alpha_t}{4\pi} A_t \mu \tan \beta \times I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu) + \dots$$

$\Rightarrow$  other parameters enter  $\Rightarrow$  strong  $\mu$  dependence

If  $g_{tbH^\pm} \sim y_t \cot \beta + y_b \tan \beta$  is the only relevant coupling:

$$\begin{aligned} g_{tbH^\pm} &\rightarrow y_t \frac{1}{\tan \beta} + \frac{y_b}{1 + \Delta_b} \tan \beta \\ &= \frac{1}{\sqrt{1 + \Delta_b}} \left( y_t \frac{\sqrt{1 + \Delta_b}}{\tan \beta} + y_b \frac{\tan \beta}{\sqrt{1 + \Delta_b}} \right) \\ &= \frac{1}{\sqrt{1 + \Delta_b}} \left( y_t \frac{1}{\tan \beta'} + y_b \tan \beta' \right) \quad \text{with} \quad \tan \beta' = \tan \beta / \sqrt{1 + \Delta_b} \end{aligned}$$

## 2A) Production cross section of the light charged Higgs

Sources of theory uncertainties:

1. PDF and  $\alpha_s$  uncertainties on  $\sigma(pp \rightarrow t\bar{t})$
2. experimental uncertainties on  $m_t$ , affecting  $\sigma(pp \rightarrow t\bar{t})$
3. Uncertainties of  $\Delta_b$
4. Experimental uncertainties in SUSY masses entering  $\Delta_b$
5. Further missing higher order corrections in  $\text{BR}(t \rightarrow H^+ b)$ 
  - How large are the uncertainties?
  - How large are the corresponding effects?

## Size of theory uncertainties (I):

1. PDF and  $\alpha_s$  uncertainties on  $\sigma(pp \rightarrow t\bar{t})$  at 7 TeV

taken over from the ATLAS top group:

$$\sigma = 165^{+4}_{-9} \text{ (scale)}^{+7}_{-7} \text{ (PDF) pb}$$

using NNLO calculation from [S. Moch, P. Uwer '08]

scale uncertainty: variation of  $\mu_R$  and  $\mu_F$ : 0.5 . . . 2

PDF uncertainty: MSTW2008, 68% C.L.

2. experimental uncertainties on  $m_t$ , affecting  $\sigma(pp \rightarrow t\bar{t})$

$$\rightarrow \Delta\sigma/\sigma \approx 5\Delta m_t^{\text{exp}}/m_t$$

⇒ combined quadratically with scale/PDF uncertainty  
in comparison relatively small

## Size of theory uncertainties (II):

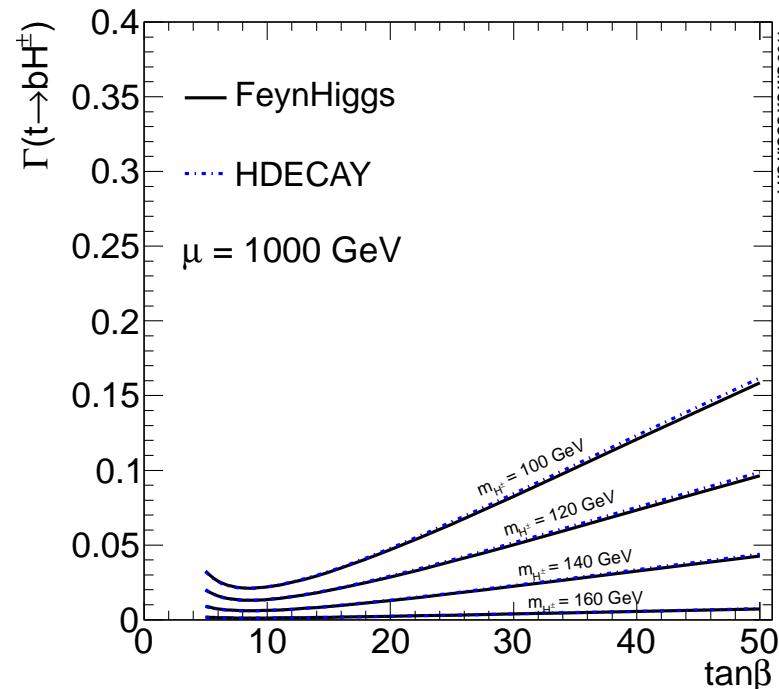
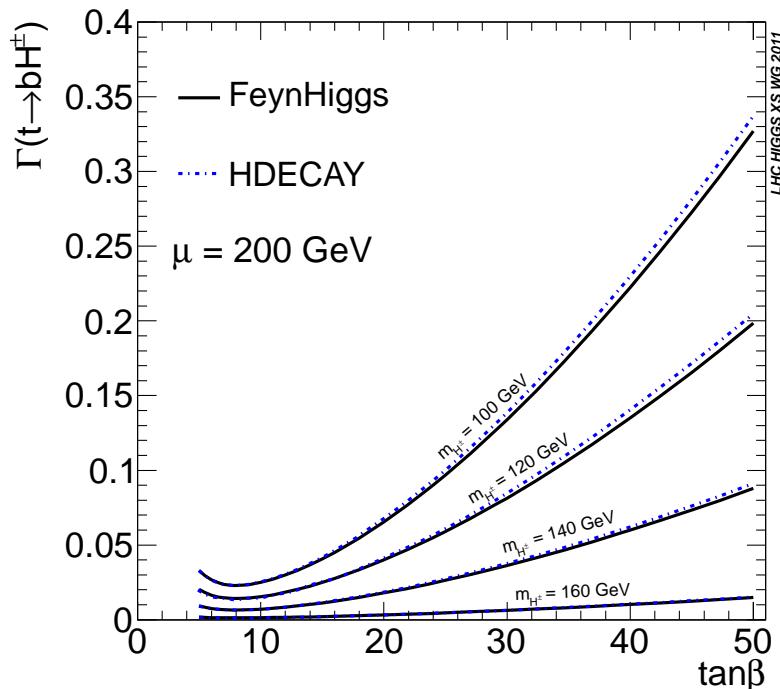
### 3. Uncertainties of $\Delta_b$

