LHC Higgs Cross Section WG:

Progress for the (light & heavy) charged Higgs

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1. What charged Higgs?
2. The light charged Higgs in the MSSM
3. Light charged Higgs decays
4. The heavy charged Higgs in the MSSM

1. What charged Higgs?

Models with charged Higgs bosons:

1. Two Higgs Doublet Model (THDM)
   $\rightarrow$ type I, II, III, IV, ...

2. Minimal Supersymmetric Standard Model (MSSM)
   $\rightarrow$ type II (+ loop corrections)

3. MSSM with extra singlet (NMSSM)
   $\rightarrow$ type II (+ loop corrections)

4. MSSM with more extra singlets
   $\rightarrow$ type II (+ loop corrections)

5. SM/MSSM with Higgs triplets
   $\rightarrow$ more options

6. ...

$\Rightarrow$ so far focus on type II: $g_{tbH^\pm} \sim m_t \cot\beta + m_b \tan\beta, \quad g_{\tau\nu H^\pm} \sim m_\tau \tan\beta$

Common and different features of Models with Charged Higgs Bosons

To my knowledge the following points 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?
  $\rightarrow$ only through $H^{\pm} \rightarrow \tau\nu_{\tau}$ (!?)
- 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?

$\Rightarrow$ very helpful: experts for the various models

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

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

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

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

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

$\Rightarrow$ in principle the same couplings are relevant for
light and heavy charged Higgs

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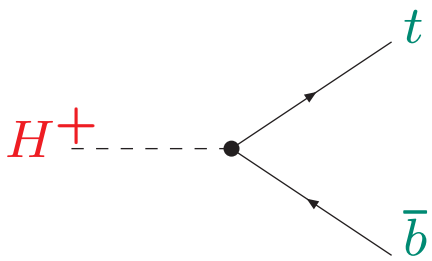
YR: production cross sections for light and heavy MSSM charged Higgs

Effects of Δ_b:



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

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

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

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

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

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

2. The light charged MSSM Higgs

Sources of theory uncertainties:

1. PDF and α_s uncertainties on $\sigma(pp \to t\bar{t})$
2. experimental uncertainties on m_t, affecting $\sigma(pp \to t\bar{t})$
3. Uncertainties of Δ_b
4. Experimental uncertainties in SUSY masses entering Δ_b
5. Further missing higher order corrections in BR$(t \to H^+ b)$
6. Theory uncertainties in Higgs decays

– How large are the uncertainties?

– How large are the corresponding effects?

Size of theory uncertainties (I):

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

taken over from the ATLAS top group:

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

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

scale uncertainty: variation of μ_R and μ_F: 0.5 . . . 2

PDF uncertainty: MSTW2008, 68% C.L.

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

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

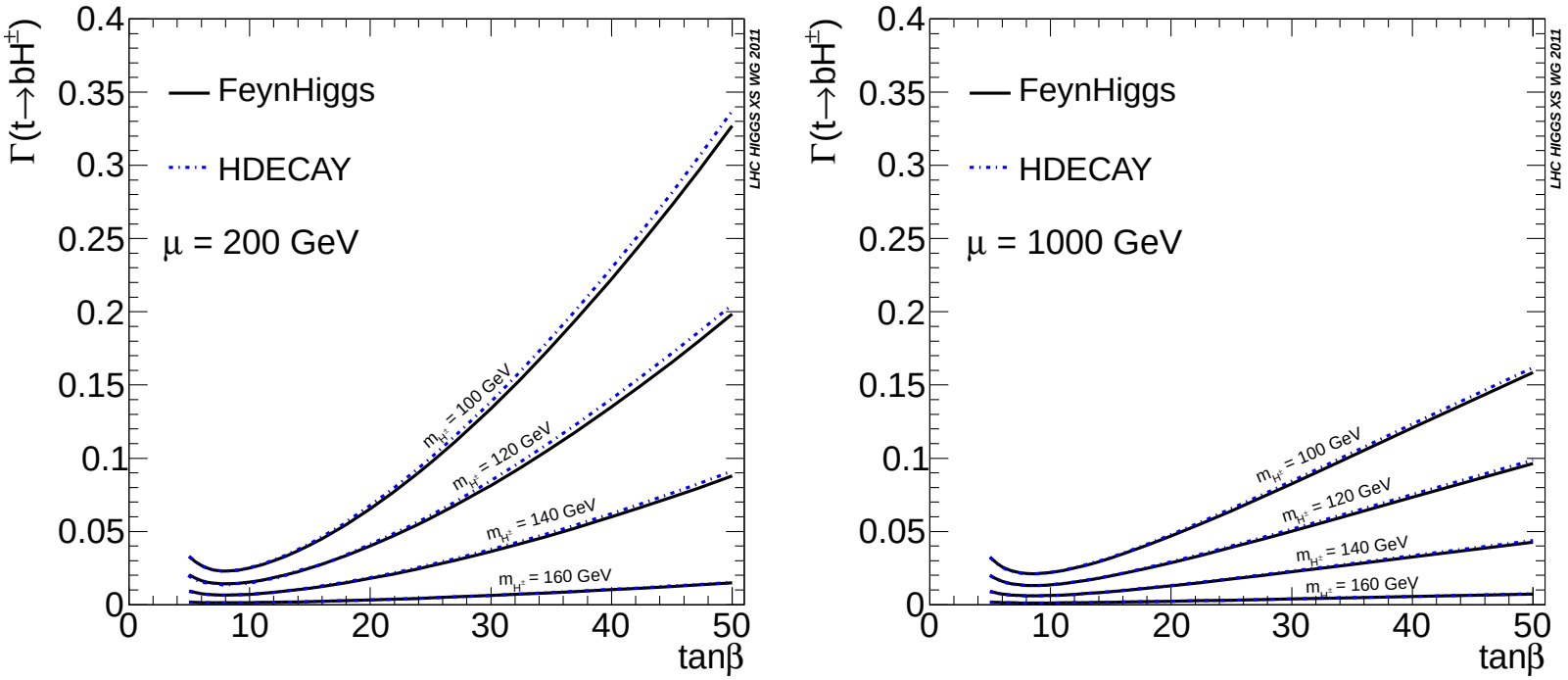
$\Rightarrow$ combined quadratically with scale/PDF uncertainty
in comparison relatively small

Size of theory uncertainties (II):

3. Uncertainties of Δ_b

Uncertainties beyond $\Delta_b (\sim \alpha_s \ldots + \alpha_t \ldots)$
$\Rightarrow$ scale variation of $\alpha_s(Q) \Rightarrow$ effect on $\Delta_b \lesssim 3\%$
after inclusion of the two-loop corrections on Δ_b [*D. Noth, M. Spira, '08*]

