Distinguishing Higgs models at large $\tan\beta$

Siannah Peñaranda

IFIC - Instituto de Física Corpuscular, CSIC/UV, Valencia, Spain

From work in collaboration with:

H.E.Haber, M.J.Herrero, H.E.Logan, S.P., S.Rigolin, D.Temes, PRD63 (2001) 055004, hep-ph/0007006, hep-ph/0102169

J.Guasch, W.Hollik, S.P., PLB515 (2001) 367, hep-ph/0106027, hep-ph/0307012

M.J.Herrero, S.P., D.Temes, PRD64 (2001) 115003, hep-ph/0105097

K. Assamagan, J. Guasch, S. Moretti, S.P, CJP55 (2005), hep-ph/0402212 hep-ph/0409189

- Supersymmetry
- The Bottom quark mass
- 1-loop effective couplings
- Neutral Higgs boson decays: $H \longrightarrow b\bar{b}/H \longrightarrow \tau^+\tau^-$
- Charged Higgs boson decays: $H^+ \longrightarrow t\bar{b}/H^+ \longrightarrow \tau\nu$
  - Theoretical analysis
  - Experimental Simulation
- Conclusions

Supersymmetry

Supersymmetry $N = 1$ (SUSY) :

fermion	f	1/2	$\Leftrightarrow$	sfermion	$\tilde{f}$	0
gauge boson	G	1	$\Leftrightarrow$	gaugino	$\tilde{g}$	1/2
Higgs boson	H	0	$\Leftrightarrow$	higgsino	$\tilde{h}$	1/2

Minimal Supersymmetric Standard Model (MSSM)

<table>
<tr><td colspan="5">Standard Model (Enlarged Higgs sector)</td></tr>
<tr><td></td><td>$m_{A^0}, \tan\beta$</td><td colspan="3"></td></tr>
<tr><td>$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L, e_R^+ \cdots \begin{pmatrix}t\\ b\end{pmatrix}_L, t_R^c, b_R^c$</td><td>$\begin{pmatrix}H_1^+\\ H_1^0\end{pmatrix}, \begin{pmatrix}H_2^0\\ H_2^-\end{pmatrix}$</td><td>$B$</td><td>$W^\pm, W^3$</td><td>$g$</td></tr>
<tr><td>$\nu_e, e^-, \ldots, t, b$</td><td>$H^\pm, A^0, H^0, h^0$</td><td colspan="2">$\gamma, Z, W^\pm$</td><td>g</td></tr>
<tr><td colspan="5">SUSY particles</td></tr>
<tr><td>$\begin{pmatrix}\tilde{\nu}_e\\ \tilde{e}^-\end{pmatrix}_L, \tilde{e}_R^+ \cdots \begin{pmatrix}\tilde{t}\\ \tilde{b}\end{pmatrix}_L, \tilde{t}_R^*, \tilde{b}_R^*$</td><td>$\begin{pmatrix}\tilde{H}_1^+\\ \tilde{H}_1^0\end{pmatrix}, \begin{pmatrix}\tilde{H}_2^0\\ \tilde{H}_2^-\end{pmatrix}$</td><td>$\tilde{B}$</td><td>$\tilde{W}^\pm, \tilde{W}^3$</td><td>$\tilde{g}$</td></tr>
<tr><td>$\tilde{\nu}_e,$ $\tilde{t}_1, \tilde{t}_2,$
$\tilde{e}_1^-, \tilde{e}_2^-$ $\cdots$ $\tilde{b}_1, \tilde{b}_2$</td><td colspan="2">$\tilde{\chi}^-_{\{1,2\}}, \ \tilde{\chi}^o_{\{1,\ldots,4\}}$</td><td></td><td>$\tilde{g}$</td></tr>
<tr><td>$M_{\tilde{L}}^2, M_{\tilde{E}}^2, M_{\tilde{Q}}^2, M_{\tilde{U}}^2, M_{\tilde{D}}^2$
$A_e,\ A_b,\ A_t$</td><td></td><td>M_1</td><td>M_2</td><td>M_3</td></tr>
<tr><td colspan="4">$\mu, \tan\beta$</td><td></td></tr>
</table>

renormalizable quantum field theory, precision calculations possible (predictions $\longleftrightarrow$ experiments)

The bottom quark mass

Tree-level Potential:

$$V = \epsilon_{ij}\left[h_b\, H_1^i\, Q^j\, b_R + h_t\, H_2^j\, Q^i\, t_R\right] + h.c. \quad , \quad Q = \begin{pmatrix} t_L \\ b_L \end{pmatrix}.$$

The Higgs fields acquire vacuum expectation values:

$$< H_1 >= \begin{pmatrix} v_1 \\ 0 \end{pmatrix} \quad < H_2 >= \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

We identify the quark mass: $V_m = h_b\, v_1\, b_L\, b_R + h_t\, v_2\, t_L\, t_R + h.c.$

$$m_b = h_b\, v_1 \qquad m_t = h_t\, v_2$$

The radiative corrections generate new terms

Effective Lagrangian approach:

Carena *et al.* hep-ph/9402253; hep-ph/9808312; hep-ph/9907422 , Pierce *et al.* hep-ph/9606211

$$V^{1-loop} = V + \epsilon_{ij}\left[h_b\, \Delta_b\, H_2^j\, Q^i\, b_R + h_t\, \Delta_t\, H_1^i\, Q^j\, t_R\right] + h.c.$$

The bottom quark mass is: $m_b = h_b(v_1 + \Delta_b\, v_2) \equiv h_b\, v_1(1 + \Delta_b\, \tan\beta)$

Δ_b is a correction, but $\Delta_b\, \tan\beta$ can be large !!

Since the numerical value of m_b is fixed from experiment, a change in the effective Yukawa coupling is induced.

In particular, the Yukawa coupling of Higgs boson to bottom quark modifies as:

$$h_b = \frac{m_b}{v_1(1 + \Delta_b \tan\beta)}$$

The Yukawa coupling of the bottom quark is:

$$h_b = \frac{m_b}{v_1(1 + \Delta_b \tan\beta)} \simeq \frac{m_b}{v_1}\left[1 - \Delta_b \tan\beta + (\Delta_b \tan\beta)^2 + \cdots\right]$$

Corrections have been resummed to all orders of perturbation theory with the help of the effective lagrangian formalism.

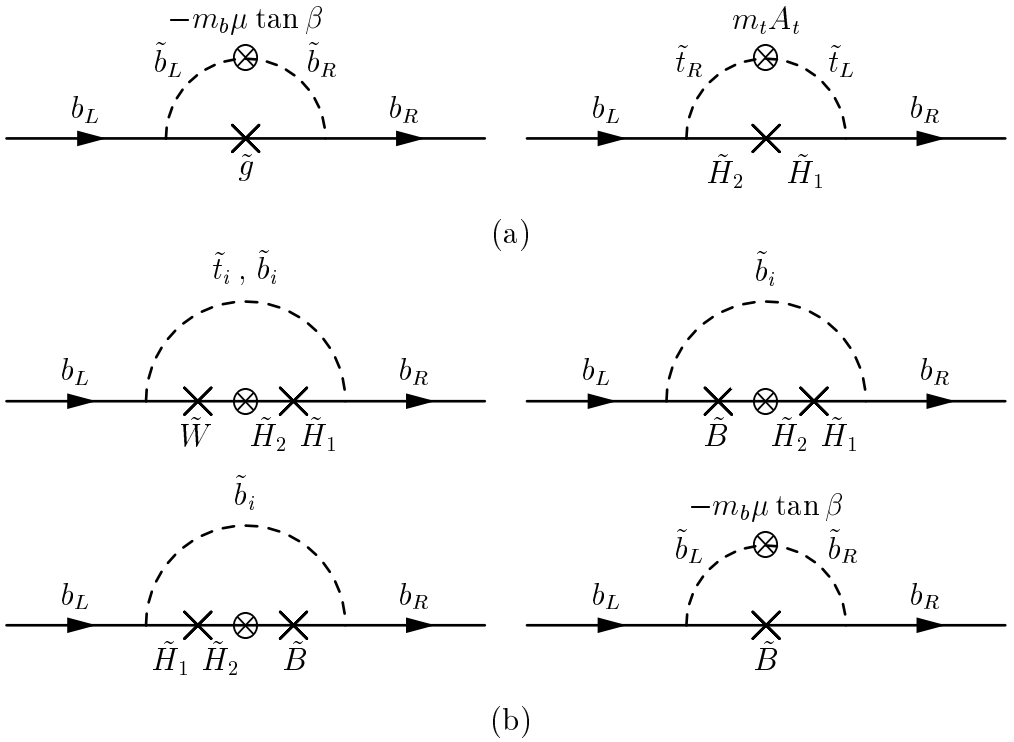
There are no other terms at n-loop order proportional to $(\tan\beta)^n$

Carena *et al.* NPB577 (2000) 88, hep-ph/9912516

$\Delta m_b = \Delta_b \tan\beta$: Finite threshold corrections to the bottom quark mass

Diagrams contributing to Δm_b

Leading $\tan\beta$ terms



The cross means a mass insertion, and the cross with a circle the coupling with H_2.