Uncertainties beyond  $\Delta_b (\sim \alpha_s \dots + \alpha_t \dots)$

$\Rightarrow$  scale variation of  $\alpha_s(Q) \Rightarrow$  effect on  $\Delta_b \lesssim 3\%$

after inclusion of the two-loop corrections on  $\Delta_b$  [D. Noth, M. Spira, '08]

Comparison of FeynHiggs and HDECAY: decay width:



$\Rightarrow$  very good agreement (despite differences in  $\Delta_b$ )

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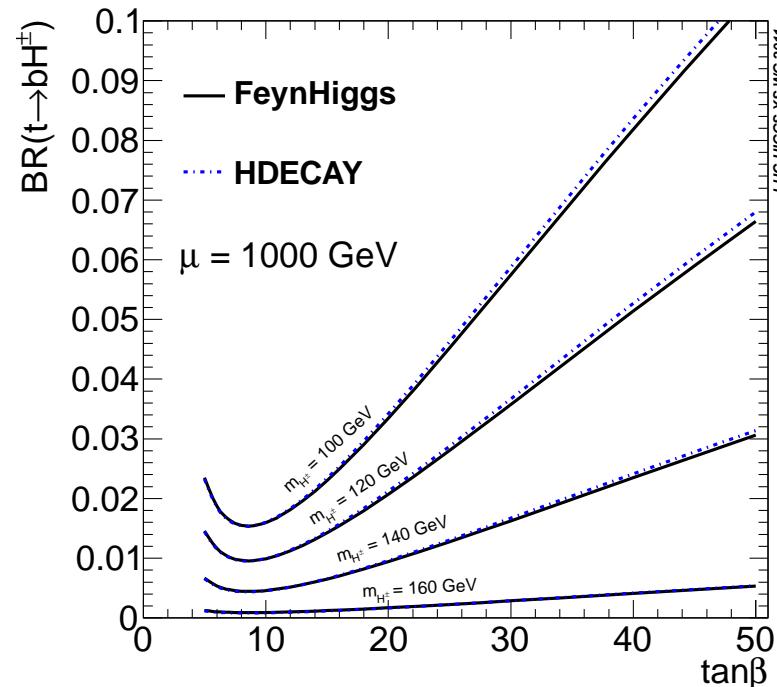
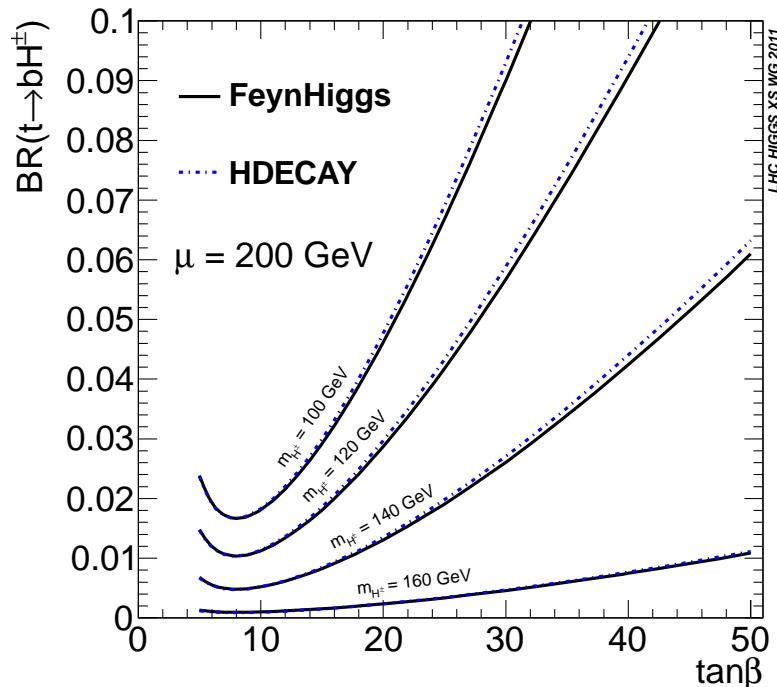
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Comparison of FeynHiggs and HDECAY: branching ratio:



$\Rightarrow$  very good agreement (despite differences in  $\Delta_b$ )

## Size of theory uncertainties (III):

4. Experimental uncertainties in SUSY masses entering  $\Delta_b$

→ beyond the scope, requires full experimental analysis,  
parameter dependent, . . .

5. Further missing higher order corrections in  $\text{BR}(t \rightarrow H^+ b)$

⇒ no dedicated analysis exists

So far assumed:

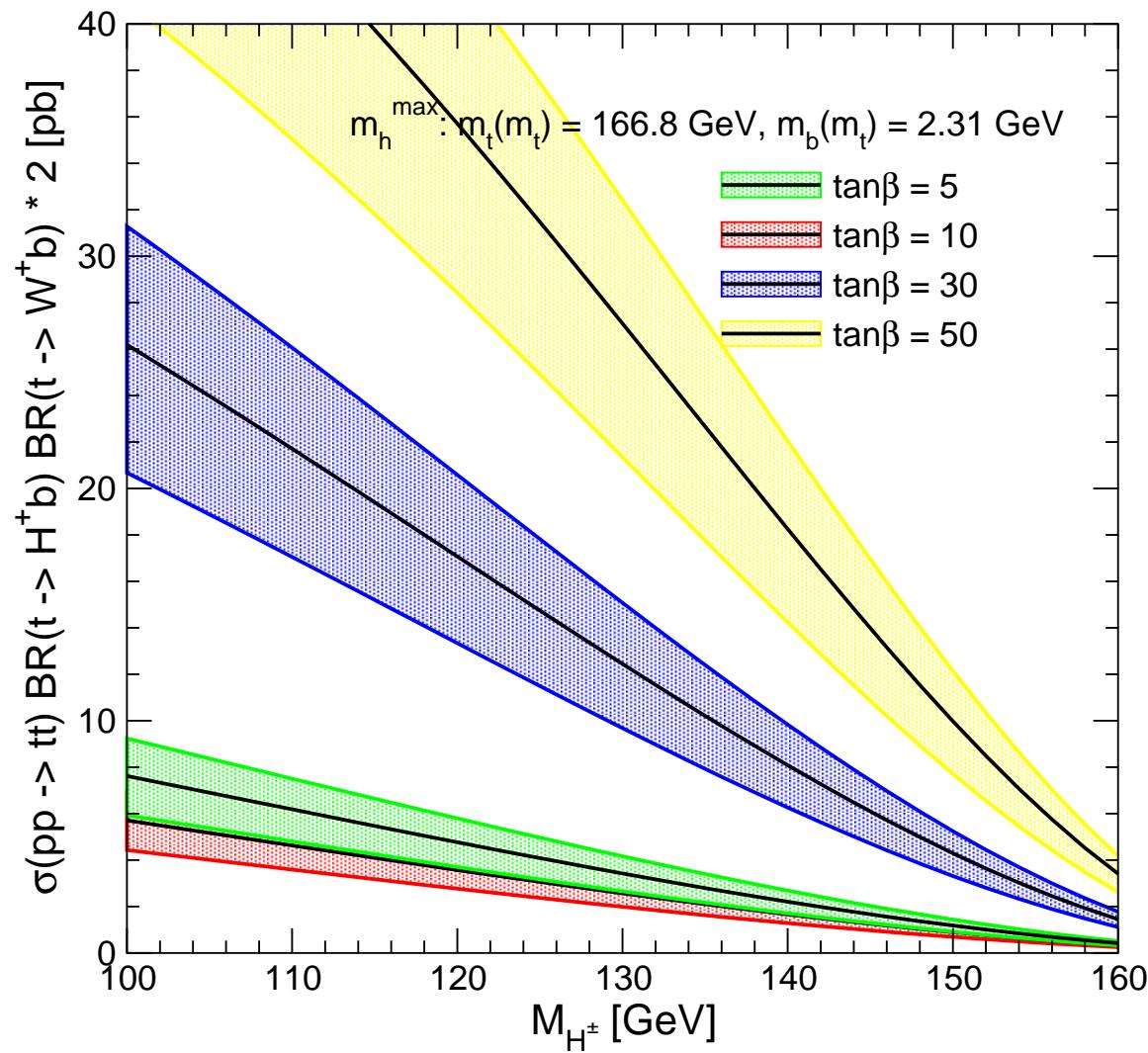
- 5% for missing 1L EW corrections
  - 2% for missing 2L QCD corrections
- to optimistic?

## Combination of everything:

Calculation of

$$\sigma(pp \rightarrow t\bar{t}) \times \text{BR}(t \rightarrow H^\pm b) \times \text{BR}(t \rightarrow W^\pm b) \times 2$$

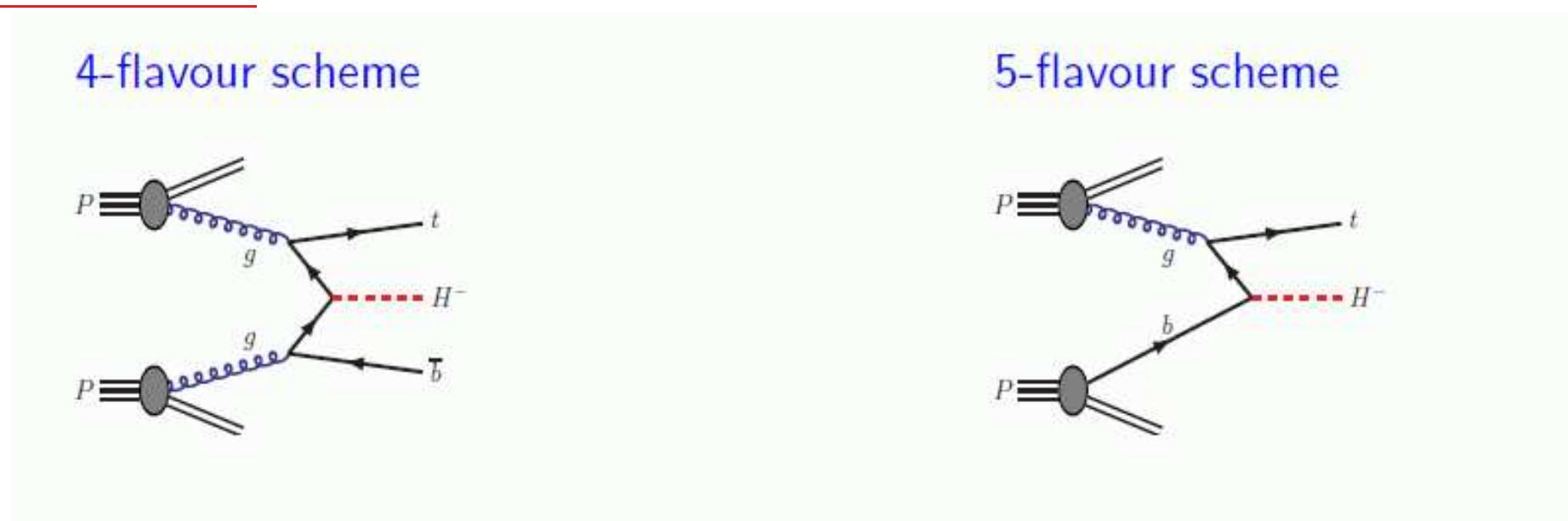
$$\sigma(pp \rightarrow t\bar{t}) \times \text{BR}(t \rightarrow H^\pm b) \times \text{BR}(t \rightarrow W^\pm b) \times 2$$



⇒ non-negligible . . .