Comparison of FeynHiggs and HDECAY: decay width:



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

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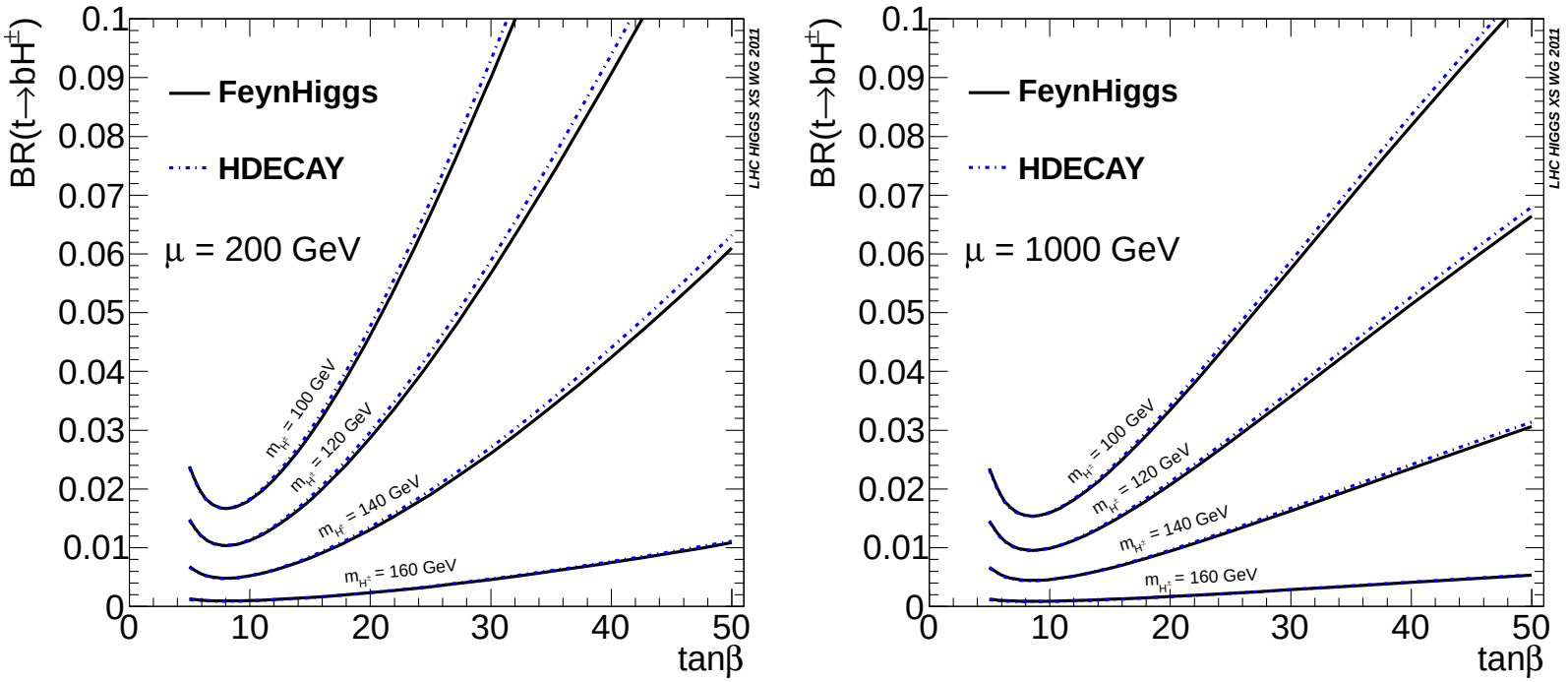
Comparison of FeynHiggs and HDECAY: branching ratio:



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

Size of theory uncertainties (III):

4. Experimental uncertainties in SUSY masses entering Δ_b

$\rightarrow$ beyond the scope, requires full experimental analysis, parameter dependent, ...

5. Further missing higher order corrections in BR($t \to H^+ b$)

$\Rightarrow$ no dedicated analysis exists

So far assumed:
- 5% for missing 1L EW corrections
- 2% for missing 2L QCD corrections

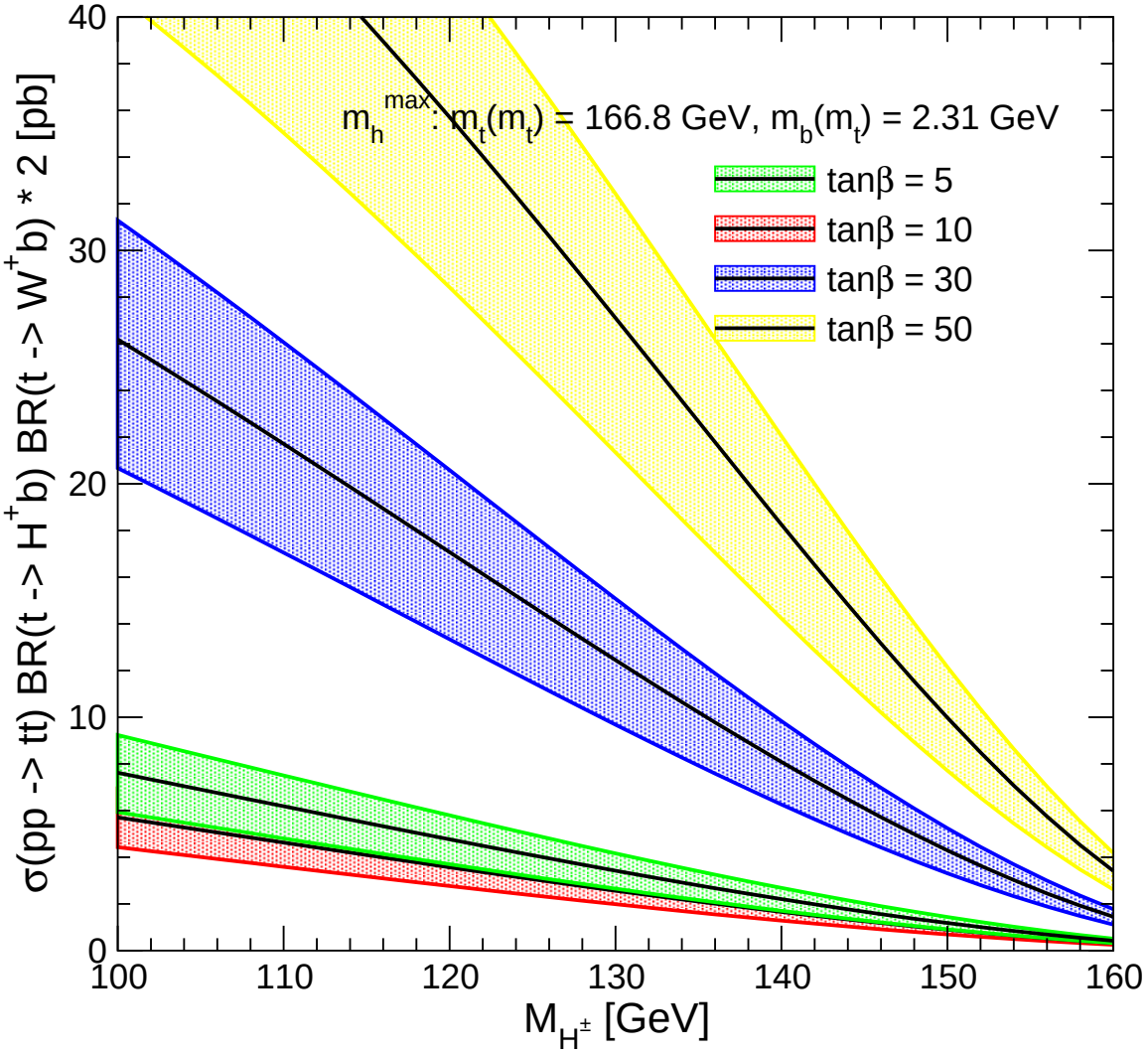
$\rightarrow$ to optimistic?