τ-leptons have similar corrections: Δm_τ

Diagrams contributing to Δm_τ are those equivalent to (b) with $b \to \tau$, $\tilde{b} \to \tilde{\tau}$, $\tilde{t} \to \tilde{\nu_\tau}$

Finite threshold corrections to the quark masses

- Special Limit: All SUSY masses are equal to M_{SUSY}:

$$\Delta m_b \simeq \text{sign}(\mu)\tan\beta\left\{\frac{\alpha_S}{3\pi}-\frac{\alpha}{16\pi s_W^2}\left(3+\frac{11}{9}\frac{s_W^2}{c_W^2}\right)+\frac{Y_t}{8\pi}\frac{A_t}{M_{SUSY}}\right\},$$

$$\Delta m_\tau \simeq -\,\text{sign}(\mu)\tan\beta\,\frac{\alpha}{16\pi s_W^2}\left(3-\frac{s_W^2}{c_W^2}\right).$$

- Δm_b and Δm_τ:
  - grow with $\tan\beta$
  - the corrections are independent of the SUSY scale
  - non-decoupling

    Large SUSY masses do not decouple from the Higgs sector !

1-loop Effective couplings

$$h^0 b\bar{b} : C_{hbb} = h_b \sin\alpha \left(1 - \frac{\Delta m_b}{\tan\beta \tan\alpha}\right)$$

$$H^0 b\bar{b} : C_{Hbb} = -h_b \cos\alpha \left(1 + \frac{\Delta m_b \tan\alpha}{\tan\beta}\right)$$

$$A^0 b\bar{b}/H^- t\bar{b} : C_{Abb/H^- tb} = -h_b \sin\beta \left(1 - \frac{\Delta m_b}{\tan\beta^2}\right)$$

- Large M_{A^0} limit: $M_{A^0} \gg M_Z \Rightarrow \alpha \to \beta - \pi/2\,,\, \tan\alpha \to -1/\tan\beta$

$$\Rightarrow C_{hbb} \to \frac{m_b}{v\cos\beta(1+\Delta m_b)} \cos\beta(1+\Delta m_b) = C_{hbb}^{SM}$$

$\Rightarrow$ The light Higgs behaves as SM!

Haber *et al.* PRD63 (2001) 055004, hep-ph/0007006 (one-loop analysis)

- BUT: The heavy Higgs retain the non-decoupling effect!

$$C_{heavy} \to \frac{m_b}{v(1+\Delta m_b)} \tan\beta(1 - \frac{\Delta m_b}{\tan\beta^2})$$

NEUTRAL HIGGS BOSONS DECAYS

$H \to b\bar{b} / H \to \tau^+\tau^-$ $\quad H \equiv h^0,\ H^0,\ A^0$

hep-ph/0106027, hep-ph/0307012

In the SM, after accounting for the leading QCD corrections:

$$R = \frac{BR(H \to b\bar{b})}{BR(H \to \tau^+\tau^-)} = \frac{3 m_b^2(M_H)}{m_\tau^2} \simeq 8.02 (M_{h^0} = 115\, GeV)$$

- Same leading expression in *any* Higgs model in which the Higgs sector follows the family structure of the SM

- Receives large SUSY corrections at large $\tan\beta$ due to Δm_b, Δm_τ
  - are non-decoupling ($M_{\rm SUSY}$)
  - CAN NOT be absorbed by a parameter redefinition
  - SUSY-like 2HDM CAN NOT give large corrections

- Systematics on Higgs production cancel in the ratio
  - NLO corrections, Luminosity, ...

- The only surviving systematic effect results from the efficiency of τ- and b-tagging

For the lightest CP-even Higgs boson, h^0:

$$\frac{R^{\rm MSSM}(h)}{R^{\rm SM}} = \frac{(1+\Delta m_\tau)^2\,(-\cot\alpha\Delta m_b+\tan\beta)^2}{(1+\Delta m_b)^2\,(-\cot\alpha\Delta m_\tau+\tan\beta)^2}\,.$$

We consider: - $M_{\tilde g} = M_{\tilde b_1} = M_{\tilde t_1} = m_{\tilde\tau} = M_2 = |\mu| = A_b = A_\tau = A_t = 1.5\,TeV$,

- GUT relation $M_1 = 5/3 M_2 s_W^2/c_W^2$,
- maximal mixing in the $\tilde b$ and $\tilde\tau$ sector: $\theta = \pm\pi/4$.

LHC: BR$(H\to b\bar b)$/BR $(H\to\tau^+\tau^-)$: $\pm 21\%$

- $BR(H\to\tau^+\tau^-)/BR(H\to\gamma\gamma)$ and $BR(H\to b\bar b)/BR(H\to\gamma\gamma)$ are measurable with an accuracy of 15%

D. Zeppenfeld, et al. Phys. Rev. **D62** (2000) 013009, hep-ph/0002036

F. Gianotti, et al. Nucl. Phys. Proc. Suppl. **89** (2000) 177, hep-ex/0006016

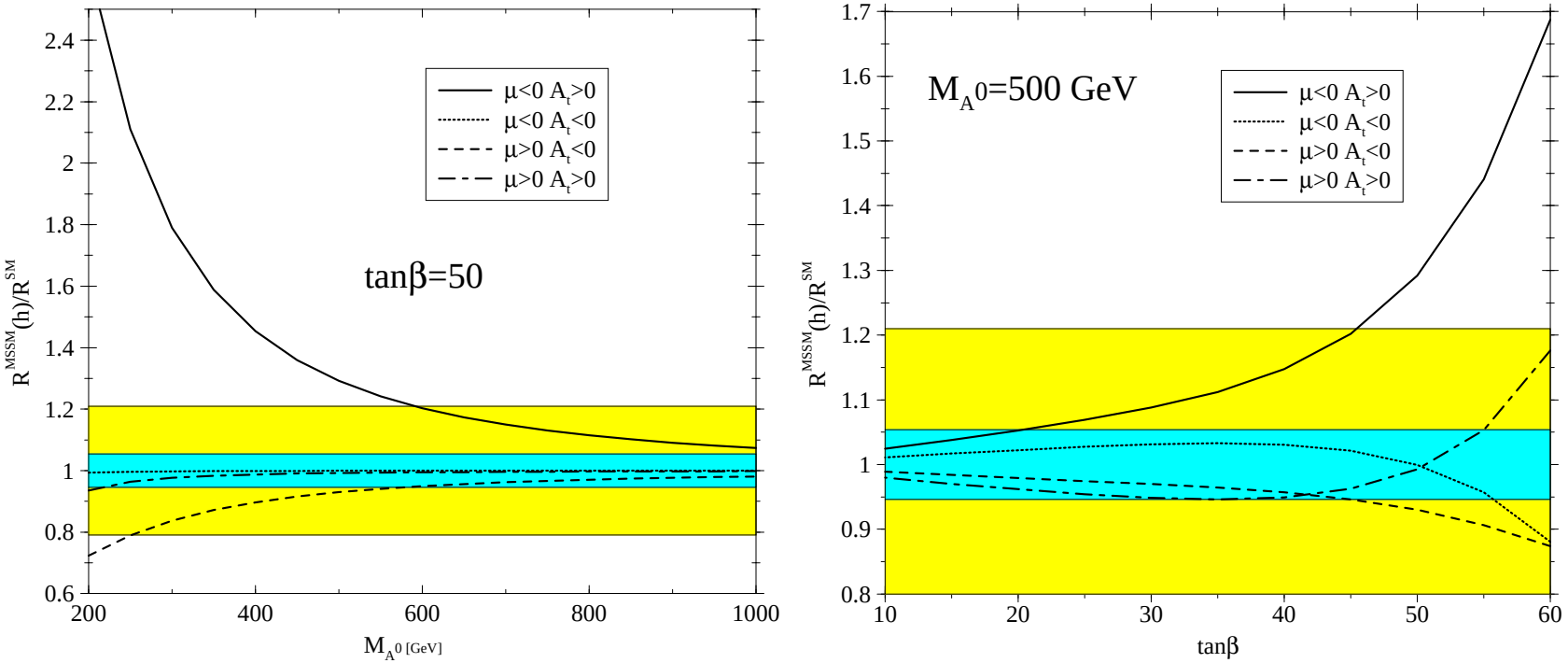
TESLA: (h_b/h_τ): $\pm 5.4\%$

- $h_b/h_\tau(\equiv\sqrt{R})$ can be measured with an accuracy of 2.7% at $500\,GeV$