## 2B) Production cross section of the heavy charged Higgs

### 4FS vs. 5FS

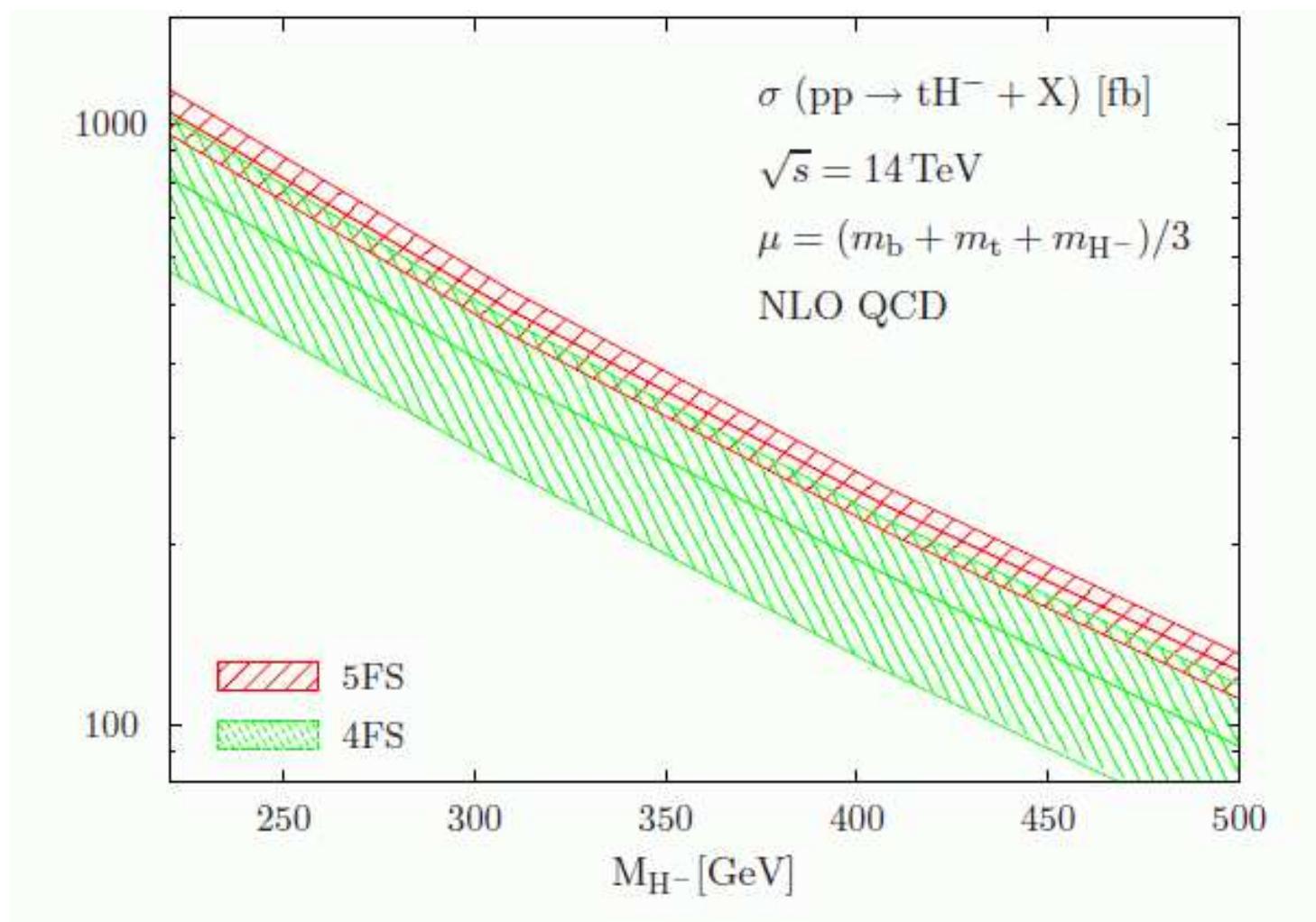


### The 4- and 5-flavor schemes

- are both theoretically consistent and well defined
- represent different ways of ordering perturbation theory
- should agree at (sufficiently) high order
- show a numerical difference at finite order

## Total cross section:

[*T. Plehn; S. Dittmaier, M. Krämer, M. Spira, M. Walser '09*]



## How to combine / get the best possible prediction?

→ solution agreed on for the  $b\bar{b} \rightarrow H$  case:

“Santander matching”

Idea:

- 5FS gets 100% weight in the limit  $M_H \rightarrow \infty$
- 4FS gets 100% weight in the limit of “small logs”  
→ where  $\log(M_H/m_b) = 2$

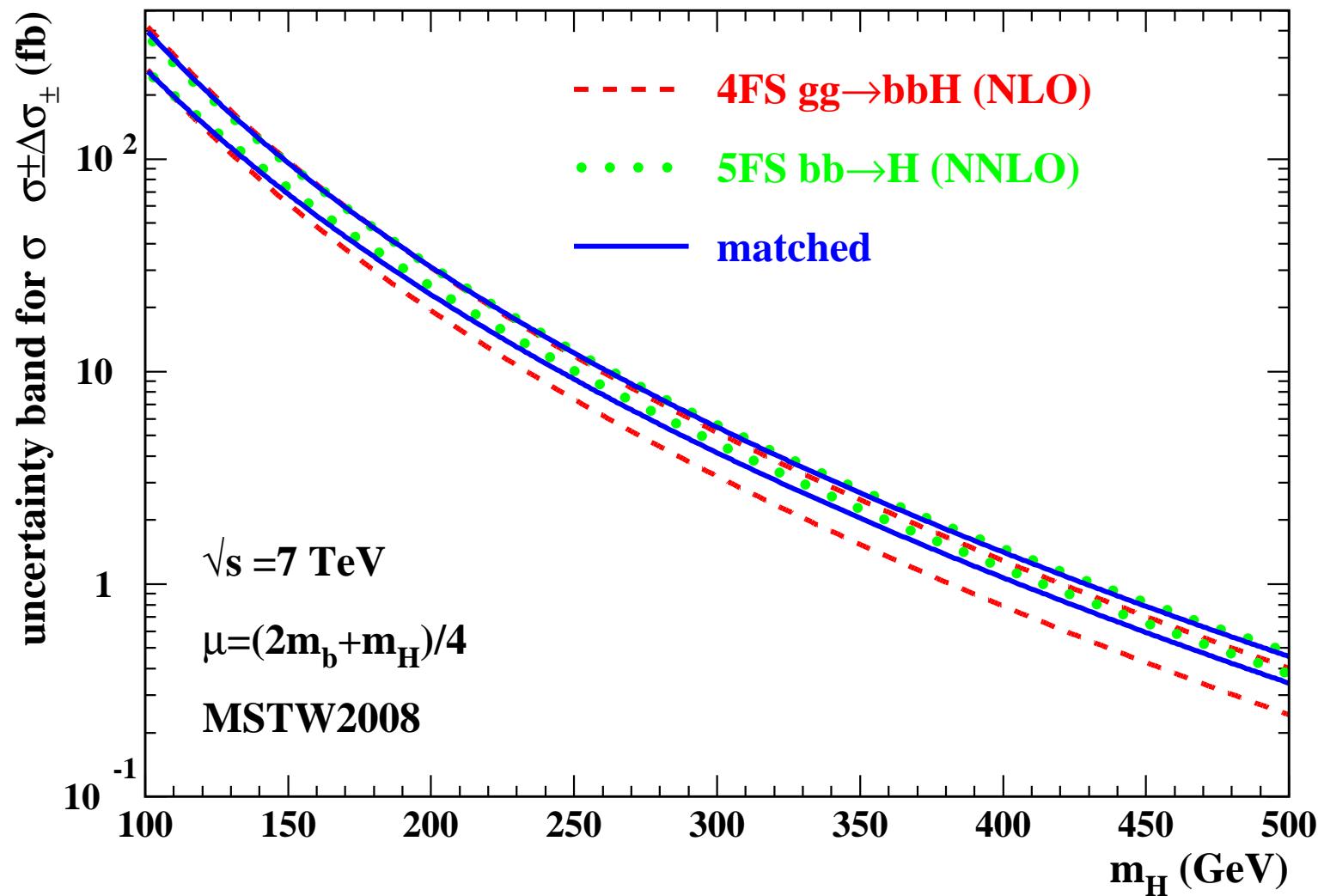
$$\Rightarrow \sigma(b\bar{b} \rightarrow H + X) = \frac{1}{1+t} [\sigma^{4\text{FS}} + t\sigma^{5\text{FS}}]$$

