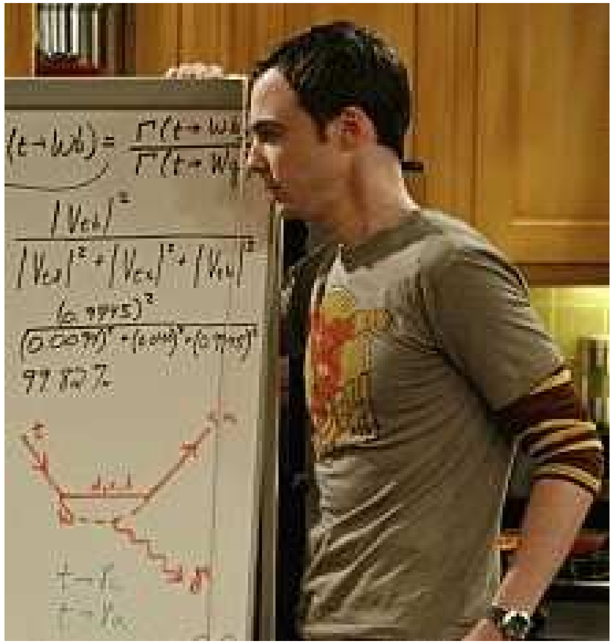
From "The Big Bang Theory":

(episode 15/01)



Sister: I am always bragging to my friends about my brother, the rocket scientist.

Sheldon: You tell people I am a rocket scientist?

Sister: Well, yeah.

Sheldon: I am a theoretical physicist.

Sister: What is the difference?

Sheldon: What is the difference?

. . .

My god! Why don't you just tell them that I am a toll taker at the Golden Gate bridge?

Rocket scientist... how humiliating!

Charged MSSM Higgs Bosons: LHC Reach and Parameter Dependence

Sven Heinemeyer, IFCA (Santander)

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in collaboration with
M. Hashemi, R. Kinnunen, A. Nikitenko and *G. Weiglein*

1. Motivation and theory
2. LHC reach for light charged Higgs bosons
3. LHC reach for heavy charged Higgs bosons
4. Theory uncertainties
5. Conclusions

1. Motivation and theory

MSSM Higgs sector: Two Higgs doublets

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

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

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) + \underbrace{\frac{g'^2 + g^2}{8}}(H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2$$

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)

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

In lowest order:

Input parameters: (to be determined experimentally)

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

$\Rightarrow$ m_h, m_H, mixing angle α, $m_{H^\pm}$: 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

$\Rightarrow$ Test of the model!

Necessary:

– discover the charged Higgs at the LHC or at the ILC
– measure its mass at the LHC or at the ILC
– compare with theory prediction for $M_{H^\pm}$

Search for the lightest MSSM Higgs boson:

Situation is more involved due to many SUSY parameters

$\longrightarrow$ investigate benchmark scenarios:

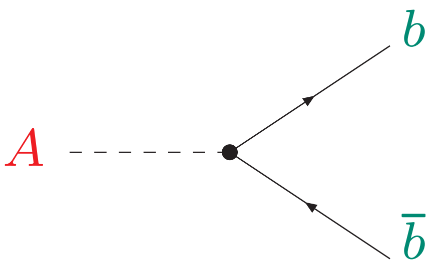
> $\longrightarrow$ Vary only M_A and $\tan\beta$
> $\longrightarrow$ Keep all other SUSY parameters fixed

1. m_h^{max} scenario:
   $\longrightarrow$ obtain conservative $\tan\beta$ exclusion bounds ($X_t = 2\,M_{\text{SUSY}}$)
2. no-mixing scenario
   $\longrightarrow$ no mixing in the scalar top sector ($X_t = 0$)
3. small α_{eff} scenario
   $\longrightarrow$ $hb\bar{b}$ coupling $\sim \sin\alpha_{\text{eff}}/\cos\beta$ can be zero: $\alpha_{\text{eff}} \to 0$:
   main decay mode vanishes, important search channel vanishes
4. gluophobic Higgs scenario
   $\longrightarrow$ hgg coupling is small: main LHC production mode vanishes

[*M. Carena, S.H., C. Wagner, G. Weiglein '02*]

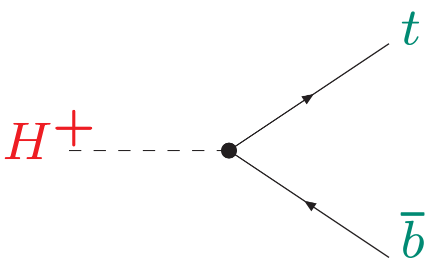
Search for the heavy MSSM Higgs bosons:

Additional enhancement factors compared to the SM case:



$$y_b \quad \longrightarrow \quad y_b \, \frac{\tan\beta}{1 + \Delta_b}$$

At large $\tan\beta$: either $H \approx A$ or $h \approx A$



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

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

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

Suggestion for new benchmark scenarios:

[*M. Carena, S.H., C. Wagner, G. Weiglein '05*]

$\rightarrow$ investigate benchmark scenarios:

$\rightarrow$ Vary only M_A and $\tan\beta$ (large!)
$\rightarrow$ Keep all other SUSY parameters fixed

$\rightarrow$ Vary in addition μ: $\mu = \pm 1000, \pm 500, \pm 200$ GeV
(if perturbativity allows)

1. m_h^{max} scenario:
   $\rightarrow$ obtain conservative $\tan\beta$ exclusion bounds ($X_t = 2\, M_{\text{SUSY}}$)