TESLA Technical Design Report DESY 2001-011, Part III,

R. Heuer, D. Miller, F. Richard, P. Zerwas Editors http://tesla.desy.de/

Deviation of $R^{\mathrm{MSSM}}(h)$ with respect to the SM value

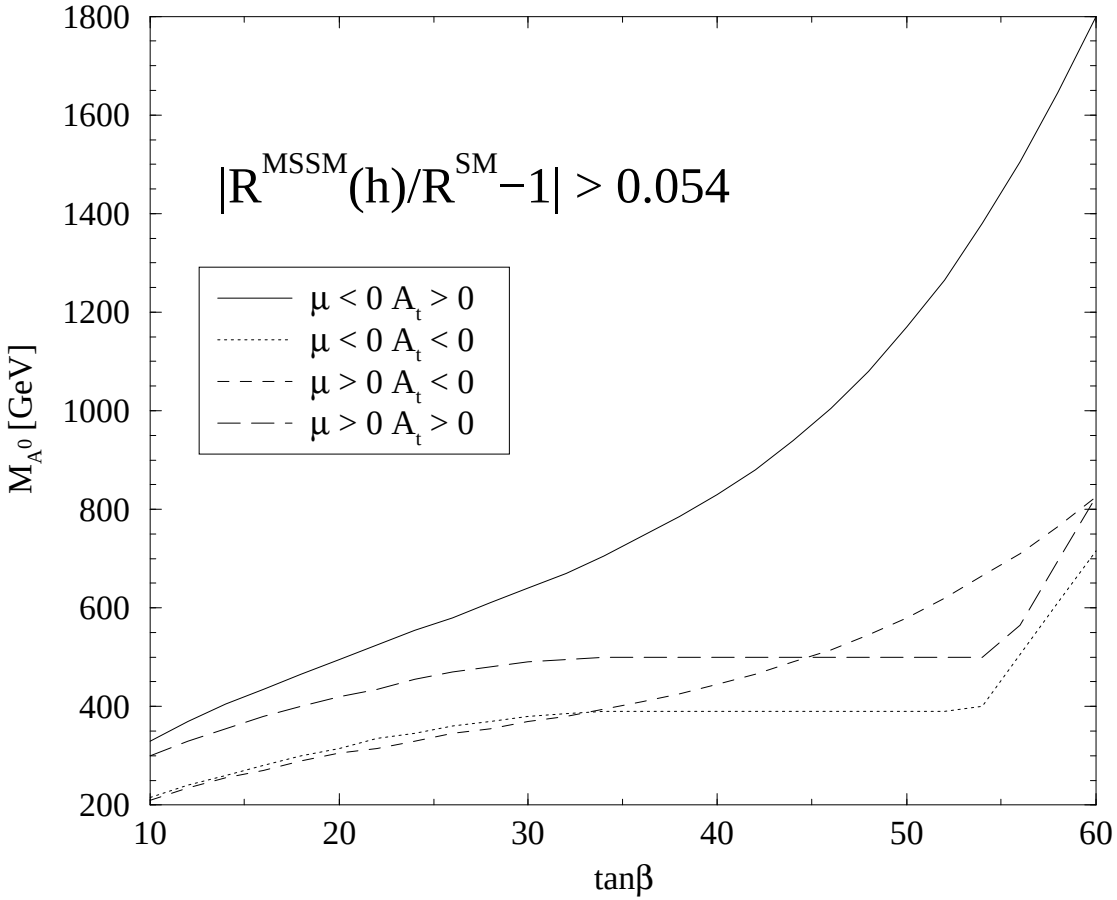


LHC: $\pm 21\%$ TESLA: $\pm 5.4\%$

- The decoupling behaviour with M_{A^0} becomes apparent.
- $R^{\mathrm{MSSM}}(h)$ deviates significantly from the reference value R^{SM}:
  i.e. small M_{A^0}, large $\tan\beta$, $\mu < 0$ and $A_t > 0$, the ratio can be as large as two.

Sensitivity regions on $R^{\mathrm{MSSM}}/R^{\mathrm{SM}}$

TESLA: (h_b/h_τ): $\pm 5.4\%$

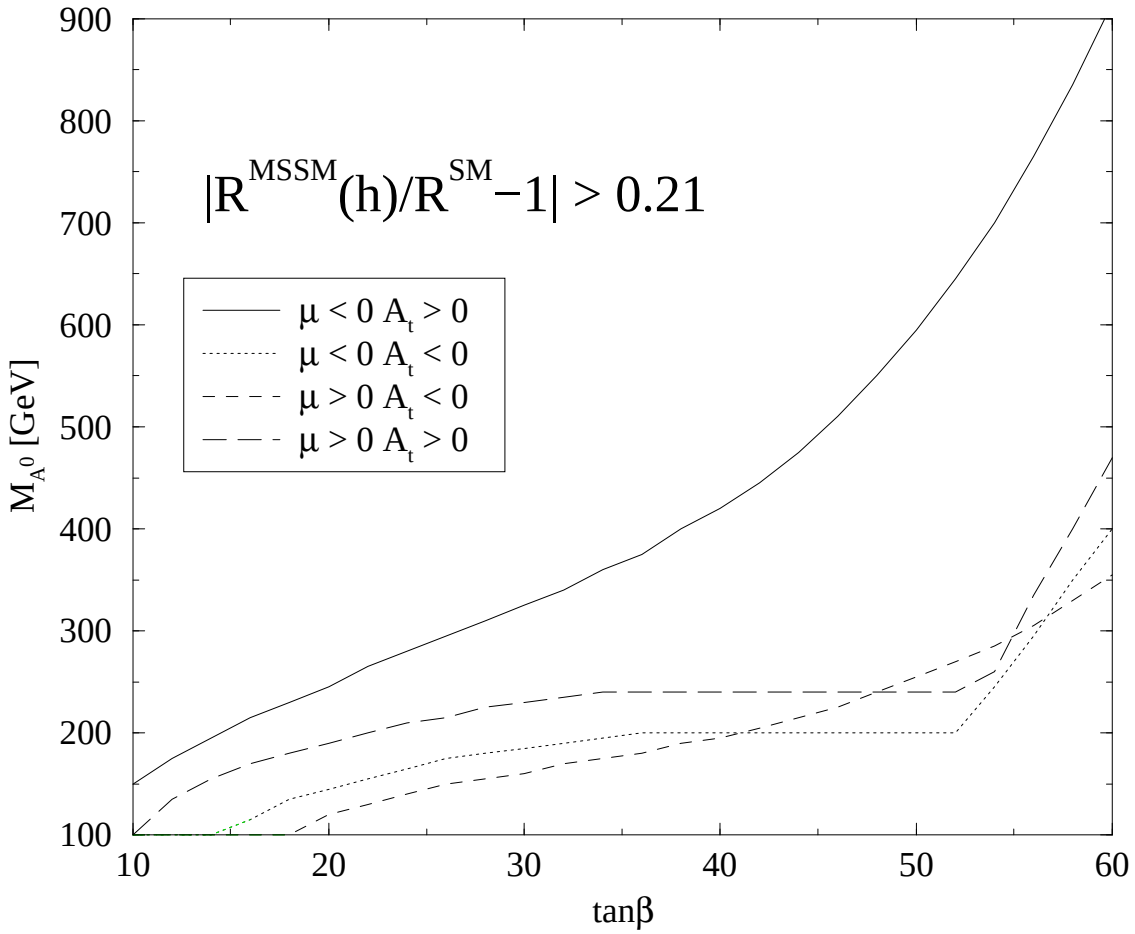


- One can have sensitivity to SUSY for M_{A^0} up to $\sim 1.8\,TeV$ in the most favorable scenario
- but there exists also regions where one is sensitive to SUSY only up to $M_{A^0} \sim 800\,GeV$ or $M_{A^0} \sim 500\,GeV$

However, all these masses are well above the threshold production of the heavy Higgs particles for a $500\,GeV$ LC.