$$t = \log\left(\frac{M_H}{m_b}\right) - 2$$

⇒ same matching will be adopted for charged Higgs

## Total $b\bar{b} \rightarrow H$ cross section with Santander matching:

[R. Harlander, M. Krämer, M. Schumacher '11]



## New evaluation of $H^\pm$ production in 4FS/5FS:

[*Klees, Krämer, Ubiali '12*]

Both calculations are available in SUSY QCD

Here: 2HDM + QCD corrections,  $\tan \beta = 30$

### 5FS:

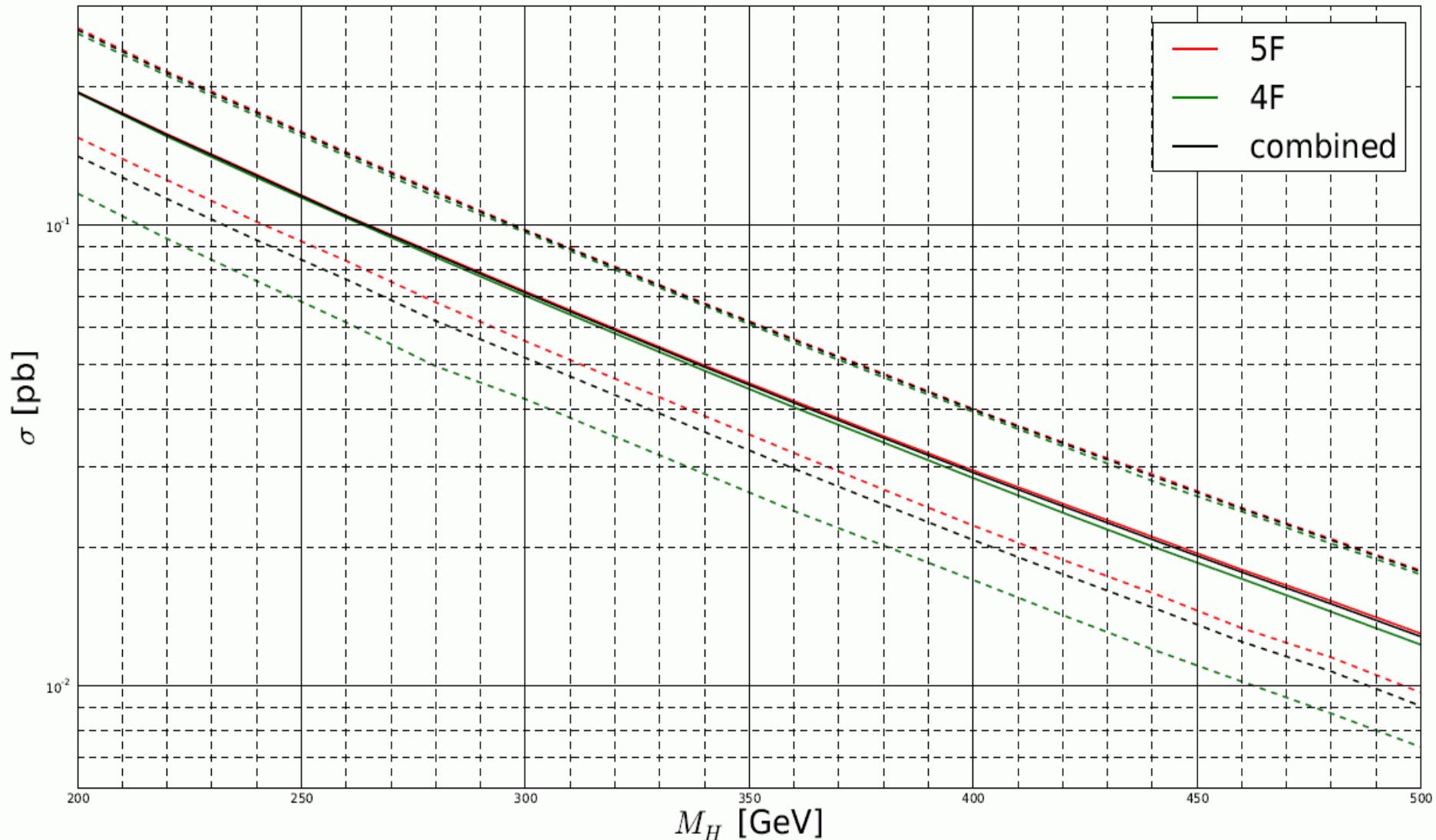
- “better” scale choice [*Maltoni, Ridolfi, Ubiali '12*]
- full analysis of theory error (pdf,  $m_b$ ,  $\alpha_s$ , . . . )

### 4FS:

- “old” scale choice
- evaluation using MSTW, CT10, NNPDF

## Total cross section, 8 TeV, with Santander matching:

[Klees, Krämer, Ubiali '12]



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### 5FS:

- “better” scale choice [*Maltoni, Ridolfi, Ubiali '12*]
- full analysis of theory error (pdf,  $m_b$ ,  $\alpha_s$ , ...)

