Charged Higgs Mass from Top-Quark Decays

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Based on the articles
M. Carena, D. Garcia, U. Nierste and C.W., NPB577 (2000) 88
E. Boos, V. Bunichev, M. Carena and C.W., hep-ph/0507100

Higgs Working Group Study, Snowmass Meeting, August 17, 2005

Higgs Spectrum in the MSSM

- Supersymmetric extensions of the SM predict and extended Higgs sector. In particular, in the MSSM there are one charged and three neutral Higgs bosons.

- The masses of these Higgs bosons satisfy relationships that are mildly affected by radiative corrections. Therefore, the precise determination of these masses provides a consistency check of the MSSM scenario.

- The couplings of these Higgs bosons to fermions are also well determined by the parameters of the model, but they may be strongly affected by radiative corrections induced by the supersymmetry breaking parameters.

Charged Higgs Mass

- The charged Higgs Mass value is also indicative of the properties of the neutral Higgs bosons.

- For large values of the charged Higgs mass, only one neutral light Higgs remains in the low-energy spectrum and has SM-like properties.

- For small values of the charged Higgs mass, smaller than about 150 GeV, instead, all neutral Higgs bosons tend to have highly non-standard properties.

- An exceptional case is the large $\tan\beta$ regime, in which one of the Higgs bosons couples mostly with SM-like couplings to the weak gauge bosons, but its couplings to fermions may be highly non-standard.

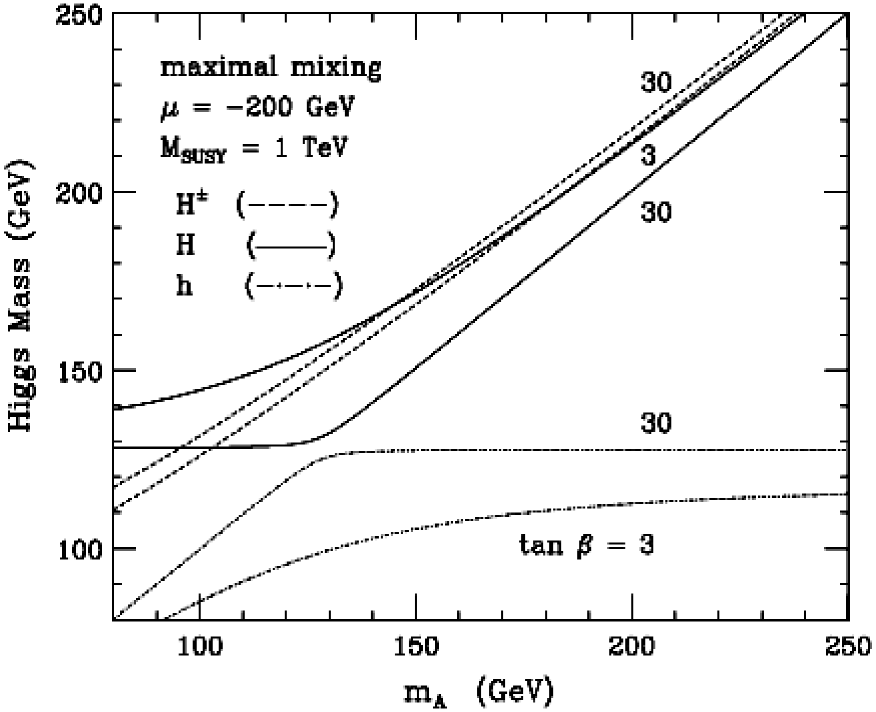
Large $\tan\beta$ regime

- At large values of $\tan\beta$, essentially only one of the two Higgs boson doublets participate in the mechanism of electroweak symmetry breaking. This doublet contains the Goldstone modes and a Higgs that couples in the standard way to the weak gauge bosons.

- The other doublet contains two non-standard Higgs bosons (a CP-odd and a CP-even Higgs boson if CP is conserved), and a charged Higgs boson.

- These CP-even and CP-odd Higgs bosons tend to be highly degenerate in mass, while the squared of the charged Higgs mass is approximately equal to the sum of the squares of the W-mass and the CP-odd Higgs mass.