Sensitivity regions on $R^{\mathrm{MSSM}}/R^{\mathrm{SM}}$

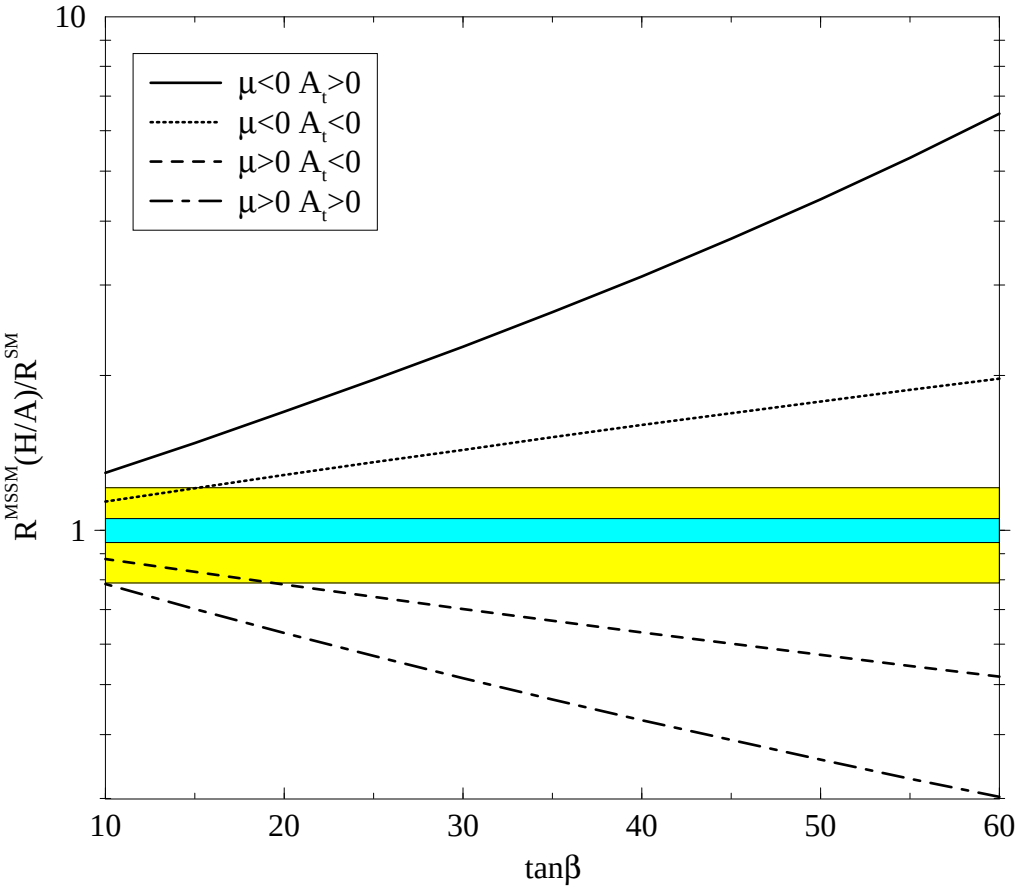
LHC: $BR(H \to b\bar{b})/BR(H \to \tau^+\tau^-)$: $\pm 21\%$



- One can probe the SUSY nature of the Higgs boson only if A^0 is lighter that $\sim 900\,GeV$.

For H^0 and A^0:

Deviation of $R^{\mathrm{MSSM}}(H)$ with respect to the SM value



LHC: $\pm 21\%$ TESLA: $\pm 5.4\%$

- A deviation of 21% with respect to the SM value is guaranteed for any scenario with $\tan\beta > 20$

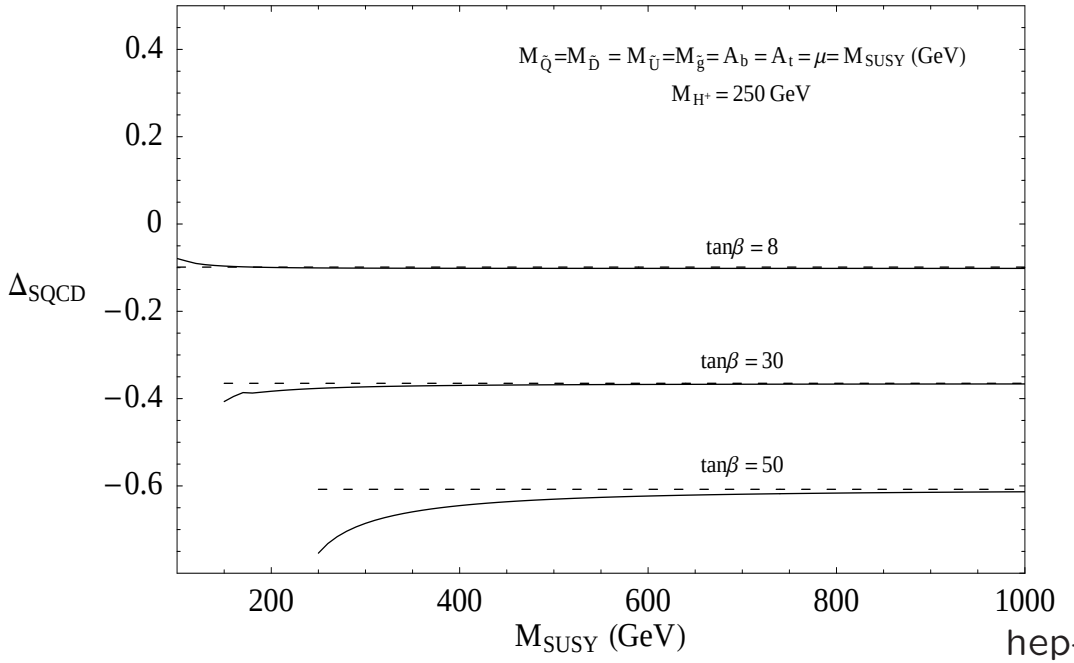
$\Rightarrow$ The SUSY nature of the Higgs sector can be determined with a moderate-precision measurement.

CHARGED HIGGS BOSON DECAYS

Charged Higgs boson decays : $H^+ \to t\bar{b}$

- (Non) Decoupling behaviour of the SUSY-QCD corrections:

Take just one scale M_S : $M_S = M_{\tilde{Q}} = M_{\tilde{U}} = M_{\tilde{D}} = M_{\tilde{g}} = A_b = A_t = \mu$



hep-ph/0105097

- Non Decoupling with M_S
- The correction can be quite large for large $\tan\beta$ even for quite heavy SUSY particles:
  For $M_{SUSY} = 1$ TeV and $\tan\beta = 30$ $\Rightarrow$ $\Delta_{SQCD} \simeq -35\%$
- 2HDM has no SUSY-QCD contributions to $H^+ \to t\bar{b}$ $\Rightarrow$ one could use these corrections in order to distinguish between MSSM and 2HDM

$H^+ \to \tau^+\nu / H^+ \to t\bar{b}$

hep-ph/0402212, hep-ph/0409189

- The discovery of a charged Higgs boson will be a clear evidence of physics Beyond the SM
- The ratio receives large SUSY corrections at large $\tan\beta$ due to Δm_b and Δm_τ
- The associated production of H^+ with a top ($pp \to H^+\bar{t} + X$) is relevant at large $\tan\beta$
- While the SUSY radiative effects might be difficult to discern in the production cross-sections themselves, they will appear neatly in the relation

$$R \equiv \frac{\sigma(pp \to H^+\bar{t} + X \to \tau^+\nu t + X)}{\sigma(pp \to H^+\bar{t} + X \to t\bar{b}t + X)}$$