Combination of everything:

Calculation of

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

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



$\Rightarrow$ non-negligible . . .

3. Light charged Higgs decays

Comparison of FeynHiggs and HDECAY for

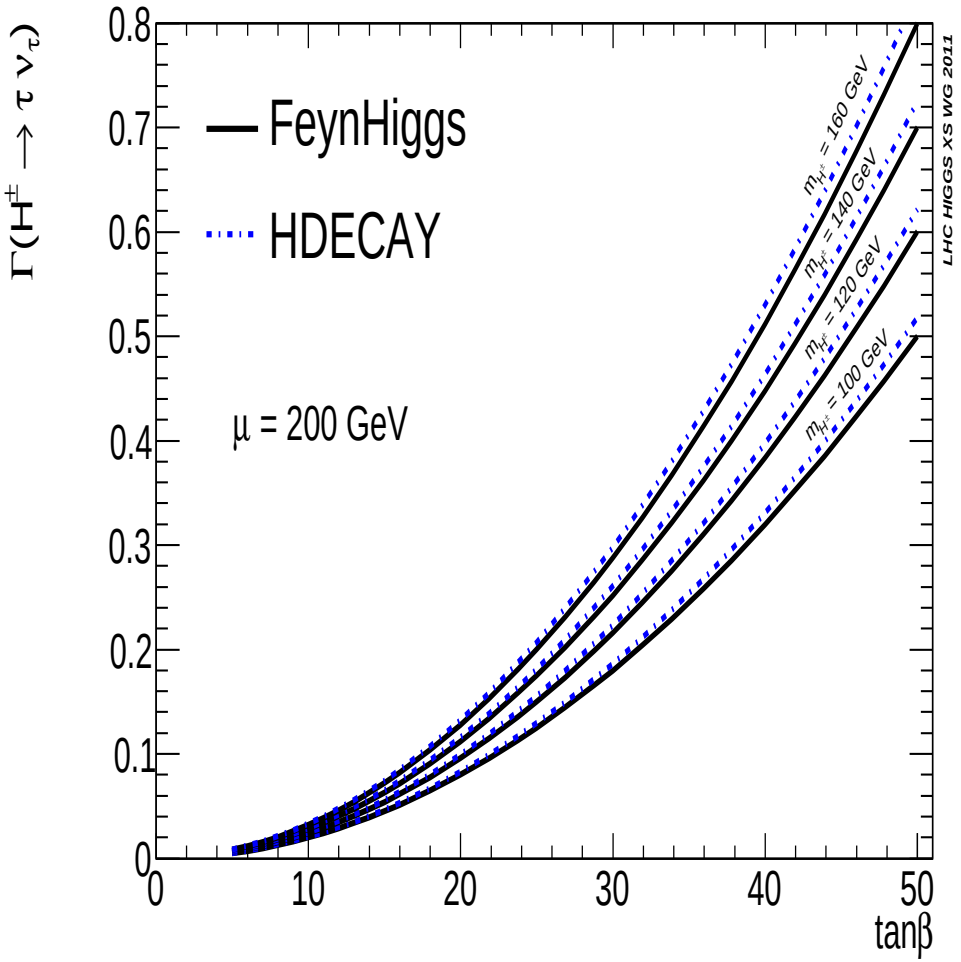
- $\Gamma(H^\pm \to \tau\nu_\tau)$
- $\Gamma(H^\pm \to \mu\nu_\mu)$
- $\Gamma(H^\pm \to cs)$
- $\Gamma(H^\pm AW)$
- $\Gamma(H^\pm HW)$