MSSM Higgs Masses as a function of M_A



$$m_H^2 \cos^2(\beta-\alpha) + m_h^2 \sin^2(\beta-\alpha) = [m_h^{max}(\tan\beta)]^2$$

- $\cos^2(\beta-\alpha) \to 1$ for large $\tan\beta$, low m_A
  $\Longrightarrow$ H has SM-like couplings to W,Z
- $\sin^2(\beta-\alpha) \to 1$ for large m_A
  $\Longrightarrow$ h has SM-like couplings to W,Z

for large $\tan\beta$:

always one CP-even Higgs with SM-like couplings to W,Z and mass below $m_h^{max} \lesssim 135$ GeV

- **Mild variation of the charged Higgs mass with SUSY spectrum**

$$m_{H^\mp}^2 = m_A^2 - (\lambda_4 - \lambda_5)v^2 \approx m_A^2 + M_W^2$$

If sizeable μ and sizeable $A_t \times A_b < 0 \Rightarrow \lambda_4 - \lambda_5 > 0$ (smaller $m_{H^\mp}$)

LEP MSSM HIGGS limits: ⟶ $m_{H^\pm} > 78.6\,\text{GeV}$

$m_h > 91.0\,\text{GeV}$; $m_A > 91.9\,\text{GeV}$; $m_h^{\text{SM-like}} > 114.6\,\text{GeV}$

Couplings of the charged Higgs

- The couplings of the charged Higgs are determined, at tree level, by the lepton and quark masses and by $\tan\beta$

- The dominant couplings are those of the third generation

$$g_{H^- t\bar{b}} = \frac{\sqrt{2}}{\mathrm{v}}\left[m_t \cot\beta \, \mathrm{P_R} + m_b \tan\beta \, \mathrm{P_L}\right]; \quad g_{H^- \tau^+ \nu} = \frac{\sqrt{2}}{\mathrm{v}}\left[m_\tau \tan\beta \, \mathrm{P_L}\right]$$

- Observe that due to the structure of the couplings, the rate of the charged Higgs decay into second generation quarks will be much smaller than the one of the decay into tau-leptons and neutrinos.

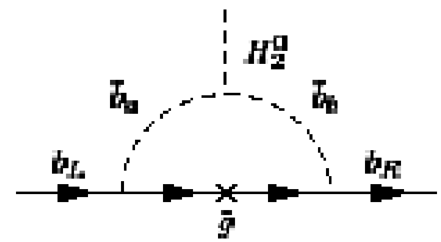
- Therefore, if the charged Higgs boson is lighter than the top quark and $\tan\beta$ is large, the charged Higgs decays predominantly into tau leptons and neutrinos.

Radiative Corrections to Higgs Couplings

As it is well known, at large values of $\tan\beta$ the couplings of the neutral and charged Higgs bosons are strongly affected by radiative corrections.

The most important ones for the charged Higgs boson are the vertex corrections

SUSY vertex correc. to Yukawa couplings, which modify the effective Lagrangian, coupling Higgs to fermions



$$\mathcal{L}_{\rm eff} \longrightarrow h_b\, H_1^0\, b\bar{b} + \Delta h_b\, H_2^0\, b\bar{b}$$

Δh_b modifies the m_b–h_b relation

$$m_b \simeq h_b v_1 + \Delta h_b v_2 = h_b\, v\, \cos\beta \left(1 + \frac{\Delta h_b}{h_b} \tan\beta\right)$$

$$\Delta_b = \frac{\Delta h_b}{h_b} \tan\beta \sim \frac{2\alpha_S}{3\pi} \frac{\mu\, M_{\tilde{g}}}{\max(m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2}, M^2_{\tilde{g}})} \tan\beta + \Delta_b^{\tilde{t}\tilde{\chi}^+}$$

$\Delta_b \sim \mathcal{O}(1)$ if $\tan\beta$ large

$$\Delta_b^{\tilde{t}\tilde{\chi}^+} \sim \frac{h_t^2}{16\pi^2} \frac{\mu\, A_t}{\max(m^2_{\tilde{t}_1}, m^2_{\tilde{t}_2}, \mu^2)} \tan\beta$$

Corrections don't decouple for large values of the SUSY parameters. They just reflect the fact that, after SUSY breaking, at low energies you get a two Higgs doublet model with specific couplings dictated by the tree-level values and these threshold effects.