- Sources of uncertainty from the production process (parton luminosity, unknown QCD corrections) cancel in the ratio

$$R = \frac{BR(H^+ \to \tau^+\nu)}{BR(H^+ \to t\bar{b})} = \frac{\Gamma(H^+ \to \tau^+\nu)}{\Gamma(H^+ \to t\bar{b})}$$

Experimental analysis

- Simulation for measurements of this ratio through the analysis of the H^+ production process using the two-body production cross–section subprocess (ATLAS)

  K. A. Assamagan et al, EPJDirect **C4** (2002) 9, hep-ph/0203121.

$$g\bar{b} \to H^+\bar{t}\ ; \qquad \begin{array}{l} H^+ \to t\bar{b} \\ H^+ \to \tau\nu \end{array}$$

  - We let the t–quark decay through the standard $t \to W^+b$

- We use
  - Pythia $\equiv$ for the signal and most of the background process

  Cross checked with Pythia of calculations of $\sigma(g\bar{b} \to H^+\bar{t})$ by T. Plehn, hep-ph/0206121, 0304034.
  - Tauola $\equiv$ for the τ–lepton decays
  - TopRex $\equiv$ for some background process with a custom interface to Pythia
  - ATLFAST $\equiv$ for the detector simulation
  - Hdecay $\equiv$ for the branching ratio of Higgs boson decays

$H^+ \to \tau\nu$

Experimental signature of the production channels under investigation is:

$$pp(g\bar{b}) \to H^+\bar{t} \to (\tau^+\nu)\bar{t} \to \tau^+\nu\,(jj\bar{b})$$

- Signal: $g\bar{b} \to H^+\bar{t}$
  - $H^+ \to \tau\nu$ and t decaying hadronically ($t \to jjb$)
  - Trigger: We search for 1 hadronic τ jet ($p_T^\tau > 30\,GeV$), 1 b-tagged jet ($p_T^b > 30\,GeV$), ≥ 2 light jets ($p_T^j > 30\,GeV$).
- Background: QCD backgrounds are considered
  - t–pair production with the $W^\pm$ decaying into $\tau\nu$: $gg \to t\bar{t}, \bar{t} \to jj\bar{b}, t \to Wb, W \to \tau\nu$
  - $W^\pm - t$ associated production: $g\bar{b} \to W\bar{t}, t \to jjb, W \to \tau\nu$
- We found that the efficiences of cuts is $\sim 1\%$ for the signal but $\sim 10^{-6}$ for backgrounds
  $\Rightarrow$ After cuts the number of signals events is much larger than backgrounds
- Signal are large enough to consider $H^+ \to \tau\nu$ as a "Golden channel" for the H^+ discovery at large $\tan\beta$

★ After the analysis it turns out that despite the small branching ratio $BR(H^+ \to \tau^+\nu)$, the τ-lepton provides an efficient trigger to observe this channel.

$H^+ \to t\bar{b}$

Experimental signature of the production channels under investigation is:

$$pp(g\bar{b}) \to H^+\bar{t} \to (t\bar{b})\bar{t} \to (jj[l\nu]b)\,\bar{b}\,(l\nu[jj]\bar{b})$$

- Signal: $g\bar{b} \to H^+\bar{t}$
  - $H^+ \to t\bar{b}$ and t decaying hadronically ($t \to jjb$) and leptonically ($t \to l\nu b$) to provide the trigger ($l = e\,,\,\mu$)
  - Trigger: 1 isolated lepton ($p_T^e > 20\,GeV$, $p_T^\mu > 8\,GeV$) , 3 b-tagged jets ($p_T^b > 30\,GeV$) , $\geq$ 2 light jets ($p_T^j > 30\,GeV$) .

- Background: Large QCD backgrounds at hadron colliders that come from $t\bar{t}q$ production with $t\bar{t} \to Wb\,Wb \to l\nu b\,jjb$
  Combinatorial and Large irreducible $t\bar{t}$ background

- Assume H^+ is discovered in $H^+ \to \tau\nu$
  We use the $m_{H^\pm}$ constraint to improve the reconstruction in $H^+ \to t\bar{b}$

- The $m_{H^\pm}$ constraint reshapes the backgrounds and in doing so the signal significance is not improved.

- Even with $m_{H^\pm}$ constraint, difficult to observe H^+ in this channel above $\sim 400\,GeV$

Knowledge of background shape and rate necessary !!!

The ratio $H^+ \to \tau\nu / H^+ \to t\bar{b}$

- Uncertainties in cross sections and luminosity cancel
- Uncertainties in the branching ratios: 5%
- $H^+ \to tb$ background uncertainty: 5% (Assuming background subtraction method)
- Scale uncertainties on jet and lepton energies: 1% and 0.1%

Experimental determination of the ratio for $300\,\text{fb}^{-1}$ and $\tan\beta = 50$.

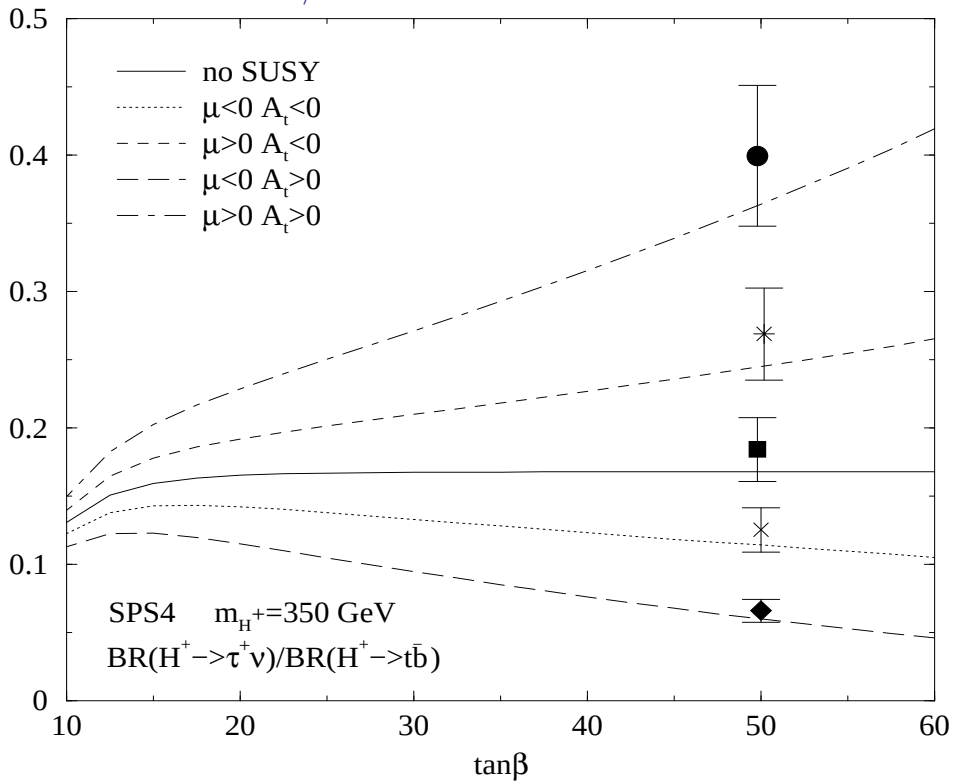
	$m_{H^\pm} = 350$	$m_{H^\pm} = 500$
Signals after cuts $\tau\nu/tb$	174 / 2100 = 0.08	96 / 784 = 0.12
Signals (corrected) $\tau\nu/tb$	0.18	0.16
Systematics unc.	$\sim 9\%$	$\sim 9\%$
Total unc.	12%	14%

Uncertainty in the ratio are dominated by knowledge of the background shape and rate under $H^+ \to tb$.

The simulation (ATLAS) shows that the ratio can be measured with an accuracy of a $\sim 12 - 14\%$ for $\tan\beta = 50$, $m_{H^\pm} = 350 - 500\,GeV$ at an integrated luminosity of $300\,\text{fb}^{-1}$.

$$R = BR(H^+ \to \tau^+\nu)/BR(H^+ \to t\bar{b})$$

MSUGRA scenario with $m_0 = 400GeV$, $m_{1/2} = 300GeV$ choosing different scenarios for the sign of μ, A_t



- R only depends on $m_{H^\pm}$ through kinematical factors: it is weak for $m_{H^\pm} \gtrsim 300GeV$.
- Experimental determination carried out and repeated for each SUSY setup.