### 4FS:

- “old” scale choice
- evaluation using MSTW, CT10, NNPDF

### Observations:

- central values nearly agree  
⇒ “clever” scale choice ...
- Santander matching gives uncertainty estimate

### 3. Charged Higgs Branching Ratios

Light charged Higgs:

Comparison of FeynHiggs and HDECAY for

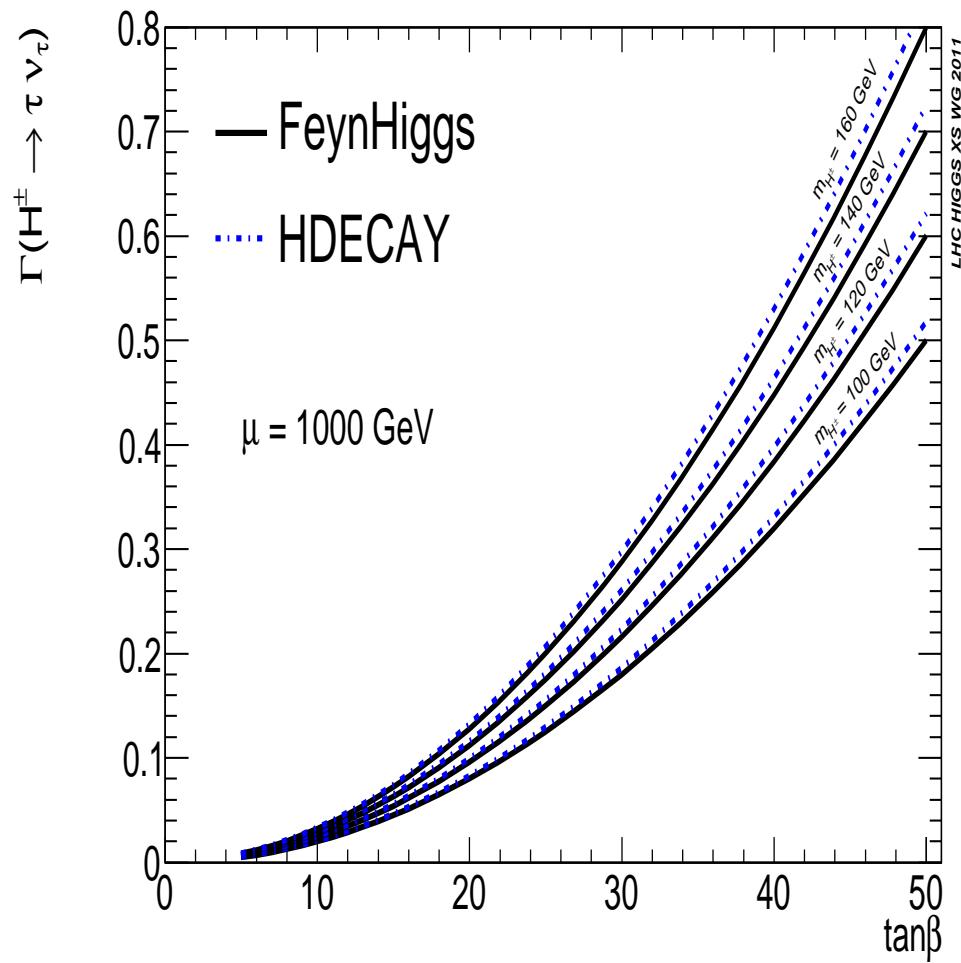
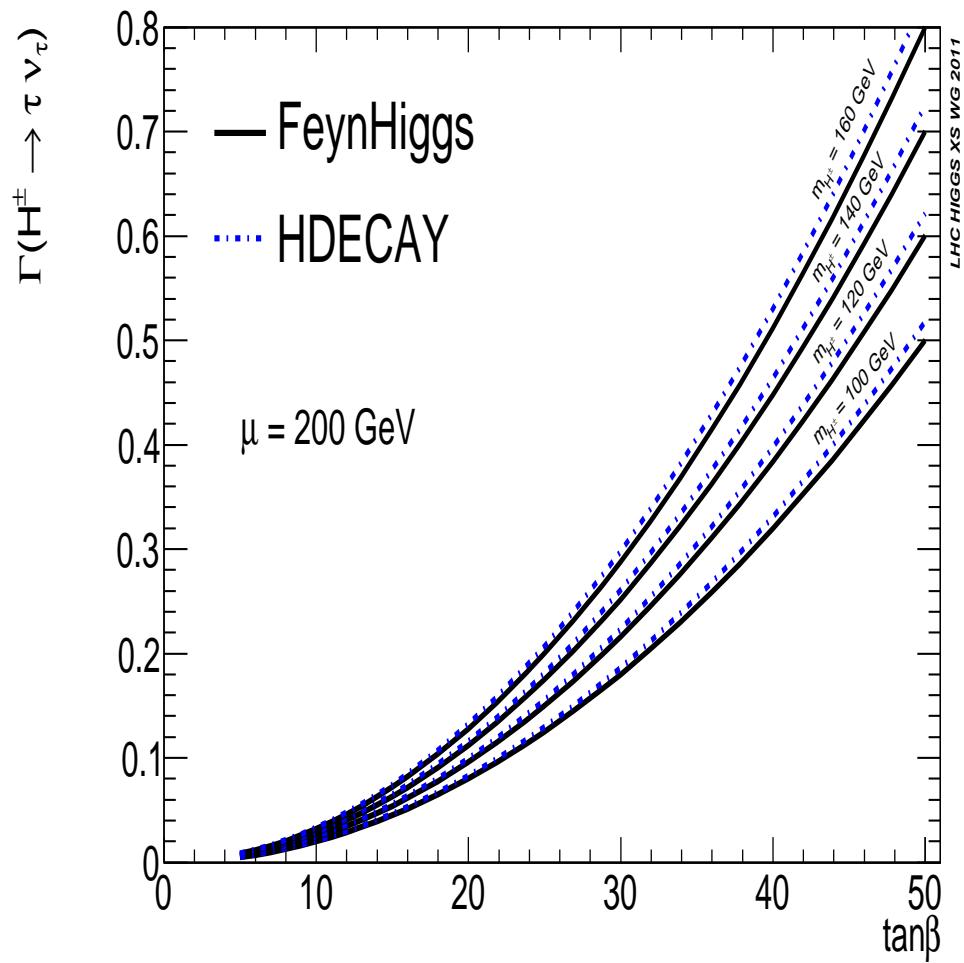
- $\Gamma(H^\pm \rightarrow \tau\nu_\tau)$
- $\Gamma(H^\pm \rightarrow \mu\nu_\mu)$
- $\Gamma(H^\pm \rightarrow cs)$
- $\Gamma(H^\pm \rightarrow AW)$
- $\Gamma(H^\pm \rightarrow HW)$