Interactions after radiative corrections

The interactions of the neutral and charged Higgs bosons with fermions are strongly affected by radiative corrections.

$$\mathcal{L}_{\rm int} = - \sum_{q=t,b,\tau} \left[g_{hq\bar{q}} h q \bar{q} + g_{Hq\bar{q}} H q \bar{q} - i g_{Aq\bar{q}} A \bar{q} \gamma_5 q \right] + \left[\bar{b} g_{H^- t\bar{b}} t H^- + {\rm h.c.} \right] .$$

$$g_{h\, b\bar{b}} \simeq \frac{-\sin\alpha\, m_b}{v \cos\beta (1+\Delta_b)} (1 - \Delta_b / \tan\alpha \tan\beta) \qquad g_{H\, b\bar{b}} \simeq \frac{\cos\alpha\, m_b}{v \cos\beta (1+\Delta_b)} (1 - \Delta_b \tan\alpha / \tan\beta)$$

$$g_{A\, b\bar{b}} \simeq \frac{m_b}{v(1+\Delta_b)} \tan\beta$$

Carena, Mrenna,C.W. ’98/99
Haber et al. ‘99

For the charged Higgs one has important radiative corrections for large tanb

$$g_{H^- t\bar{b}} \simeq \left\{ \frac{m_t}{v} \cot\beta \left[1 - \frac{1}{1+\Delta_t} \frac{\Delta h_t}{h_t} \tan\beta \right] P_R + \frac{m_b}{v} \tan\beta \left[\frac{1}{(1+\Delta_b)} \right] P_L \right\}$$

Carena, Garcia, Nierste,C.W.’99; Gambino et al.’00

Radiative corrections to the tau coupling tend to be small, and we shall ignore them, since they don’t play a relevant role in our analysis.

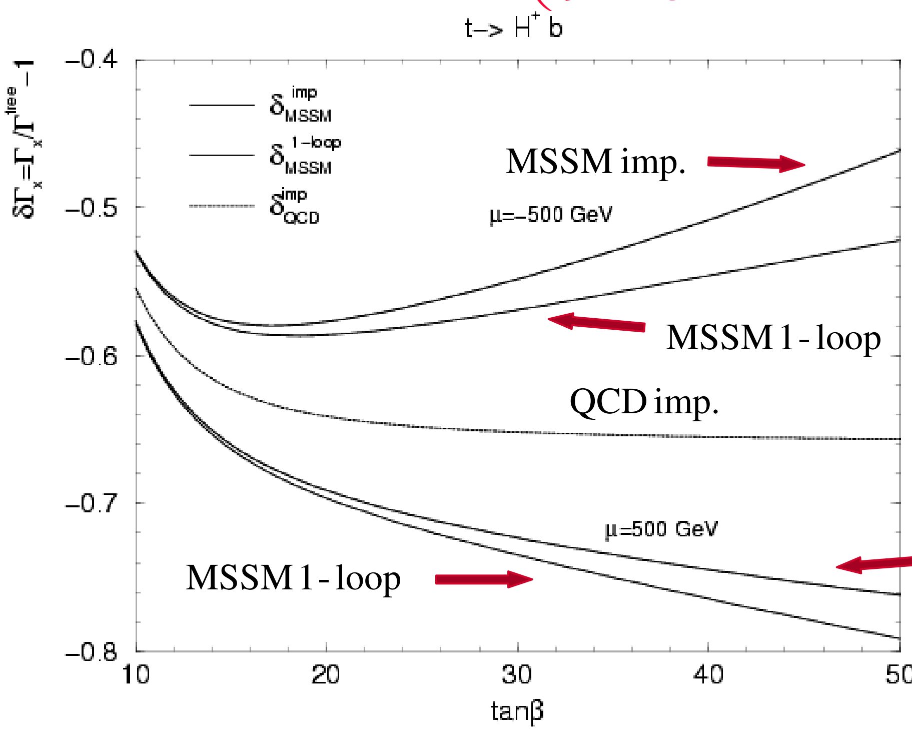
Quantum Corrections to $\Gamma\left(t \to bH^+\right)$