- Radiative SUSY effects are visible at the LHC at a large significance.
- $\mu < 0$ scenarios can easily be discriminated
  $\mu > 0$ will be more difficult to establish

  $\Rightarrow$ It also provides a measurement of the sign of μ parameter

Impact of the SUSY radiative corrections

1. By changing the value of the Yukawa coupling they change the value of the observable $R = BR(H^+ \to \tau^+\nu)/BR(H^+ \to t\bar{b})$.
2. SUSY corrections can change the value of production cross-section $\sigma(pp \to H^+\bar{t} + X)$
   A. Belyaev et. al, hep-ph/0210253, 0203031, 0105053 ...

Corrected Production Rates:

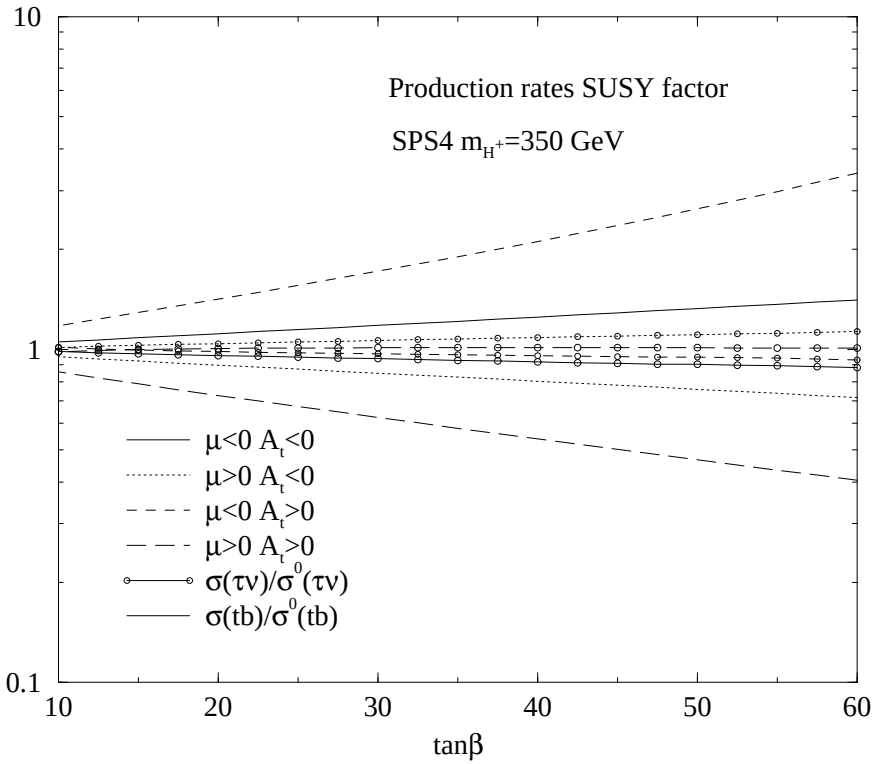
$$\sigma^{\rm corr}(g\bar{b} \to H^+\bar{t} \to t\bar{b}\bar{t}) = \sigma^{\rm corr}(g\bar{b} \to H^+\bar{t}) \times BR^{\rm corr}(H^+ \to t\bar{b}) \simeq \frac{\sigma^0(g\bar{b} \to H^+\bar{t})}{(1+\Delta m_b)^2} \ ,$$

$$\sigma^{\rm corr}(g\bar{b} \to H^+\bar{t} \to \tau^+\nu\bar{t}) = \sigma^{\rm corr}(g\bar{b} \to H^+\bar{t}) \times \frac{\Gamma(H^+ \to \tau^+\nu)}{\Gamma^{\rm corr}(H^+ \to t\bar{b})}$$

$$\simeq \frac{\sigma^0(g\bar{b} \to H^+\bar{t})}{(1+\Delta m_b)^2} \times \frac{\Gamma(H^+ \to \tau^+\nu)}{\Gamma^0(H^+ \to t\bar{b}) \times \frac{1}{(1+\Delta m_b)^2}} \ .$$

- Hadronic $t\bar{b}$ production channel receives large radiative corrections
- Production rate in the τ-channel is fairly independent of the SUSY radiative corrections . Therefore, tree-level analysis can (to a very good approximation) be kept.

Production rates enhancement/suppression factors for the τ and the tb channels



- τ-channel : fairly independent of the SUSY radiative corrections.
- Hadronic $t\bar{b}$ production channel : receives large radiative corrections that can be either positive (enhancing the signal, and therefore the significance), or negative (reducing it).

  $\longrightarrow$ Production rate can be enhanced by a factor larger than 3 in certain scenarios, which would enhance significantly the signal, and overcome the low signal/background ratio in this channel.

CONCLUSIONS I

- Higgs particles in SUSY theories
  - Large radiative corrections in the fermion couplings
  - Must be taken into account in phenomenological analyses
- $R = BR(H \to b\bar{b})/BR(H \to \tau^+\tau^-)$

  One could distinguish between MSSM and SM (2HDM):

  – LHC: At $\pm 21\%$ accuracy, is sensitive to the SUSY nature of h^0 if

  * Best case: $M_{A^0} \lesssim 900\, GeV \quad (\mu < 0\,,\, A_t > 0)$
  * Normal conditions: $M_{A^0} \lesssim 400\, GeV \quad (\mu > 0\,,\, A_t < 0)$

  – TESLA: A $\pm 5.4\%$ measurement, to be made at 500 GeV,

  * Best case: $M_{A^0} \lesssim 1.8\, TeV$
  * Normal conditions: $M_{A^0} \lesssim 500\, GeV$

  For A^0 and H^0 a deviation of 21% with respect to the SM value is guaranteed for any scenario with $\tan\beta > 20$.
- Moderate accuracy is sufficient
- Even if SUSY is discovered, this is a high precision test of the Model

CONCLUSIONS II

$$R = BR(H^+ \to \tau^+ \nu^-)/BR(H^+ \to t\bar{b})$$

- Theoretically *clean* observable.

  Affected by MSSM quantum contributions that do not decouple even in the heavy SUSY mass limit.

- SUSY corrections of the b and τ Yukawa couplings can be determined from this ratio.

- The determination of the sign of μ can be made with a $\sim 14\%$ measurement of this ratio for $\tan\beta > 30$.

- Simulation for measurement of this ratio have been done (ATLAS): A $\sim 12 - 14\%$ measurement can be achieved for $\tan\beta = 50$, $m_{H^\pm} = 300 - 500\, GeV$ at an integrated luminosity of $300\,\text{fb}^{-1}$

- We have quantitatively shown that an LHC measurement of R can give clear evidence for, or against, the SUSY nature of charged Higgs bosons

Slides as "SUPPORT"

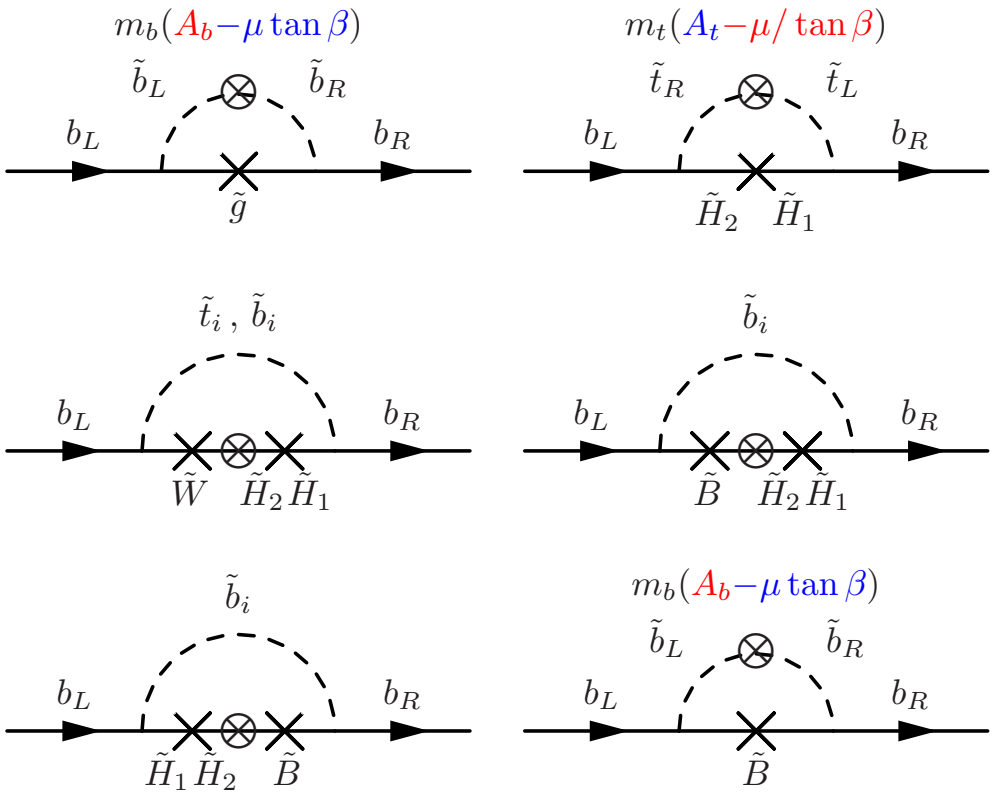
- Δm_b is non-decoupling

  Large SUSY masses do not decouple from the Higgs sector !