   A_t large $\Rightarrow$ large $\mathcal{O}(\alpha_t)$ contribution to Δ_b

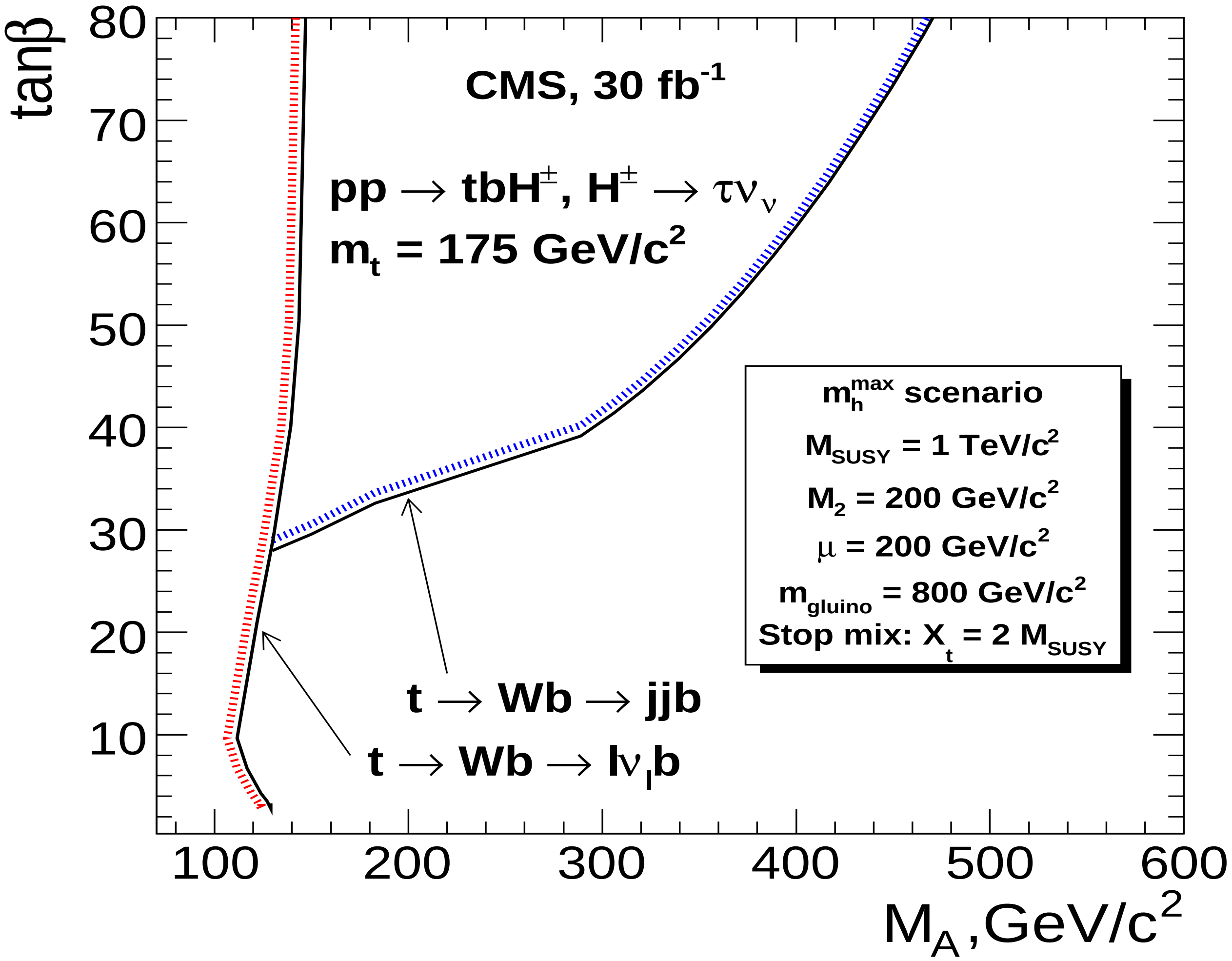
2. no-mixing scenario
   $\rightarrow$ no mixing in the scalar top sector ($X_t = 0$)

   A_t small $\Rightarrow$ small $\mathcal{O}(\alpha_t)$ contribution to Δ_b

   $\Rightarrow$ large difference to m_h^{max} scenario

Charged Higgs boson searches:

MSSM Higgs discovery contours in M_A–$\tan\beta$ plane
(m_h^{max} benchmark scenario): *[CMS PTDR '06]*



light charged Higgs:

$$M_{H^\pm} < m_t$$

heavy charged Higgs:

$$M_{H^\pm} > m_t$$

Most powerful search modes for charged MSSM Higgs bosons:

$$gb \to tH^\pm + X, \;\; H^\pm \to \tau\nu_\tau$$
$$pp \to t\bar{t} \to H^\pm + X, \;\; H^\pm \to \tau\nu_\tau$$

Enhancement factors compared to the SM case:

$$H/A \;:\; \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \frac{\text{BR}(H \to \tau^+\tau^-) + \text{BR}(A \to \tau^+\tau^-)}{\text{BR}(H \to \tau^+\tau^-)_{\text{SM}}}$$

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

$\Rightarrow$ Δ_b effects so far neglected by ATLAS/CMS

also relevant for BR($H/A \to \tau^+\tau^-$), BR($H^\pm \to \tau\nu_\tau$)

also relevant: correct evaluation of $\Gamma(H/A/H^\pm \to \text{SUSY})$

$\Rightarrow$ additional effects on BR($H/A \to \tau^+\tau^-$), BR($H^\pm \to \tau\nu_\tau$)

2. LHC reach for the light charged Higgs boson

$$M_{H^\pm} < m_t$$

Main production channel:

$$pp \longrightarrow t\bar{t} \longrightarrow t\ H^-\bar{b} \quad \text{or} \quad H^+ b\ \bar{t}$$

Close to threshold also contribution from:

$$gb \longrightarrow H^- t \quad \text{or} \quad g\bar{b} \longrightarrow H^+ \bar{t}$$

Relevant decay channel:

$$H^\pm \longrightarrow \tau\nu_\tau$$

Experimental analysis for CMS PTDR:

full simulation, 30 fb^{-1}

[*M. Baarmand, M. Hashemi and A. Nikitenko, CMS Note 2006/056*]

$\rightarrow$ no details here

Number of signal-like events:

channel	exp. efficiency
$pp \to t\bar{t} \to H^+ b\,\bar{t} \to (\tau^+ \bar{\nu}_\tau)\,(W^+ b)$; $\tau \to$ hadrons, $W \to l\nu_l$	0.0052
$pp \to t\bar{t} \to W^+\,W^- \to (\tau\nu_\tau)\,(l\nu_l)$; $\tau \to$ hadrons	0.00217
$pp \to t\bar{t} \to W^+\,W^- \to (l\nu_l)\,(l\nu_l)$	0.000859
$pp \to t\bar{t} \to W^+\,W^- \to$ (jet jet) $(l\nu_l)$	0.000134
$g\bar{b} \to H^+\bar{t} \to (\tau\nu_\tau)\,(Wb)$; $\tau \to$ hadrons, $W \to l\nu_l$	0.0052

$5\,\sigma$ discovery with 30 fb^{-1} $\Leftrightarrow$ $N_{\text{ev}} > 5260$

Theory evaluation:

$\sigma(pp \to t\bar{t}) = 840\,\text{pb}$

$\sigma(gb \to H^{\pm}t)$: state-of-the-art

[*T. Plehn '02*] [*E. Berger, T. Han, J. Jiang and T. Plehn '03*]

$+ \ \Delta_b$ corrections

$\text{BR}(t \to H^{\pm}b)$: Δ_b corrections included

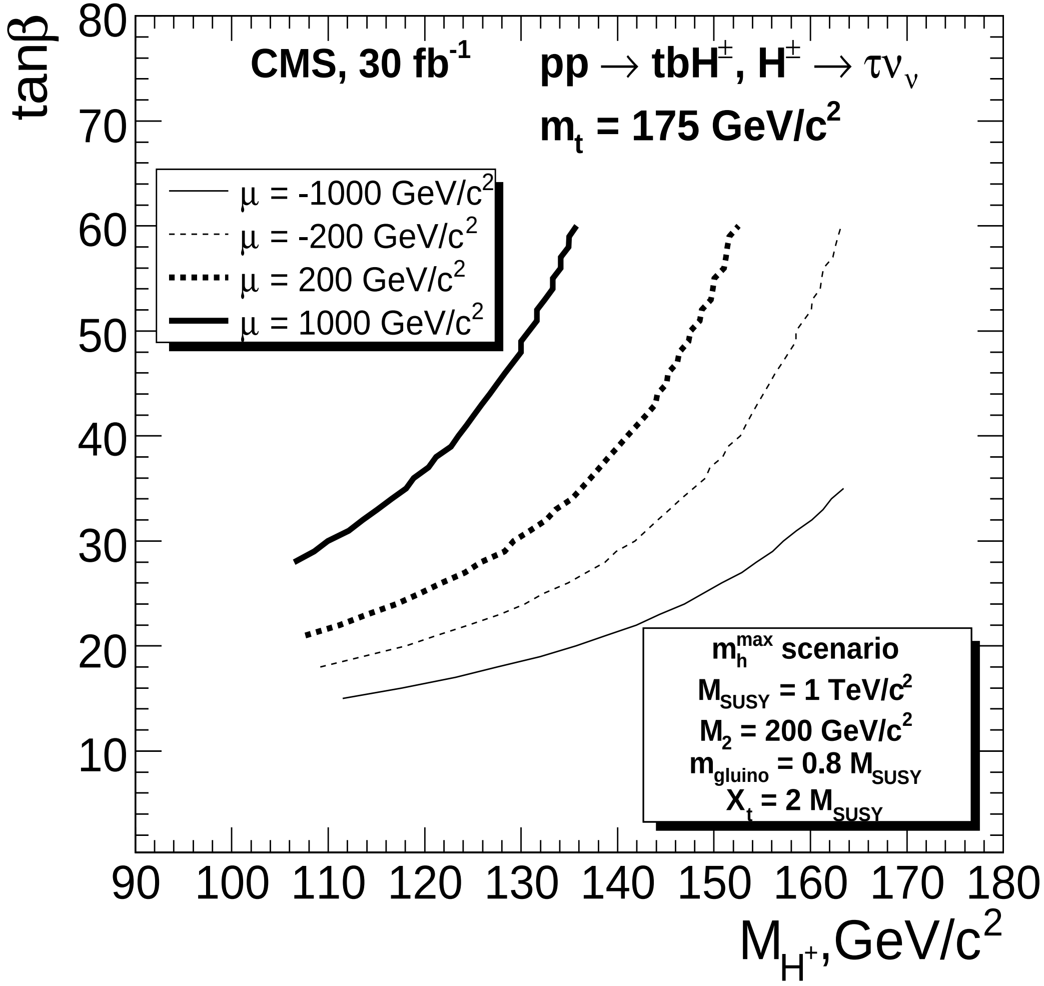
$\text{BR}(H^{\pm} \to \tau\nu_\tau, tb, W^{\pm(*)}h, \ldots)$: Δ_b corrections included