- leading and subleading log(Q/mb) resummed using m_b running in Γ^0 &
- One-loop finite QCD terms also included

$$\Gamma^{imp.}_{QCD}(t \to bH^+, \tan\beta \geq 10) = \frac{g^2}{64\pi M_W^2} m_t (1-q_{H^+})^2 \overline{m}_b^2(m_t^2)\tan^2\beta \times \left\{1 + \frac{\alpha_s(m_t^2)}{\pi} \times \left[7 - \frac{8\pi^2}{9} - 2\log(1-q_{H^+}) + 2(1-q_{H^+}) + \left(\frac{4}{9} + \frac{2}{3}\log(1-q_{H^+})\right)(1-q_{H^+})^2\right]\right\}$$

$$q_{H^+} = \frac{m_{H^+}^2}{m_t^2}$$

$A_t = M_{\tilde{g}} =$ 500 GeV

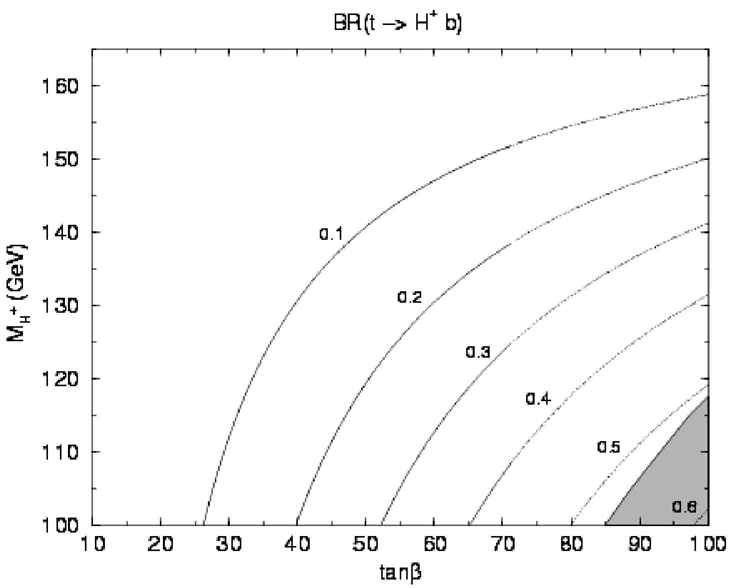


$m_{H^{\mp}} = 125$ GeV

➔ After higher order tanb enhanced SUSY corrections included:

$$\Gamma^{imp.}_{MSSM}(t \to bH^+, \tan\beta \geq 10) = \Gamma^{imp.}_{QCD} \frac{1}{(1+\Delta m_b)^2}$$