$$\Delta m_b = \Delta_b \tan\beta \simeq \mu \tan\beta \left\{ \frac{2\alpha_S}{3\pi} M_{\tilde{g}}\, I(M_{\tilde{b}_1}, M_{\tilde{b}_2}, M_{\tilde{g}}) + \frac{Y_t}{4\pi} A_t\, I(M_{\tilde{t}_1}, M_{\tilde{t}_2}, \mu) \right.$$
$$+ \frac{\alpha}{4\pi} \left(-\frac{M_2}{s_W^2} \left(\left[c_t^2\ I(M_{\tilde{t}_1}, M_2, \mu) + s_t^2\ I(M_{\tilde{t}_2}, M_2, \mu) \right] \right.\right.$$
$$\left. + \frac{1}{2} \left[c_b^2\ I(M_{\tilde{b}_1}, M_2, \mu) + s_b^2\ I(M_{\tilde{b}_2}, M_2, \mu) \right] \right)$$
$$- \frac{M_1}{3\, c_W^2} \left(\frac{1}{3} I(M_{\tilde{b}_1}, M_{\tilde{b}_2}, M_1) \right.$$
$$+ \frac{1}{2} \left[c_b^2\ I(M_{\tilde{b}_1}, M_1, \mu) + s_b^2\ I(M_{\tilde{b}_2}, M_1, \mu) \right]$$
$$\left.\left. \left. + \left[s_b^2\ I(M_{\tilde{b}_1}, M_1, \mu) + c_b^2\ I(M_{\tilde{b}_2}, M_1, \mu) \right] \right) \right) \right\} .$$

$$Y_t \equiv \frac{h_t^2}{4\pi} = \frac{g^2 m_t^2}{8\pi m_W^2 \sin\beta^2}\,, \quad I(a,b,c) = \frac{a^2 b^2 \ln(a^2/b^2) + b^2 c^2 \ln(b^2/c^2) + c^2 a^2 \ln(c^2/a^2)}{(a^2-b^2)(b^2-c^2)(a^2-c^2)} \to \frac{1}{max(a^2,b^2,c^2)}.$$

Full one-loop contribution



The cross means a mass insertion, and the cross with a circle the coupling with H_2.

- A_b is a SUSY parameter: What if $A_b \sim \mu \tan\beta$?
- A_b enters also in one-loop triangle diagrams: $\sim A_b - \mu/\tan\beta$
  $\Rightarrow$ The leading A_b-terms cancel!!

A_b-enhanced terms?

At n-order of perturbation theory,
all the terms proportional to $(A_b)^n$ are (1-loop)^n

J.Guasch, P. Häfliger, M. Spira, PRD68 115001 (2003), hep-ph/0305101

$\Rightarrow$ The A_b terms are resumed!!!

$$SUSY: V_{hbb}^{1-loop} = \epsilon_{ij}\left[h_b^s(1+\Delta_2)\, H_1^i\, Q^j\, b_R + h_b^s\, \Delta_b\, H_2^j\, Q^i\, b_R\right] + h.c.$$

$$SM: V_{hbb}^{1-loop} = \epsilon_{ij}\left[h_b\, H_1^i\, Q^j\, b_R + h_b^s\, \Delta_b\, H_2^j\, Q^i\, b_R\right] + h.c.$$

$$h_b = \frac{m_b(Q)}{v_1}\frac{1}{1+\frac{h_b^s}{h_b}\Delta m_b} \quad , \quad \frac{h_b^s}{h_b} = \frac{1}{1+\Delta_2}$$

- The leading A_b-enhanced terms cancel!!
- The first non-vanishing A_b terms are of higher order and proportional to $\Delta m_b \Rightarrow \Delta_2 \Delta m_b$

One-loop effective couplings:

$$h^0 b\bar{b} : C_{hbb} = h_b \sin\alpha \left(1 - \frac{h_b^s}{h_b}\frac{\Delta m_b}{\tan\beta \tan\alpha}\right)$$

$$H^0 b\bar{b} : C_{Hbb} = -h_b \cos\alpha \left(1 + \frac{h_b^s}{h_b}\frac{\Delta m_b \tan\alpha}{\tan\beta}\right)$$

$$A^0 b\bar{b}/H^- t\bar{b} : C_{Abb/H^- tb} = -h_b \sin\alpha \left(1 - \frac{h_b^s}{h_b}\frac{\Delta m_b}{\tan\beta^2}\right)$$

$$\frac{h_b^s}{h_b} = \frac{1}{1+\Delta_2},$$

$$\Delta_2 = -A_b \left\{\frac{2\alpha_S}{3\pi} M_{\tilde{g}}\, I(M_{\tilde{b}_1}, M_{\tilde{b}_2}, M_{\tilde{g}}) - \frac{\alpha}{4\pi}\frac{M_1}{9\, c_W^2} I(M_{\tilde{b}_1}, M_{\tilde{b}_2}, M_1)\right\}.$$

- if the chosen parameters are such that:

$$|A_b| \simeq |\mu| \simeq M_{SUSY}$$

  - We can approximate $h_b^s \simeq h_b$ and use the old expressions.

Background Suppression ($H^+ \to \tau\nu$)

- High cut on p_T of the $\tau-$jet : $p_T^\tau > 100 GeV$

- Small azimuthal opening angle $\Delta\phi$ between the τ-jet and the missing transverse momentum $\not{p}_T \Rightarrow$
  We have the cut $\Delta\phi(\not{p}_T, p_T^\tau) > 1$.

- The missing transverse momentum is harder for the signal than for the background.