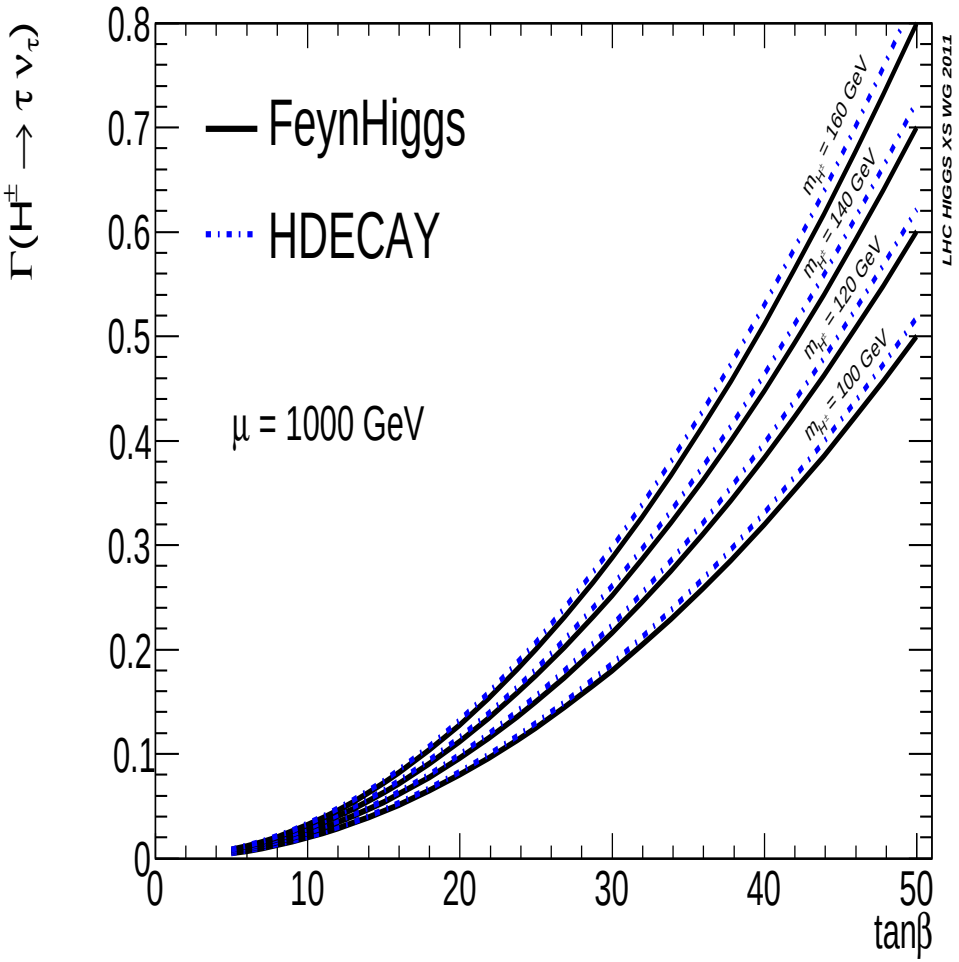
$\Rightarrow$ in m_h^{max} scenario BR$(H^\pm \to \tau\nu_\tau) \approx 96\%$

$\Rightarrow$ all uncertainties irrelevant

$\Rightarrow$ but comparison serves for general purposes

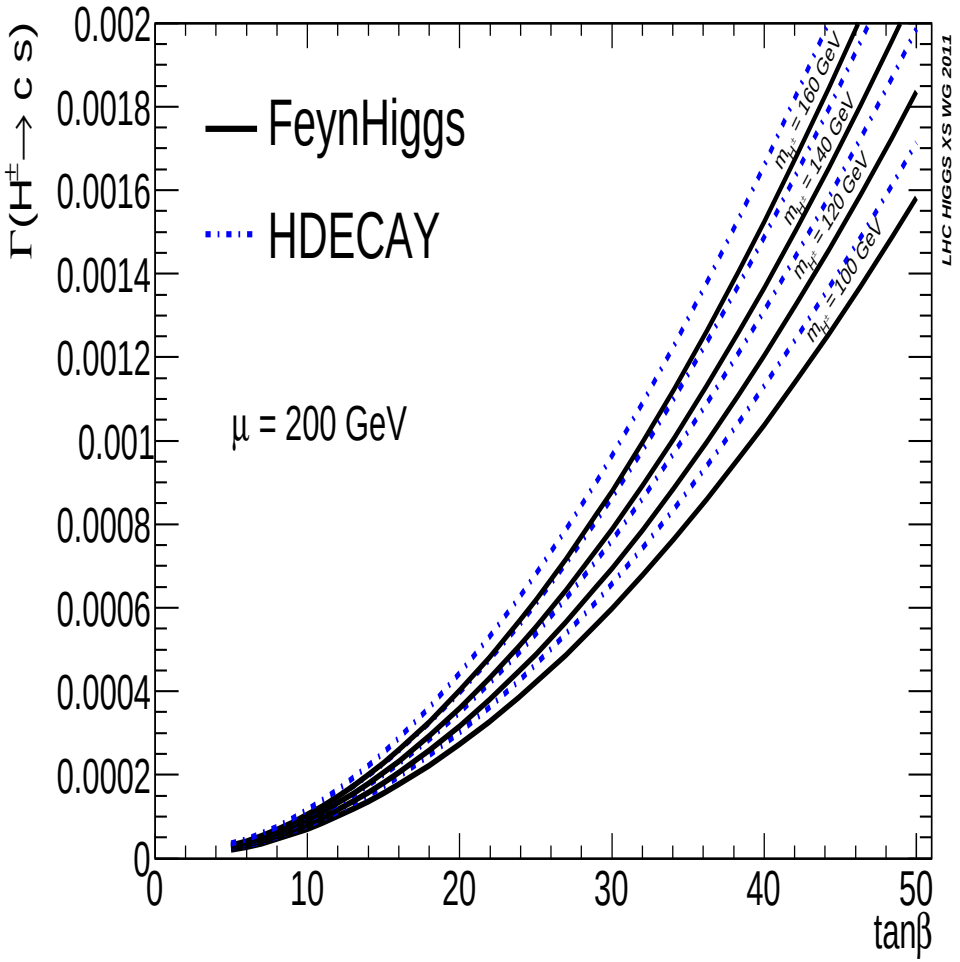
$\Gamma(H^\pm \to \tau\nu)$:

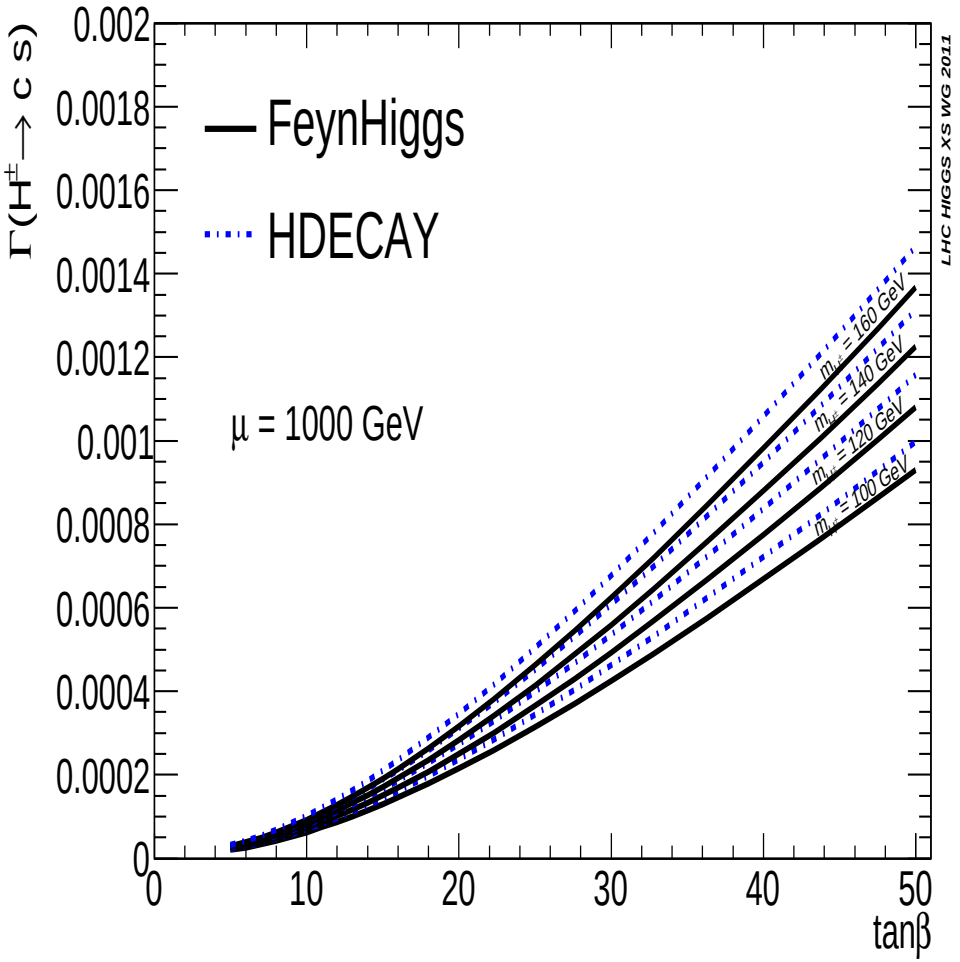




$\Rightarrow$ difference of a few percent (full 1L in FeynHiggs . . .)

$\Gamma(H^{\pm} \to cs)$:



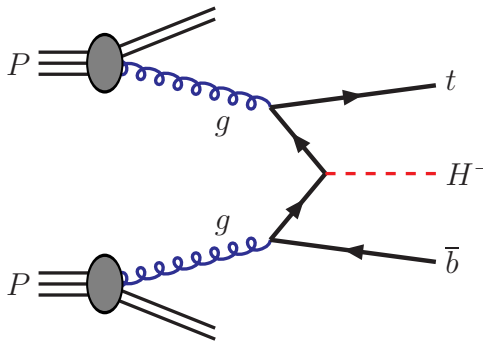


$\Rightarrow$ difference of a ~ 10 percent (more complete Δ_s corrections in FH, more complete QCD corrections in HD)

Heavy charged Higgs production: two calculational schemes

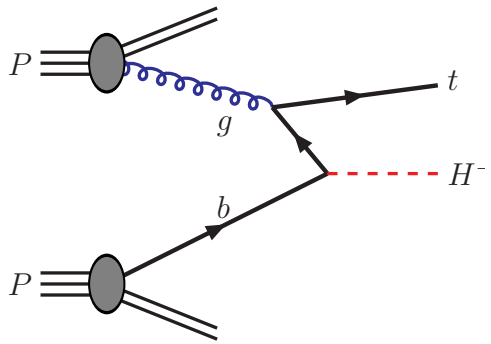
There are two schemes to calculate the charged Higgs cross section:

the 4-flavour scheme



+ exact $g \to b\bar{b}$ splitting & mass effects
− no summation of $\ln(M_H/M_b)$ terms

and the 5-flavour scheme



+ summation of $\ln(M_H/M_b)$ terms
− LL approx. to $g \to b\bar{b}$ splitting

The 4- and 5-flavour schemes

- are both theoretically consistent & well-defined
- represent different ways of ordering perturbation theory
- should agree at sufficiently high order
- do not match exactly at finite order

Heavy charged Higgs production: comparison of 4FS and 5FS

- In both schemes NLO SUSY-QCD calculations have been performed (Dittmaier, MK, Spira, Walser; Plehn; Berger et. al; Weydert et al.).

- At the recommended central scales

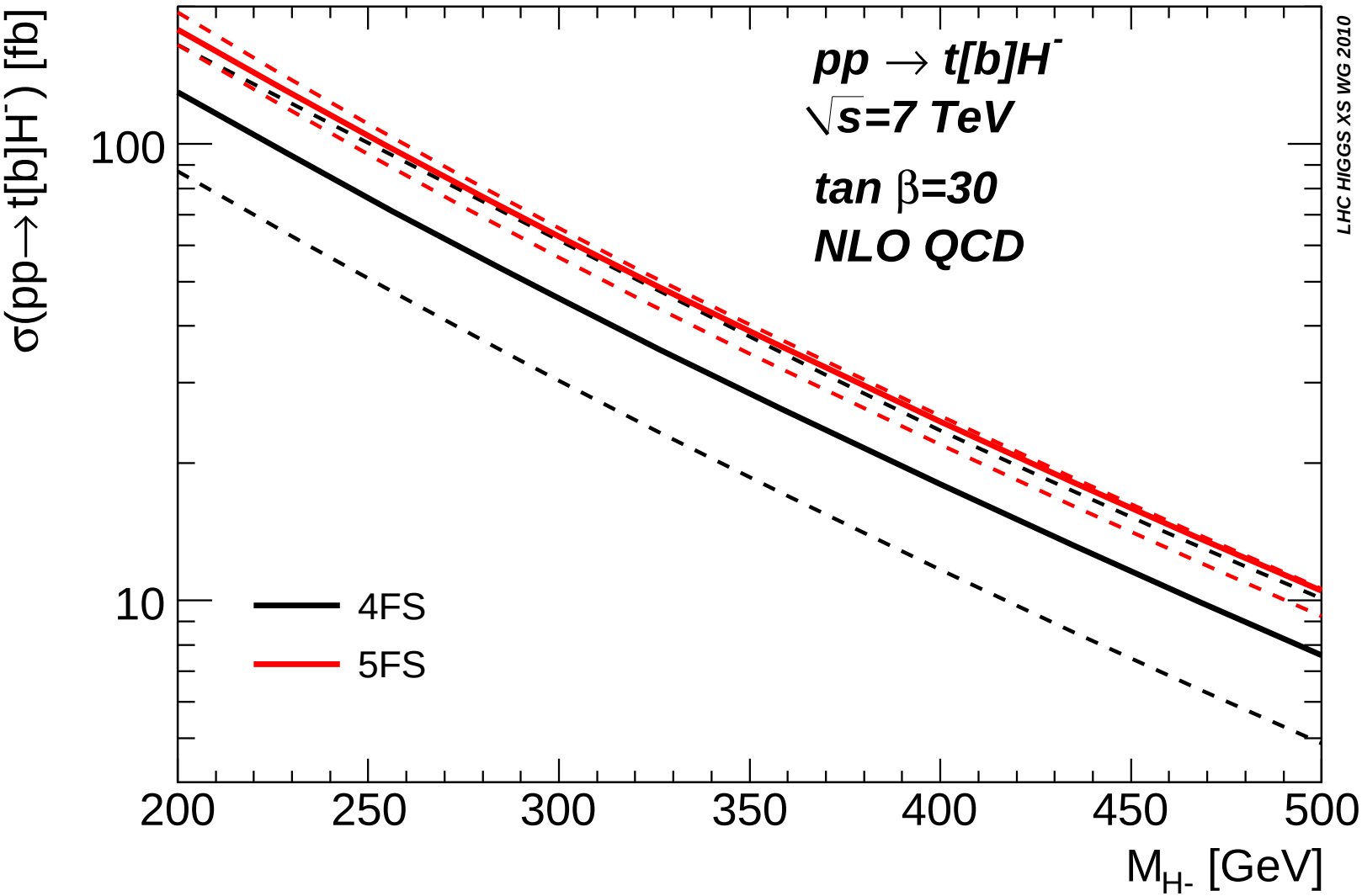
$$\text{4FS:} \quad \mu_0 = (m_\mathrm{b} + m_\mathrm{t} + m_\mathrm{H})/3;$$
$$\text{5FS:} \quad \mu_0 = (m_\mathrm{t} + m_\mathrm{H})/4$$