Fixed values for all other BRs

Everything evaluated with

`FeynHiggs (www.feynhiggs.de)`

Results for the m_h^{max} scenario:



$\Rightarrow$ strong variation with μ

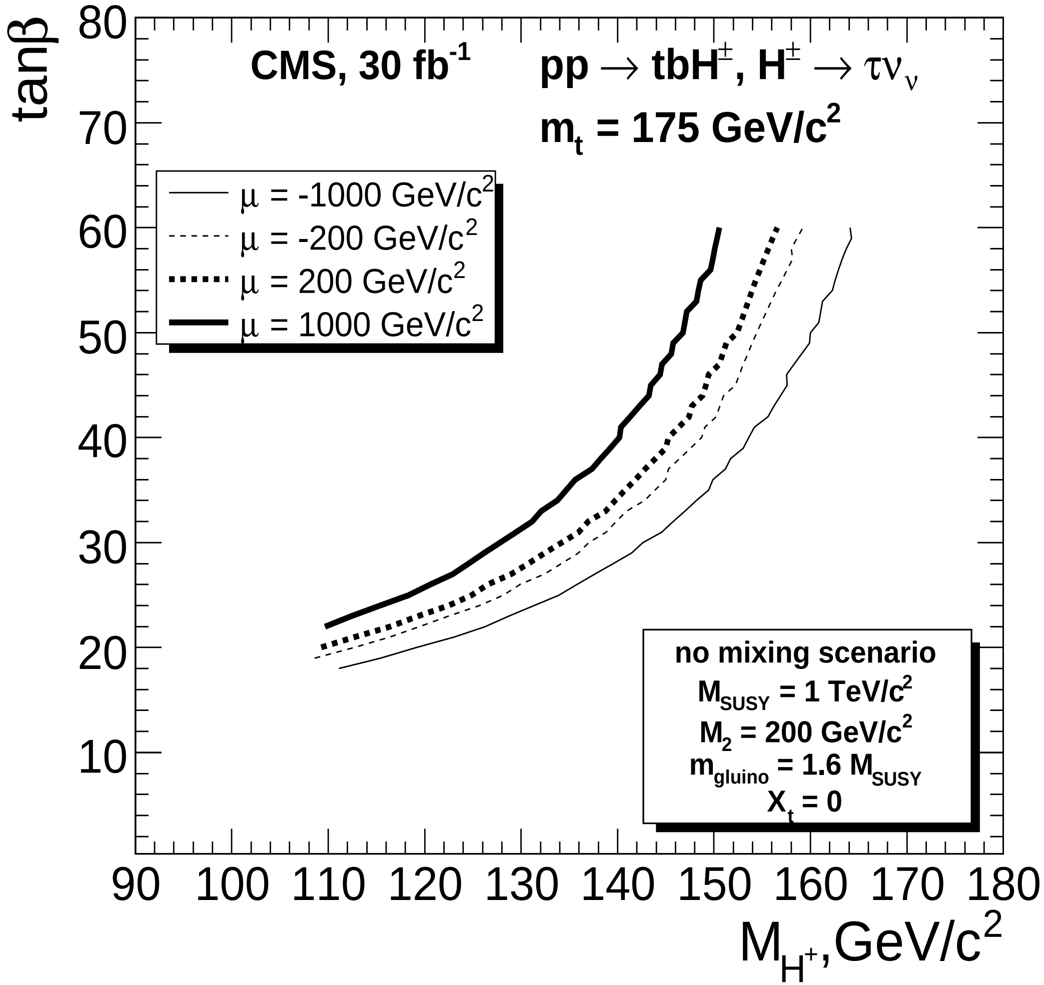
$\Delta \tan\beta \gtrsim 15$

best coverage for $\mu = -1000$ GeV

worst coverage for $+1000$ GeV

$\Rightarrow$ corresponds to XS evaluation

Results for the no-mixing scenario:



$\Rightarrow$ smaller variation with μ

$\Delta \tan\beta \gtrsim 5$

best coverage for $\mu = -1000$ GeV

worst coverage for $+1000$ GeV

$\Rightarrow$ corresponds to XS evaluation

smaller variation $\Leftrightarrow$ smaller Δ_b

3. LHC reach for the heavy charged Higgs boson

$$M_{H^\pm} > m_t$$

Main production channel:

$$gb \longrightarrow H^- t \quad \text{or} \quad g\bar{b} \longrightarrow H^+ \bar{t}$$

Close to threshold also contribution from:

$$pp \longrightarrow t\bar{t} \longrightarrow t\, H^- \bar{b} \quad \text{or} \quad H^+ b\, \bar{t}$$

Relevant decay channel:

$$H^\pm \longrightarrow \tau \nu_\tau$$

Experimental analysis for CMS PTDR:

full simulation, 30 fb^{-1}

[*R. Kinnunen, CMS Note 2006/100*]

$\rightarrow$ no details here

Number of signal events:

$$N_{\text{ev}} = \mathcal{L} \times \sigma(pp \rightarrow H^{\pm} + X) \times \text{BR}(H^{\pm} \rightarrow \tau\nu_{\tau}) \times \text{BR}(\tau \rightarrow \text{hadrons}) \times \text{exp. eff.}$$

Experimental efficiencies:

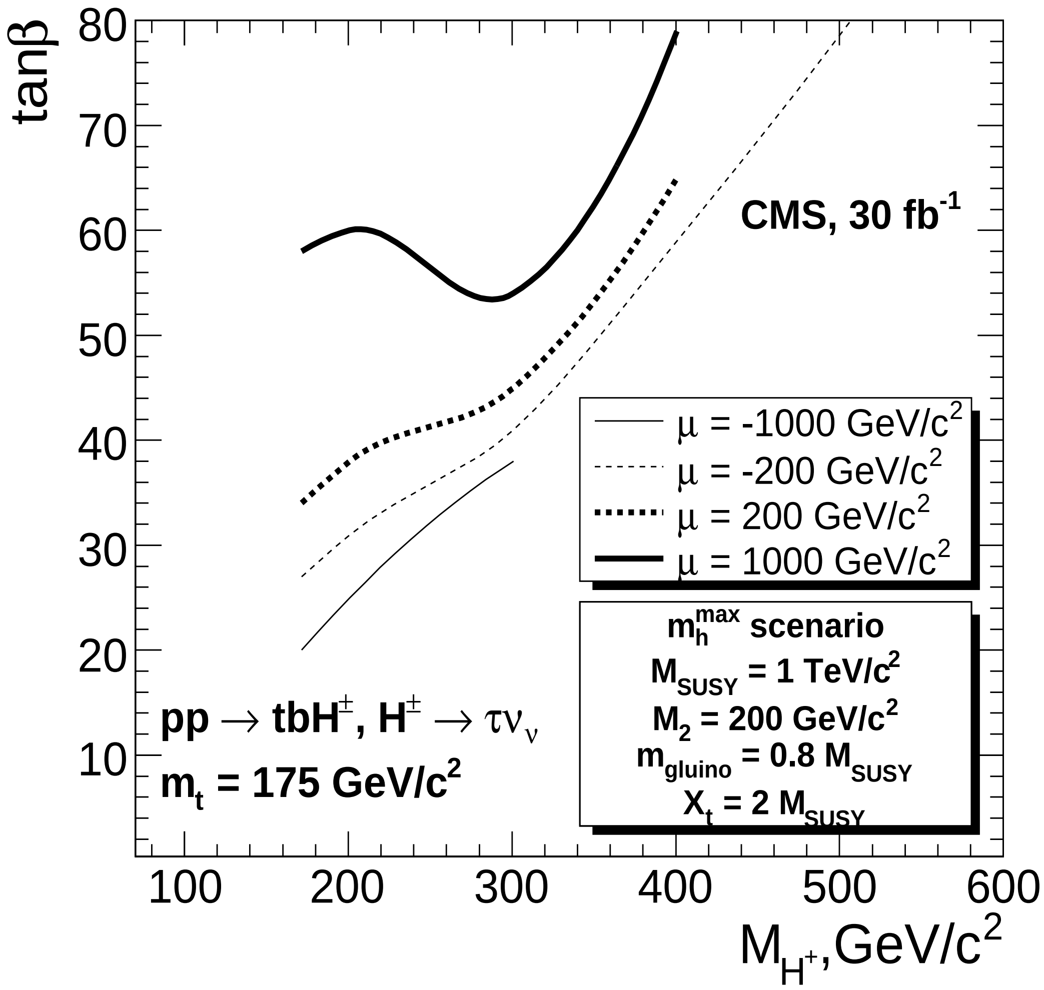
$M_{H^{\pm}}$ [GeV]	171.6	180.4	201.0	300.9	400.7	600.8
exp. eff. [10^{-4}]	3.5	4.0	5.0	23	32	42

$5\,\sigma$ discovery with 30 fb^{-1} $\Leftrightarrow$ $N_{\text{ev}} > 14.1$

Everything evaluated with

`FeynHiggs (www.feynhiggs.de)`

Results for the m_h^{max} scenario:



$\Rightarrow$ strong variation with μ

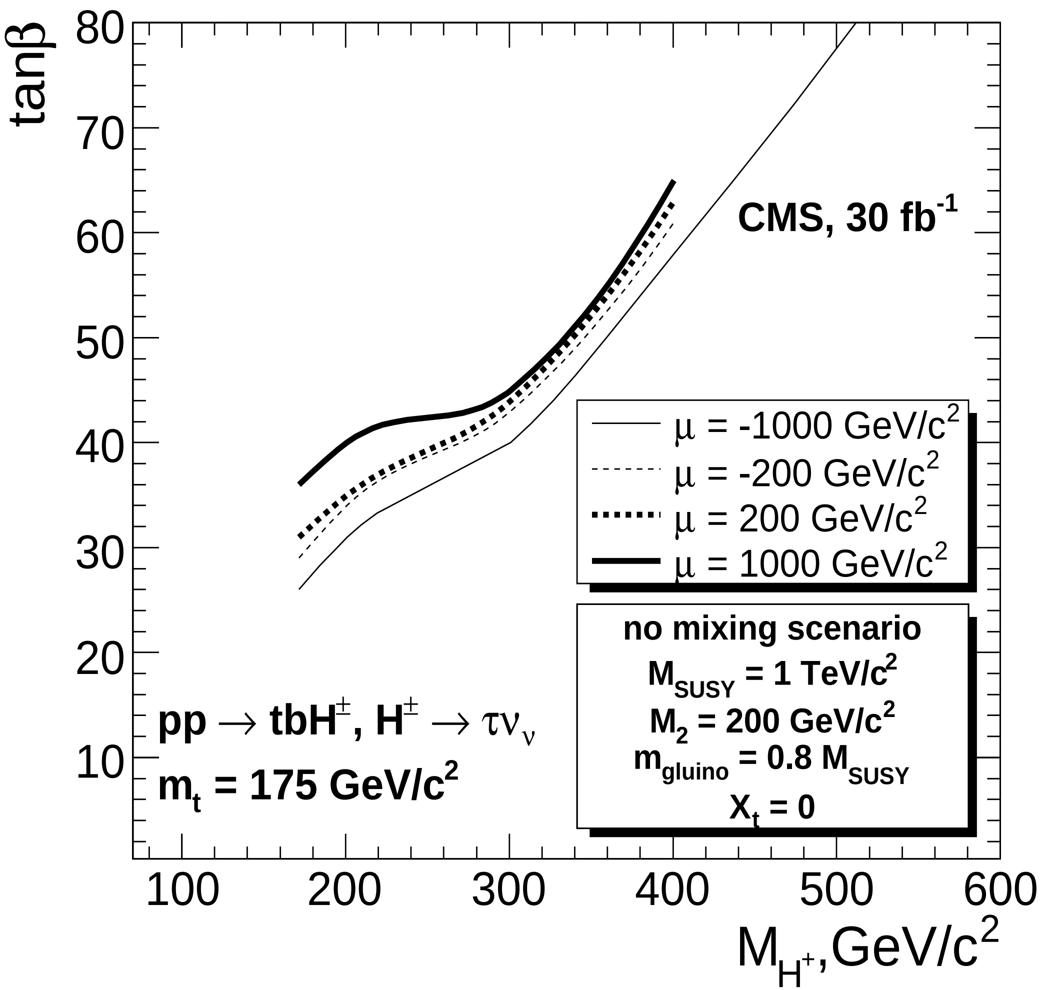
$\Delta \tan\beta$ up to ~ 40

best coverage for $\mu = -1000$ GeV

worst coverage for $+1000$ GeV

$\Rightarrow$ corresponds to XS evaluation

Results for the no-mixing scenario:



$\Rightarrow$ smaller variation with μ

$\Delta \tan\beta$ up to ~ 10

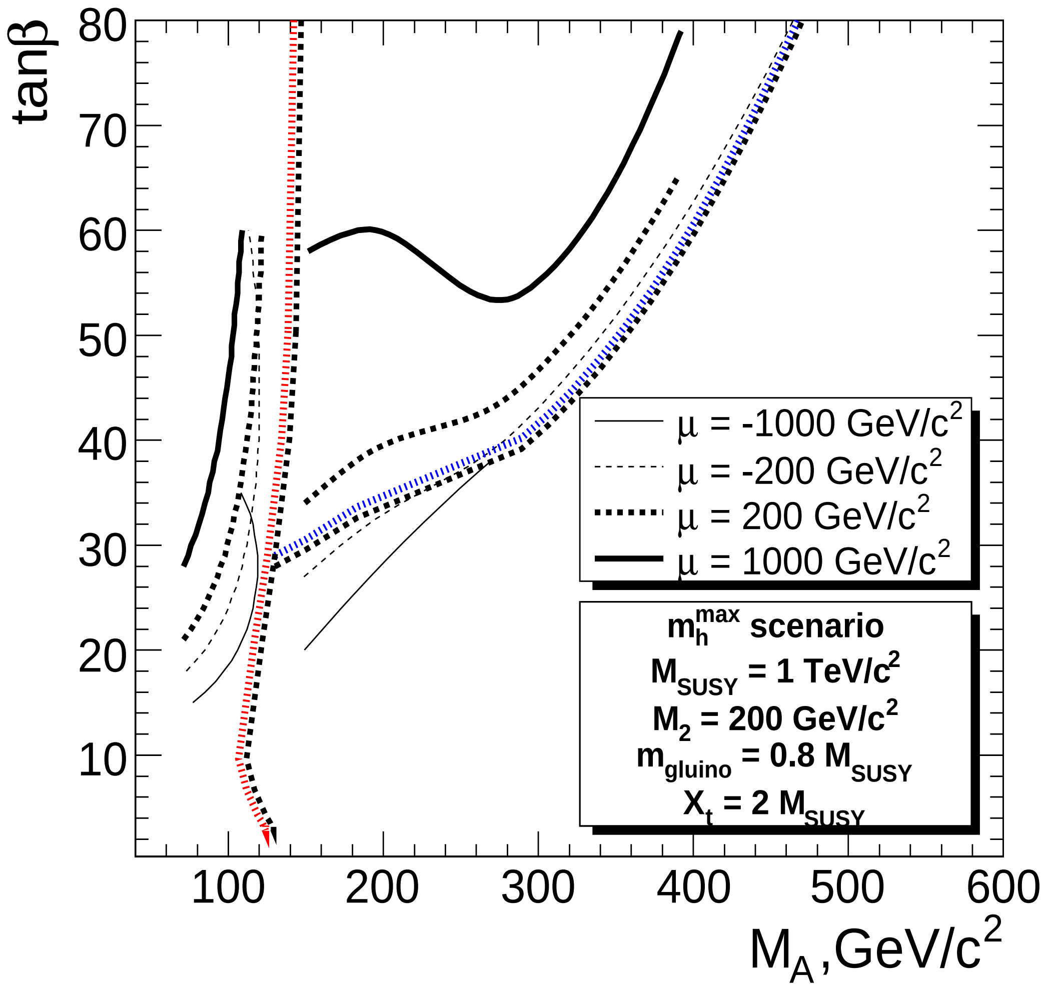
best coverage for $\mu = -1000$ GeV

worst coverage for $+1000$ GeV

$\Rightarrow$ corresponds to XS evaluation

smaller variation $\Leftrightarrow$ smaller Δ_b

Comparison with CMS PTDR ($m_h^{\rm max}$ scenario):



$\to$ note: M_A–$\tan\beta$ plane

light charged Higgs:

always worse than PTDR

better $M_{H^\pm}$ calculation!

inclusion of Δ_b effects

heavy charged Higgs:

PTDR in “the middle”

new results partially

substantially worse

4. Theory uncertainties

Sources of theory uncertainties:

1. Uncertainties on $\sigma(pp \to t\bar{t})$ (for $M_{H^\pm} < m_t$)

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

3. SM Uncertainties on $\sigma(pp \to H^\pm + X)$ (for $M_{H^\pm} > m_t$)

4. Uncertainties beyond Δ_b

– How large are the uncertainties?

– How large are the corresponding effects?

Size of theory uncertainties:

1. Uncertainties on $\sigma(pp \to t\bar{t})$ (for $M_{H^\pm} < m_t$)
   $\to \sim 5\%$ (now, or in the near future)

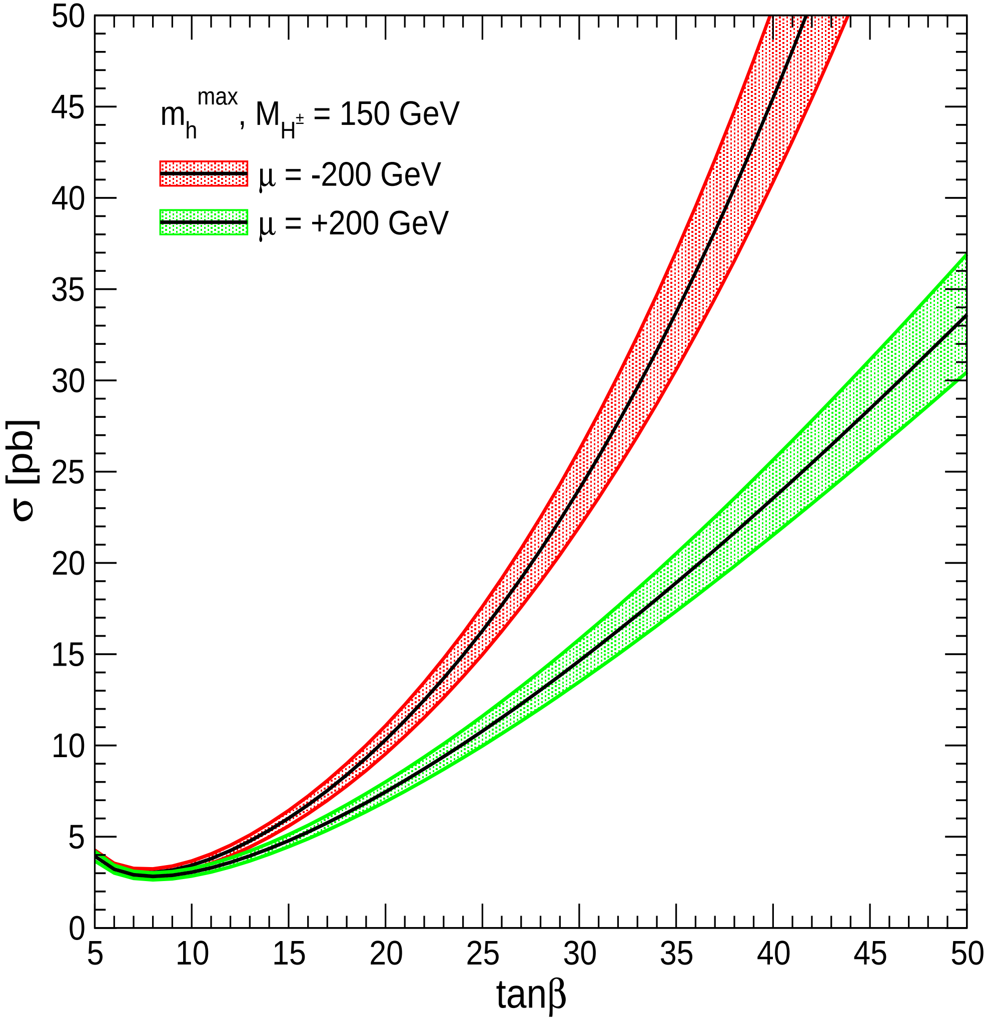
2. experimental uncertainties on m_t, affecting $\sigma(pp \to t\bar{t})$
   $\to \Delta\sigma/\sigma \approx 5\Delta m_t^{\text{exp}}/m_t$
   combined error on σ: $\sim 6.5\%$

3. SM Uncertainties on $\sigma(pp \to H^\pm + X)$ (for $M_{H^\pm} > m_t$)
   comparison of 4 and 5 flavor scheme: $\lesssim 20\%$