⇒ in  $m_h^{\max}$  scenario  $\text{BR}(H^\pm \rightarrow \tau\nu_\tau) \approx 96\%$

⇒ all uncertainties irrelevant

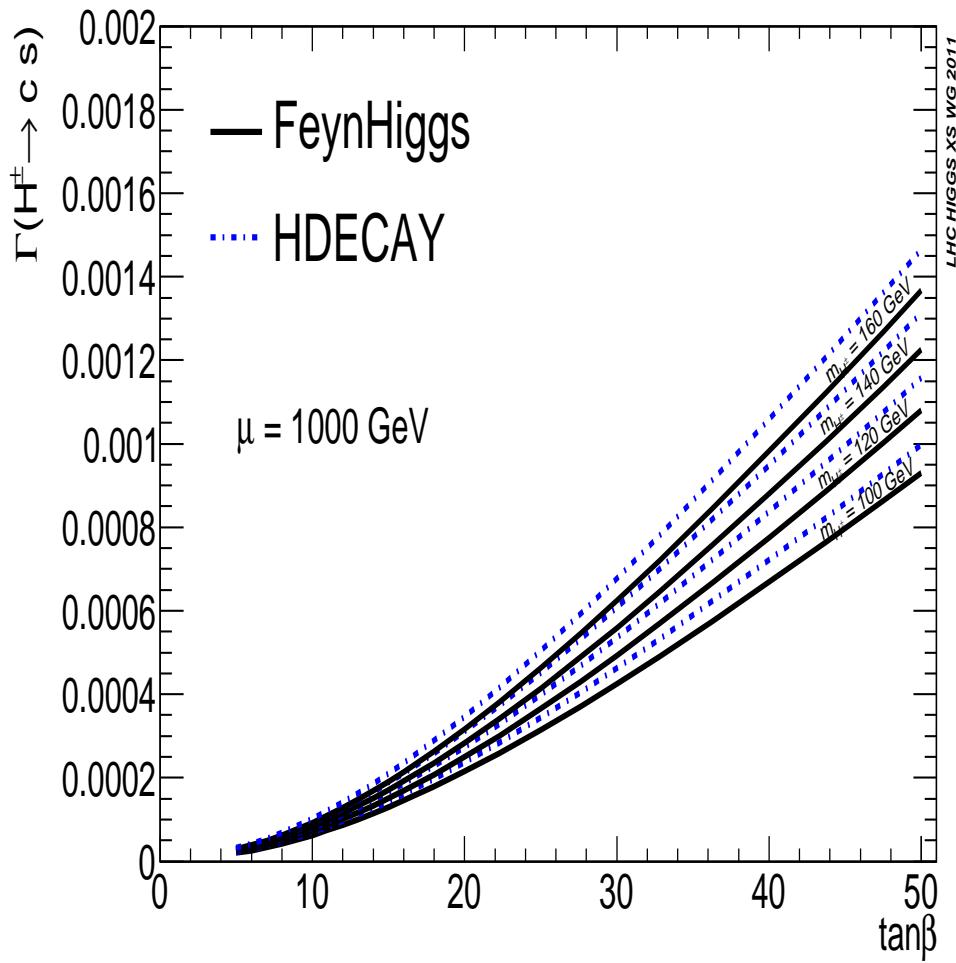
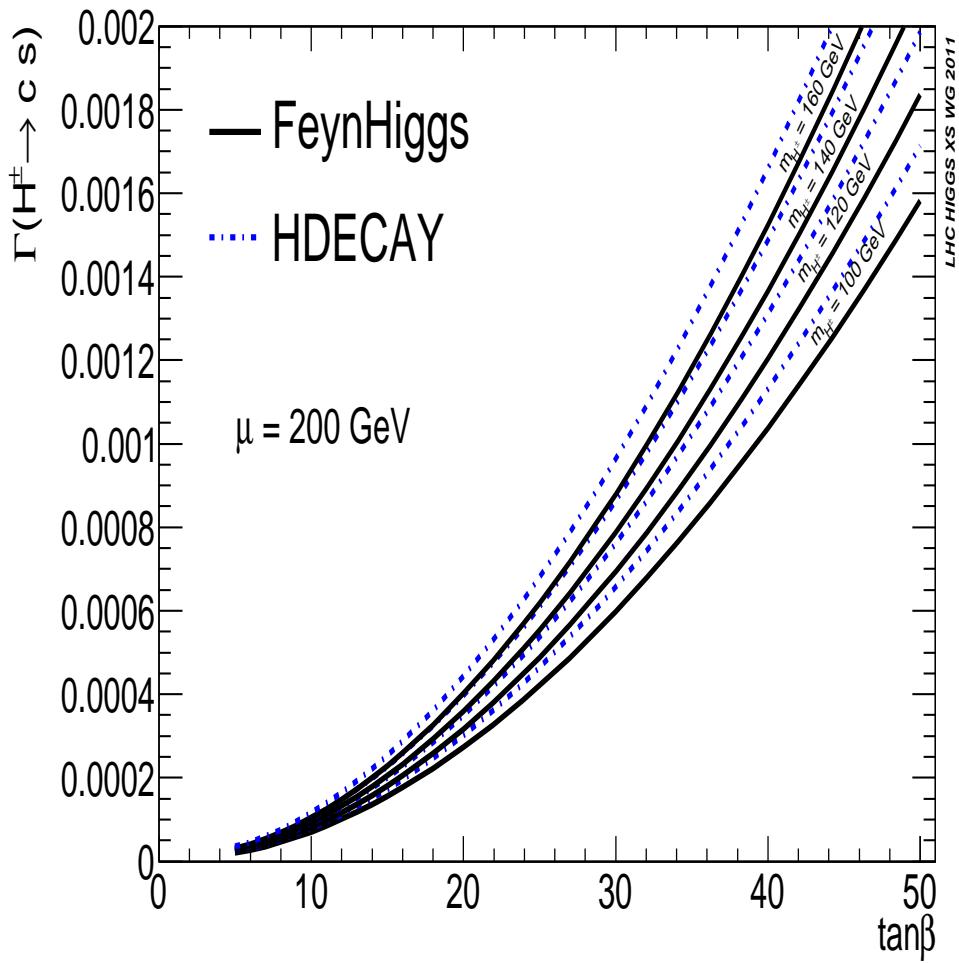
⇒ but comparison serves for general purposes