  the 5FS prediction is about 35% larger than the 4FS, nearly independent of m_H.

- Taking the scale uncertainty, $\mu_0/3 \leq \mu \leq 3\mu_0$, into account, the 4FS and 5FS cross sections at NLO are consistent, i.e. the error bands overlap.

- This comparison has been made with MSTW2008 4FS and 5FS pdfs. We have not yet quantified the pdf error of the 5FS calculation.

Heavy charged Higgs production: comparison of 4FS and 5FS



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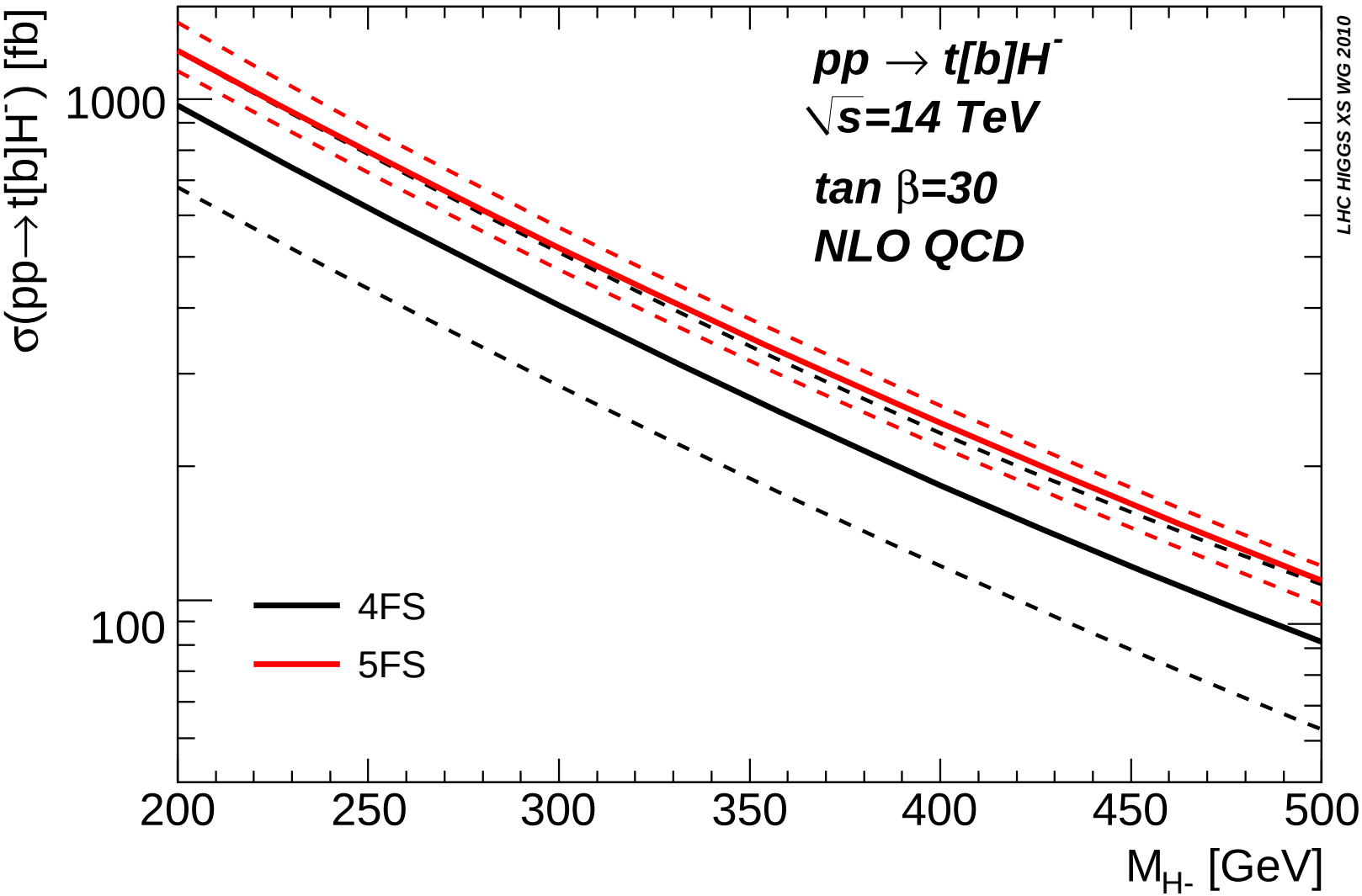
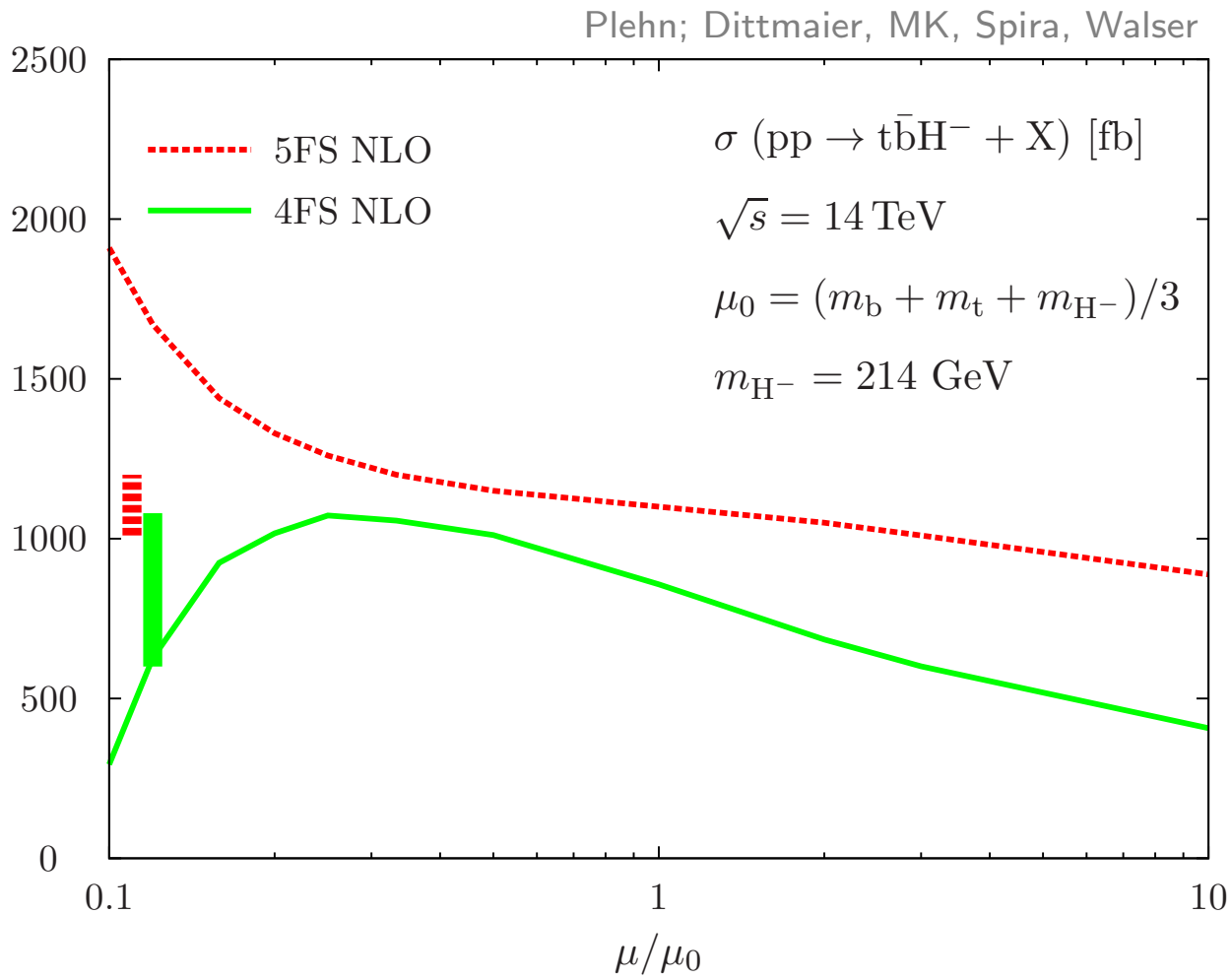