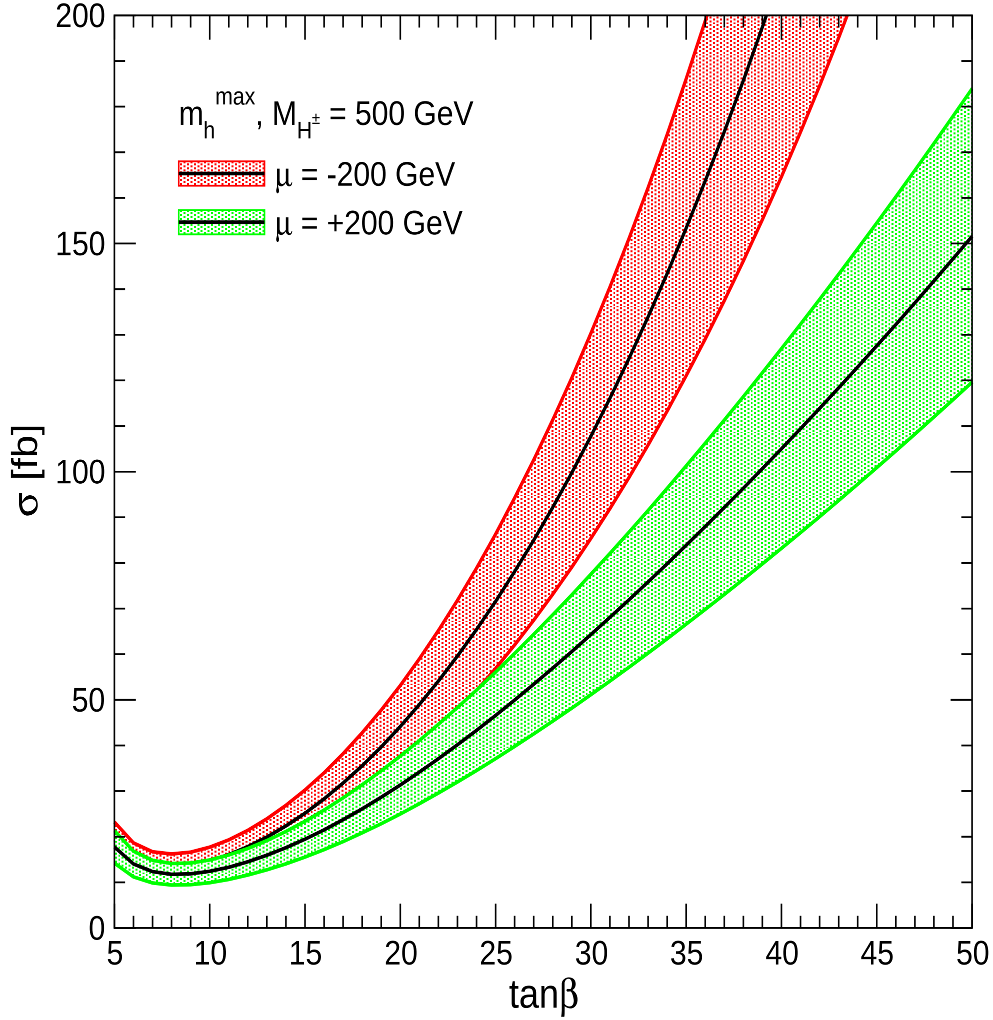
4. Uncertainties beyond $\Delta_b (\sim \alpha_s \ldots + \alpha_t \ldots)$
   $\Rightarrow$ scale variation of $\alpha_s(Q)$ $\Rightarrow$ effect on Δ_b $\lesssim 20\%$
   ($\Rightarrow$ smaller effects for $\mu \propto \Delta_b > 0$, larger effects for $\mu \propto \Delta_b < 0$)

Theory uncertainties on cross section evaluations:

light charged Higgs

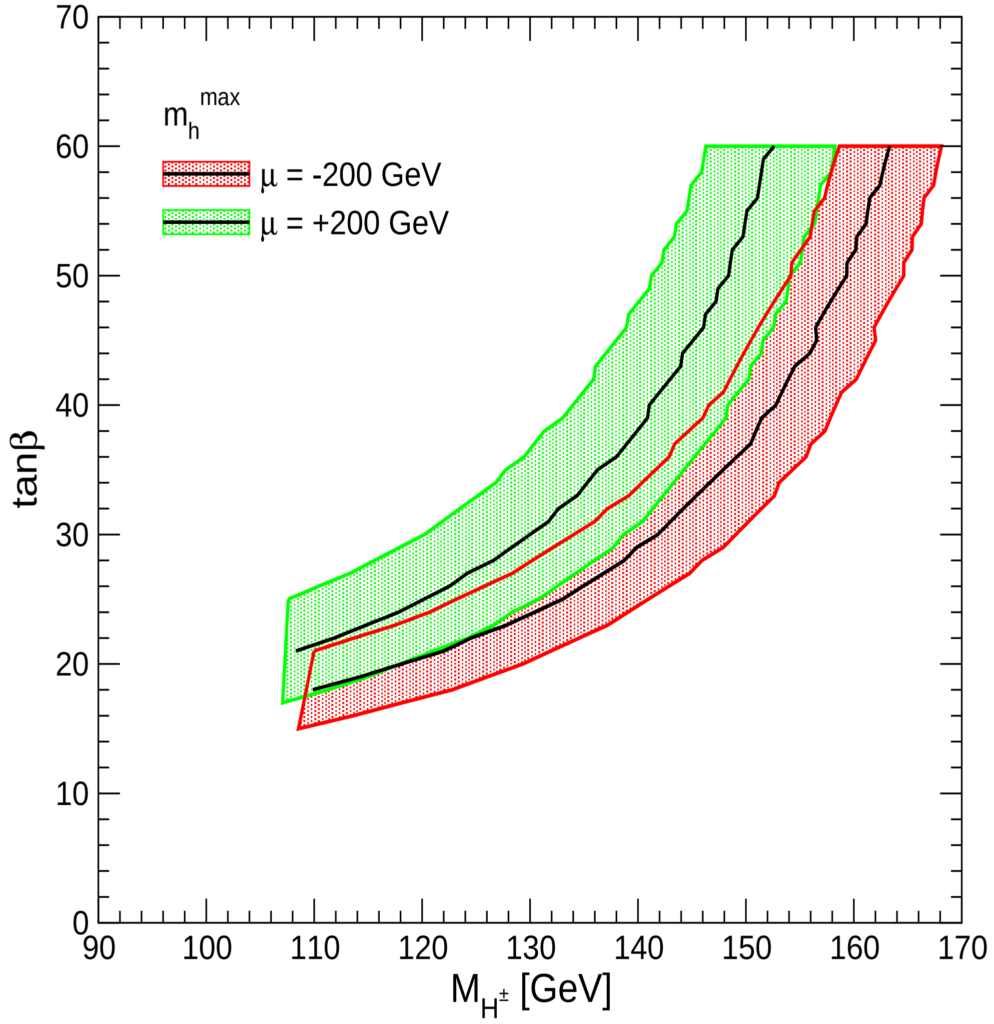


heavy charged Higgs

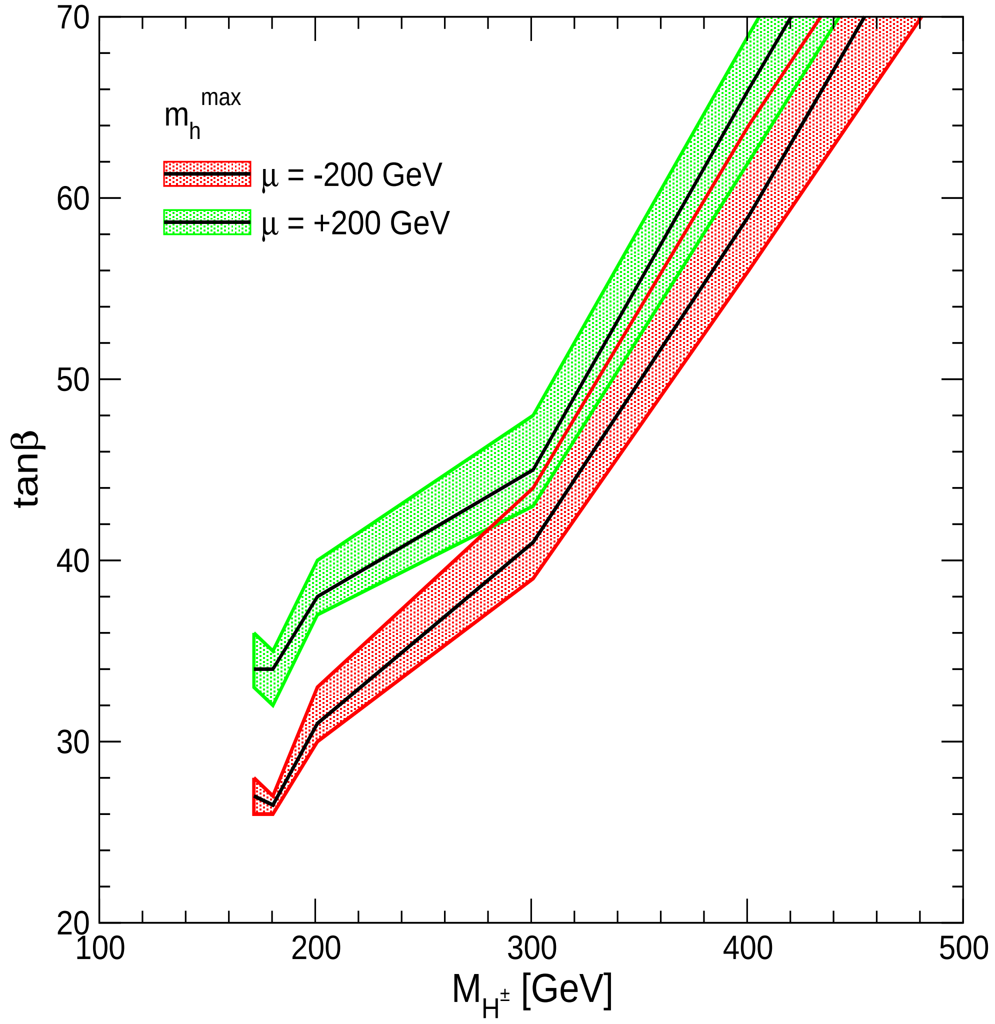


Theory uncertainties on 5 σ discovery contours:

light charged Higgs

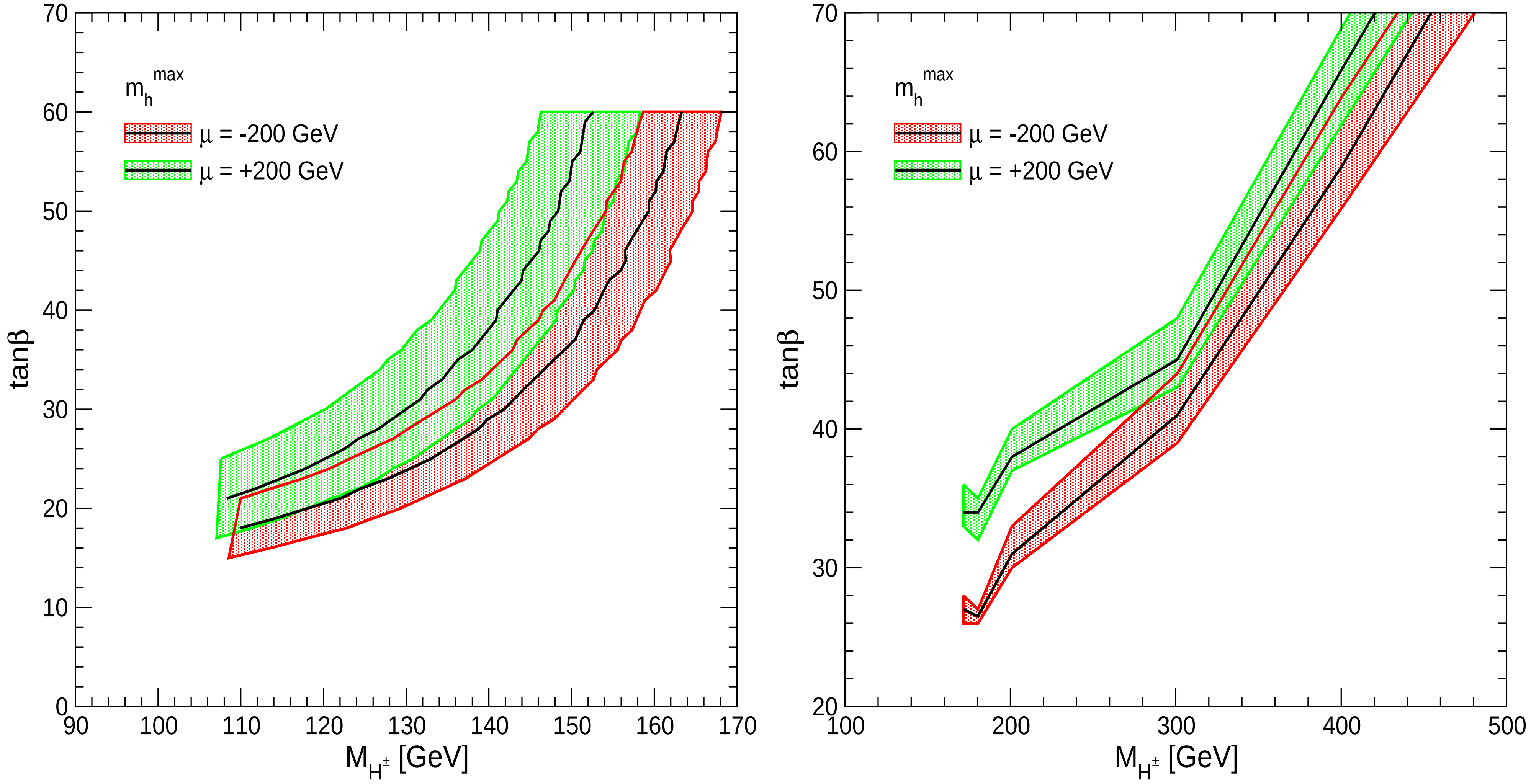


heavy charged Higgs



Theory uncertainties on $5\,\sigma$ discovery contours:

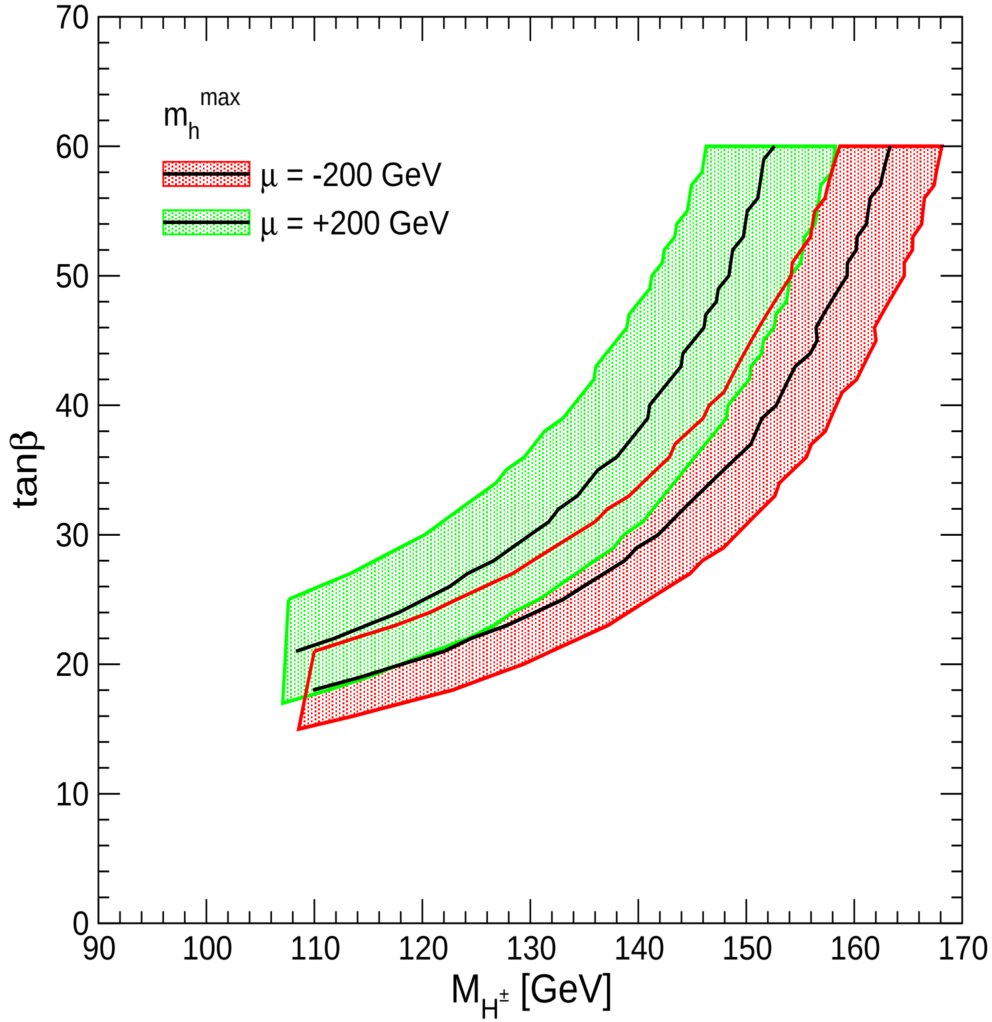
light charged Higgs | heavy charged Higgs

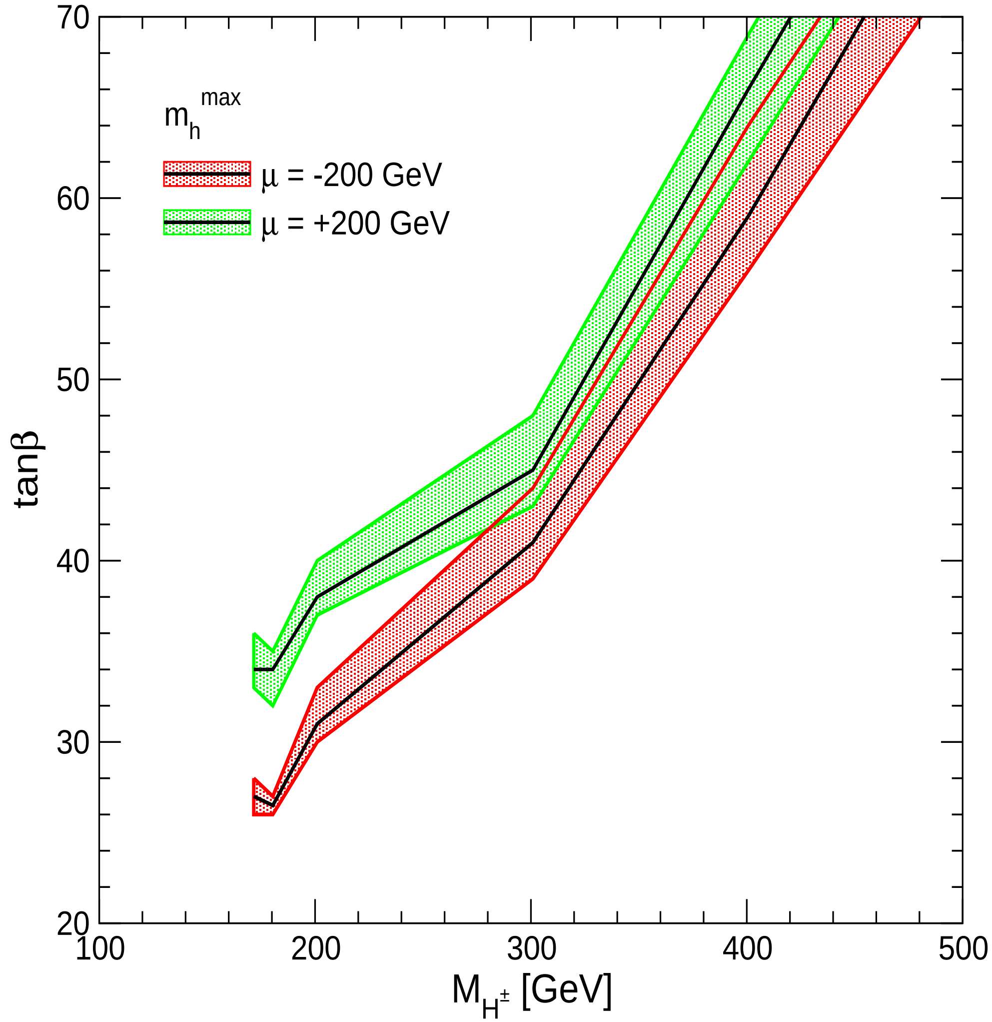


$\Rightarrow$ uncertainties have to be reduced to get reliable prediction

Theory uncertainties on 5 σ discovery contours:

light charged Higgs — heavy charged Higgs





$\Rightarrow$ uncertainties have to be reduced to extract parameters from $H^\pm$ meas.

5. Conclusinos

- MSSM: enlarged Higgs sector: large higher-order corrections
- Important for charged Higgs: Δ_b corrections
  $\Rightarrow$ impact on $\sigma(gb \to H^\pm t)$, BR$(t \to H^\pm b)$,
  BR$(H^\pm tb)$, BR$(H^\pm \tau\nu_\tau)$(indirectly)
- $\Rightarrow$ combination of full CMS simulations for 30 fb^{-1} and
  state-of-the-art theory evaluations
  $\to$ we are also interested in ATLAS results!
- light charged Higgs ($M_{H^\pm} < m_t$):
  strong variation with μ: $\Delta \tan\beta \sim 15$
- heavy charged Higgs ($M_{H^\pm} > m_t$):
  strong variation with μ: $\Delta \tan\beta \lesssim 40$
- Comparison with CMS PTDR:
  – light charged Higgs always worse (mostly due to $M_{H^\pm}$, Δ_b)
  – heavy charged Higgs: new results vary around PTDR (Δ_b)
- theory uncertainties:
  still large: 5–20% on σ, BRs, . . .
  $\Rightarrow$ have to be reduced to extract parameters from $H^\pm$ measurements