$\Gamma(H^\pm \rightarrow \tau\nu)$ :



⇒ difference of a few percent (full 1L in FeynHiggs . . . )

$\Gamma(H^\pm \rightarrow cs)$ :



⇒ difference of a  $\sim 10$  percent: more complete  $\Delta_s$  corrections in FH,  
more complete QCD corrections in HD

⇒ inclusion of  $\Delta_s$  crucial!

## Analysis of heavy charged Higgs decays:

→ new initiative of BR group of LHCHXSWG  
[S. Lehti et al. '12]

Comparison of FeynHiggs, Hdecay and(?) CPsuperH(?)

- $\Gamma(H^\pm \rightarrow tb)$
- $\Gamma(H^\pm \rightarrow \tau\nu_\tau)$
- $\Gamma(H^\pm \rightarrow \mu\nu_\mu)$
- $\Gamma(H^\pm \rightarrow cs)$
- $\Gamma(H^\pm \rightarrow AW)$
- $\Gamma(H^\pm \rightarrow HW)$
- ...

⇒ results at cH<sup>±</sup>rged 2014

## Preliminary evaluation of charged Higgs decays:

[*BR group in LHCHXSWG (D. Rebuzzi, S.H.) '12*]

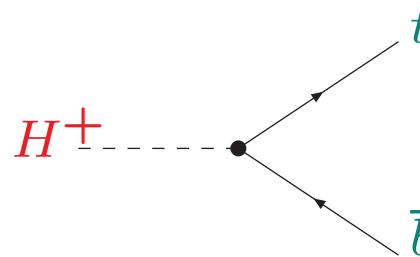
- $\Gamma(H^\pm \rightarrow tb) \rightarrow \text{Hdecay}$
- $\Gamma(H^\pm \rightarrow \tau\nu_\tau) \rightarrow \text{FeynHiggs}$
- $\Gamma(H^\pm \rightarrow \mu\nu_\mu) \rightarrow \text{FeynHiggs}$
- $\Gamma(H^\pm \rightarrow cs) \rightarrow \text{Hdecay}$
- $\Gamma(H^\pm \rightarrow AW) \rightarrow \dots$
- $\Gamma(H^\pm \rightarrow HW) \rightarrow \dots$
- $\dots$

$$\begin{aligned}\Gamma_{\text{tot}} = & \Gamma^{\text{HD}}(H^\pm \rightarrow tb) + \Gamma^{\text{FH}}(H^\pm \rightarrow \tau\nu_\tau) + \Gamma^{\text{FH}}(H^\pm \rightarrow \mu\nu_\mu) \\ & + \Gamma^{\text{HD}}(H^\pm \rightarrow cs) + \Gamma^{\dots}(H^\pm \rightarrow AW) + \Gamma^{\dots}(H^\pm \rightarrow HW) + \dots\end{aligned}$$

$$\text{BR}(H^\pm \rightarrow xy) = \Gamma(H^\pm \rightarrow xy)/\Gamma_{\text{tot}}$$

⇒ ready by end of 2012

## Effects of $\Delta_b$ on production $\times$ decay:



$$y_b \frac{\tan \beta}{1 + \Delta_b}$$

$$\Delta_b = \frac{2\alpha_s}{3\pi} m_{\tilde{g}} \mu \tan \beta \times I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) + \frac{\alpha_t}{4\pi} A_t \mu \tan \beta \times I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu) + \dots$$

$\Rightarrow$  other parameters enter  $\Rightarrow$  strong  $\mu$  dependence

$$H^\pm : \frac{\tan^2 \beta}{(1 + \Delta_b)^2} \times \text{BR}(H^\pm \rightarrow \tau \nu_\tau)$$

$$: \frac{\tan^2 \beta}{(1 + \Delta_b)^2} \times \frac{\Gamma(H^\pm \rightarrow \tau \nu_\tau)}{\Gamma^{\text{THDM}}(H^\pm \rightarrow tb)/(1 + \Delta_b)^2 + \Gamma(H^\pm \rightarrow \tau \nu_\tau) + \dots}$$

$\Rightarrow$  no compensation of  $\Delta_b$  effects for light charged Higgs  
 $\Rightarrow$  partial compensation for heavy charged Higgs

## 4. Conclusions

- Many models predict charged Higgses . . .
- THDM type II:  $g_{tb}H^\pm \sim m_t \cot\beta + m_b \tan\beta$ ,  $g_{\tau\nu}H^\pm \sim m_\tau \tan\beta$   
→ relevant for light and heavy charged Higgs
- Light charged Higgs production:  
Evaluation of full uncertainties ( $\sigma(pp \rightarrow t\bar{t})$ ,  $m_t$ ,  $\Delta_b$ ,  $\text{BR}(t \rightarrow H^+ b)$ , . . .)  
→ sizable uncertainties
- Heavy charged Higgs production:  
**4FS** vs. **5FS** ⇒ **Santander matching**  
new evaluation including all uncertainties, clever scale choice:
  - central values nearly agree
  - Santander matching gives uncertainty estimate
- Light charged Higgs decays:  
in the MSSM:  $\Gamma(H^\pm \rightarrow \tau\nu_\tau)$  dominant, uncertainties drop out  
Comparison of FeynHiggs and Hdecay ⇒ some differences in  $H^\pm \rightarrow cs$
- Heavy charged Higgs decays:  
analysis in progress in **LHCXSWG**