Heavy charged Higgs production: 4FS and 5FS scale uncertainty

The 5FS calculation exhibits a very unusual (and small) scale dependence:



Santander matching

Based on: Harlander, MK, Schumacher, CERN-PH-TH/2011-134

The 4FS and 5FS provide unique descriptions of the cross sections in the asymptotic limits

$$m_{\rm H}/m_{\rm b} \to 1 \quad : \quad 4{\rm FS}$$
$$m_{\rm H}/m_{\rm b} \to \infty \quad : \quad 5{\rm FS}$$

The difference between the 4FS and 5Fs is formally logarithmic. We have proposed to combine the two schemes with a weight that depends logarithmically on $m_{\rm H}/m_{\rm b}$:

$$\text{The} \left\{ \begin{array}{c} 4{\rm FS} \\ \\ 5{\rm FS} \end{array} \right\} \text{gets 100\% weight as} \left\{ \begin{array}{c} \ln(m_{\rm H}/m_{\rm b}) \to 2 \\ \\ m_{\rm H}/m_{\rm b} \to \infty \end{array} \right\}$$

Santander matching

The Santander-matched cross section thus is

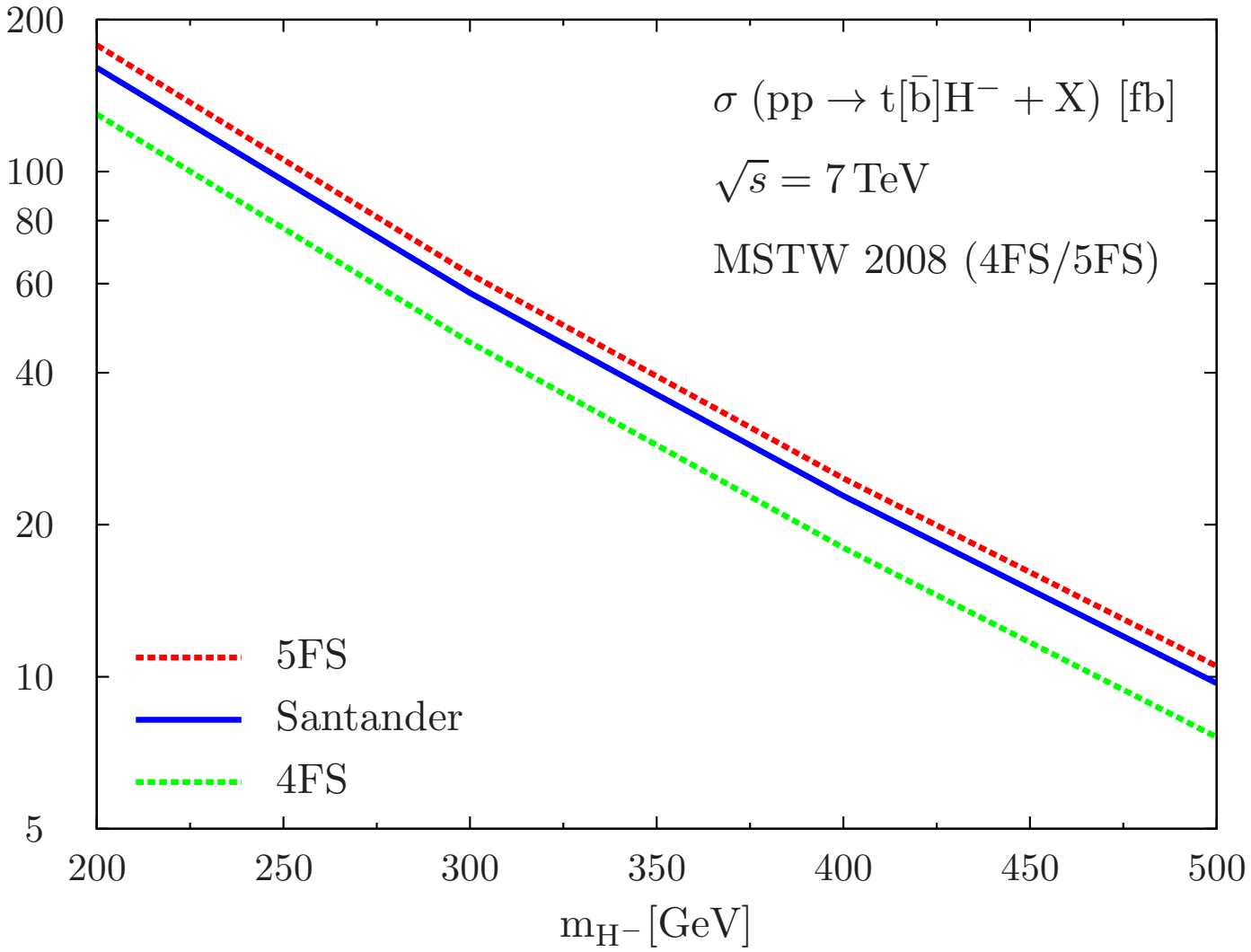
$$\sigma^{\text{matched}} = \frac{\sigma^{\text{4FS}} + w\,\sigma^{\text{5FS}}}{1+w}\,,$$