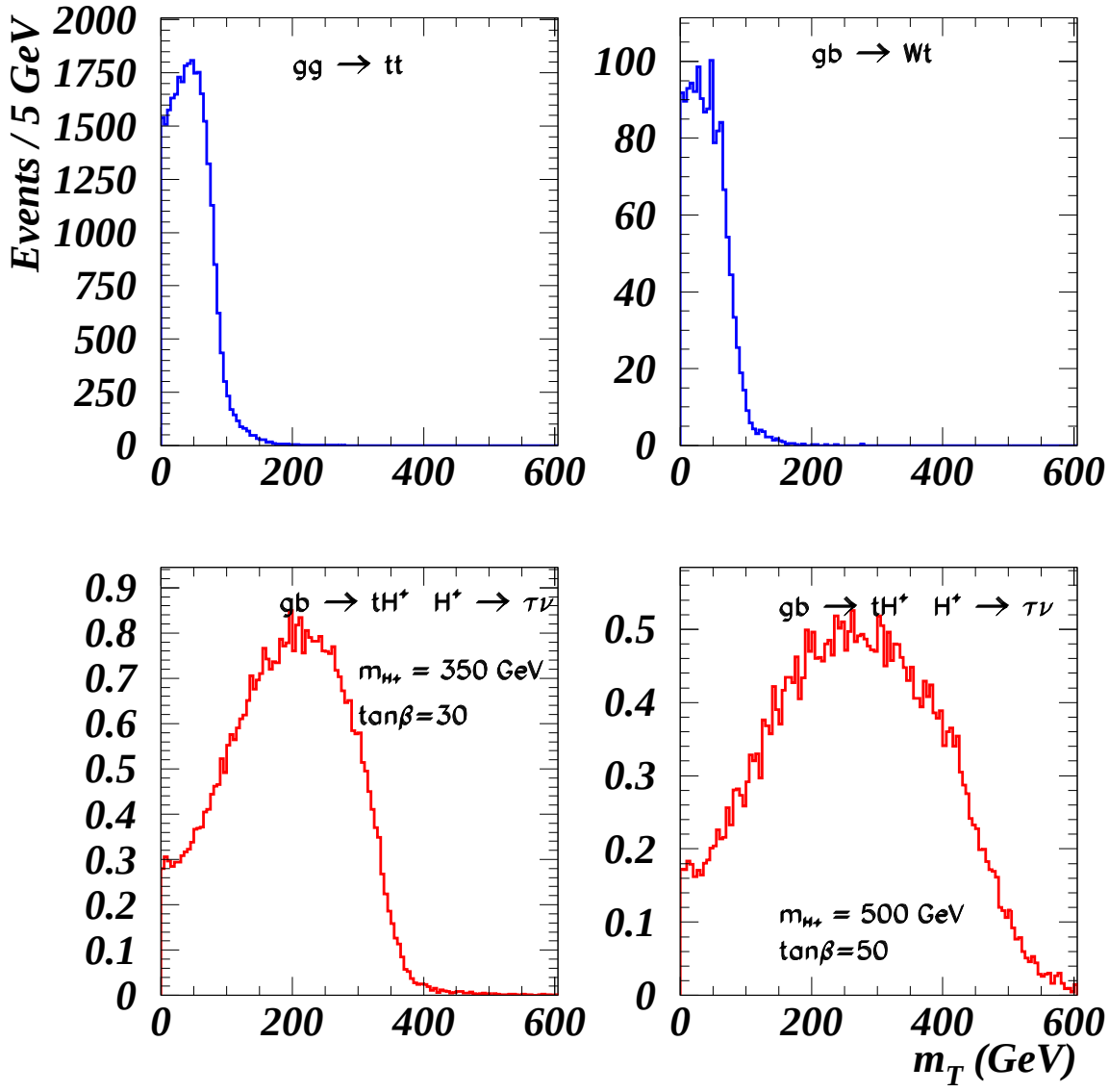
  These effects are well cumulated in the transverse mass of $\tau\nu$,

$$m_T = \sqrt{2 p_T^\tau \not{p}_T \, [1 - \cos(\Delta\phi)]},$$

  which provides good discrimination between the signal and the backgrounds

- We use a final cut $m_T > 200$ GeV for the calculations of the signal-to-background ratios and for the signal significances.

Transverse mass m_T distribution for signal and total background in the leptonic channel, taking into account the polarization of the τ-lepton, for an integrated luminosity of 30 fb^{-1}



Signal and background cross-sections, Efficiencies and Significances

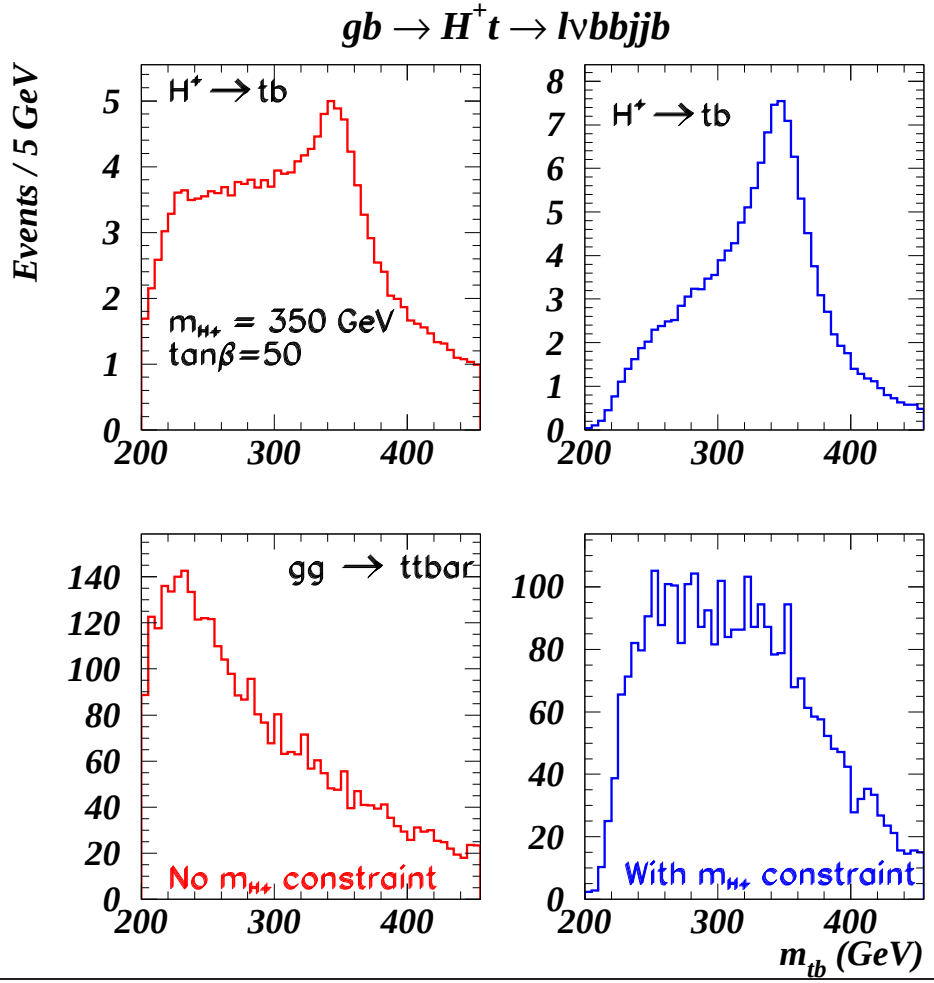
For $300\,\text{fb}^{-1}$ integrated luminosity and $\tan\beta = 50$:

	$m_{H^\pm} = 350$	$m_{H^\pm} = 500$	$t\bar{t}$	$W^\pm t$
$\sigma \times BR$	99.9 fb	30.7 fb	79.1 pb	16.3 pb
Events	29958	9219	2.3×10^6	4.89×10^5
Events after cuts	174	96	17	3
Efficiency	0.6%	1%	8×10^{-6}	6×10^{-6}
S/B	7.9	4.4		
$S/\sqrt{B}$	37.1	20.5		

- Before cuts production rates for background are largest than for signal
- We found that the efficiences of cuts is $\sim 1\%$ for the signal but $\sim 10^{-6}$ for backgrounds
  $\Rightarrow$ After cuts the number of signals events is much larger than backgrounds
- Signal are large enough to consider $H^+ \to \tau\nu$ as a "Golden channel" for the H^+ discovery at large $\tan\beta$

W, t and H^+ mass Reconstruction ($H^+ \to t\bar{b}$)

- jj combinations such that $|m_W - m_{jj}| < 25\,GeV$
- Use m_W constraint to find the longitudinal component of $\nu-$ momentum in $W^\pm \to l\nu$
- Keep the best two top quarks candidates that minimize $\chi^2 \equiv (m_t - m_{l\nu b})^2 + (m_t - m_{jjb})^2$
- The remaining b-jet can be paired with either t to give two H^+.
  Use m_{H^+} from $H^+ \to \tau\nu$ to select the best candidate: min $\chi^2 = (m_{tb} - m_{H^+})^2$.



Integrated luminosity of 30 fb^{-1}

Even with m_{H^+} constraint, some irreducible combinatorial noise still appear.

m_{H^+} constraint reshapes the background.

Signal and background cross-sections, Efficiencies and Significances

For $300\,\text{fb}^{-1}$ integrated luminosity and $\tan\beta = 50$:

	$m_{H^\pm} = 350$	$m_{H^\pm} = 500$	$t\bar{t}q$
$\sigma \times BR$	248.4 fb	88 fb	85 pb
Events	74510	26389	2.55×10^7
Events after cuts	2100	784	59688
Efficiency	2.8%	3%	0.2%
S/B	0.035	0.013	
$S/\sqrt{B}$	8.6	3.2	

- Production rates for background are largest than for signal before cuts
- The $m_{H^\pm}$ constraint reshapes the backgrounds and in doing so the signal significance is not improved.
- Even with $m_{H^\pm}$ constraint, difficult to observe H^+ in this channel above $\sim 400\,GeV$
- Knowledge of background shape and rate necessary!