with the weight w defined as $\quad w = \ln\frac{m_{\text{H}}}{m_{\text{b}}} - 2\,.$

For $m_{\text{b}} = 4.75\,\text{GeV}$ and specific values of m_{H}, this leads to

$$\begin{aligned}
\sigma^{\text{matched}}\big|_{m_{\text{H}}=100\,\text{GeV}} &= 0.49\,\sigma^{\text{4FS}} + 0.51\,\sigma^{\text{5FS}}\,,\\
\sigma^{\text{matched}}\big|_{m_{\text{H}}=200\,\text{GeV}} &= 0.36\,\sigma^{\text{4FS}} + 0.64\,\sigma^{\text{5FS}}\,,\\
\sigma^{\text{matched}}\big|_{m_{\text{H}}=300\,\text{GeV}} &= 0.31\,\sigma^{\text{4FS}} + 0.69\,\sigma^{\text{5FS}}\,,\\
\sigma^{\text{matched}}\big|_{m_{\text{H}}=400\,\text{GeV}} &= 0.29\,\sigma^{\text{4FS}} + 0.71\,\sigma^{\text{5FS}}\,,\\
\sigma^{\text{matched}}\big|_{m_{\text{H}}=500\,\text{GeV}} &= 0.27\,\sigma^{\text{4FS}} + 0.73\,\sigma^{\text{5FS}}\,.
\end{aligned}$$

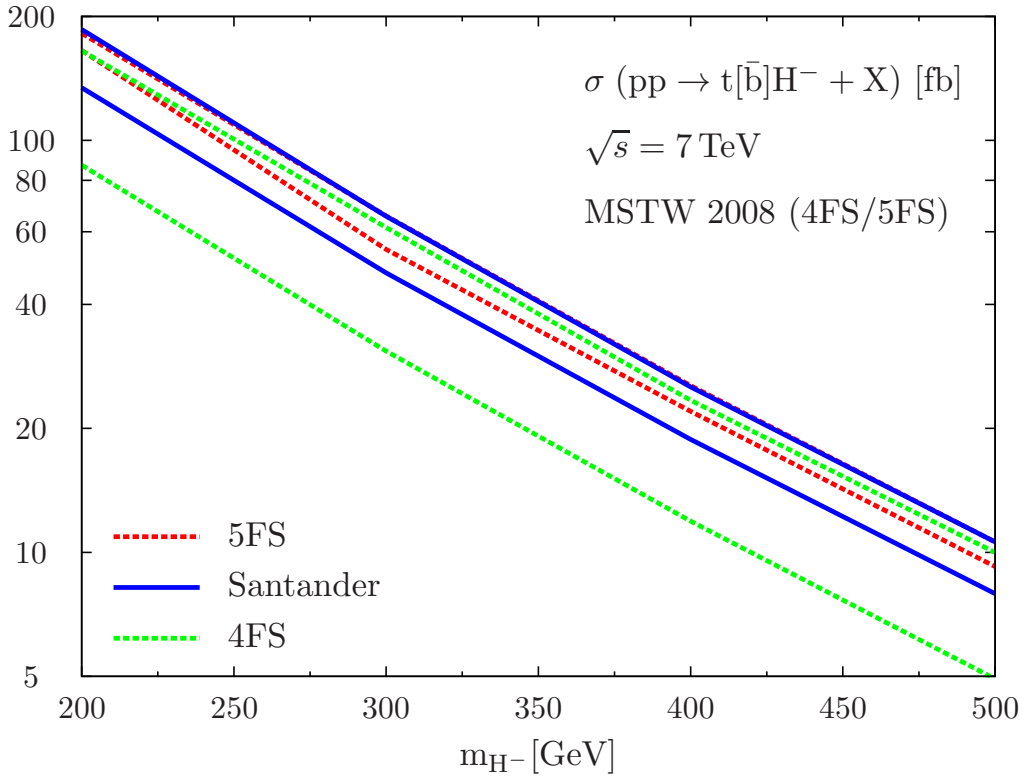
Santander matching: the charged Higgs cross section



Santander matching: uncertainties

We have proposed to add the uncertainties linearly, with weight w:

$$\Delta\sigma_{\pm} = \frac{\Delta\sigma_{\pm}^{\text{4FS}} + w\,\Delta\sigma_{\pm}^{\text{5FS}}}{1+w}\,.$$



Heavy charged Higgs production: comments

- The agreement between the 4FS and 5FS calculations is worse than for neutral Higgs production; maybe this is related to the fact that the 5FS is only NLO, and the scale dependence as evaluated with standard prescriptions does not really reflect the theoretical uncertainty?
- The choice of scale for the 5FS calculations is delicate: it depends on the mass ratio $m_{\mathrm{H}}/m_{\mathrm{b}}$ and on the kinematics of the process [see work by Maltoni, McElmurry, Putman, Willenbrock and work in progress by Maltoni, Ridolfi and Ubiali].
- We need to quantify the bottom pdf uncertainty, including the bottom mass dependence.
- Differential distributions are available at NLO in the 4FS and at LO/NLO with parton shower in the 5FS: we are finalising a comparison of the shape of the bottom p_t distribution (as Sven speaks...) and hope to be able to include the results in the Yellow report.