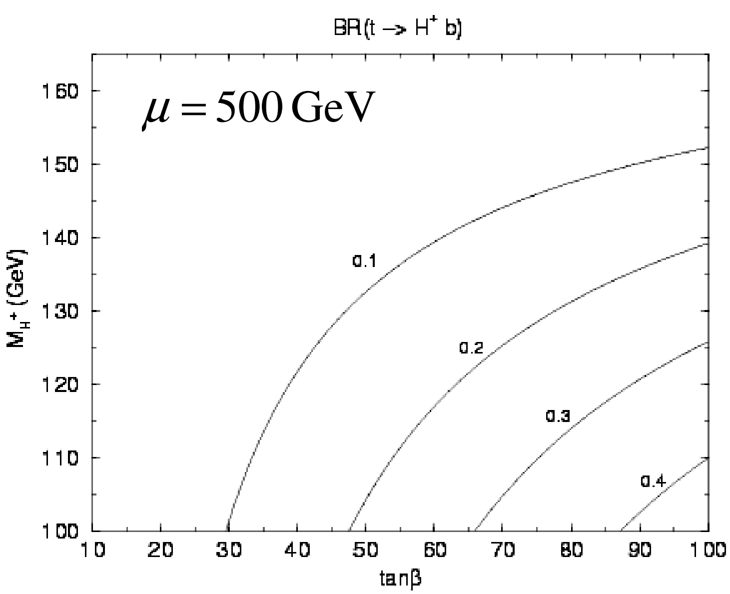
Charged Higgs Searches at theTevatron

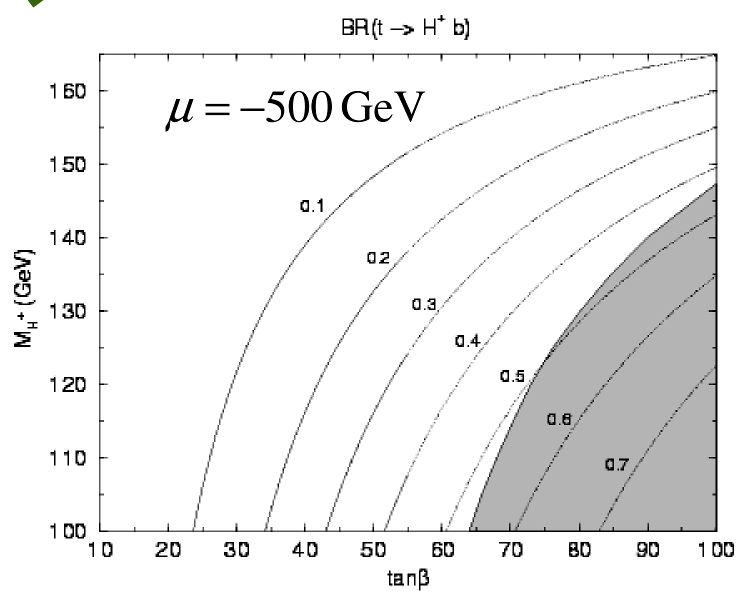


Curves of constant $\mathrm{BR}\left(t \rightarrow bH^{+}\right)$ after resummation of LOand NLO logs fo QCD

Shaded area excluded by DO RunI analysis
Similar for CDF.

Including SUSY corrections for large tanb and a heavy SUSY spectrum





Drastic variations on bounds in the $\tan\beta - m_{H^{\mp}}$ plane depending on MSSM parameter space

M.C., Garcia, Nierste, Wagner

Tau Polarization & Charged Higgs Measurements

- In the range $m_{H^+} < m_t \Rightarrow \mathrm{BR}(\mathrm{H}^\pm \to \tau^+\nu / \tau^-\overline{\nu}) \approx 1$

it seems difficult to identify $\mathrm{H}^\pm \to \tau\nu$ decays from $\mathrm{W}^\pm \to \tau\nu$

Crucial Observation:

$$\mathrm{W}^- \to \tau_L^-\overline{\nu}_R \qquad (\mathrm{W}^+ \to \tau_R^+\nu_L)$$

Due to the lefthandness of the charged current: $L \propto W^- \overline{e}_L \gamma_\mu \nu_L + h.c.$

whereas

$$\mathrm{H}^- \to \tau_R^-\overline{\nu}_R \qquad (\mathrm{H}^+ \to \tau_L^+\nu_L)$$

➔ a consequence of the helicity-flip (conserving) of the SM Higgs (vector boson) couplings

Hence:

$$P_\tau^H = +1 \qquad P_\tau^W = -1$$

- The decay distributions of the τ_R^- are sufficiently different from those of τ_L^-

- Considering the main contributions to one-prong hadronic tau decays:

$$\tau^{\pm} \to \pi^{\pm}\nu_{\tau} \ \ (12.5\%);$$

$$\tau^{\pm} \to \rho^{\pm}\nu_{\tau} \to \pi^{\pm}\pi^{0}\nu_{\tau} \ \ (24\%) \qquad \tau^{\pm} \to a_1^{\pm}\nu_{\tau} \to \pi^{\pm}\pi^{0}\pi^{0}\nu_{\tau} \ \ (7.5\%)$$

The dependence of the tau polarization of the angular distributions of the primary decay modes in the tau rest frame

$$\frac{2}{\Gamma_{\pi}}\frac{d\Gamma_{\pi}}{d\cos\theta} = \left(1 + P_{\tau}\cos\theta\right)$$

It will be easier if one can make use of kinematic variables other than angular distribution. Energy distributions are easier to determine, and, as we will show allow to distinguish signal from background.

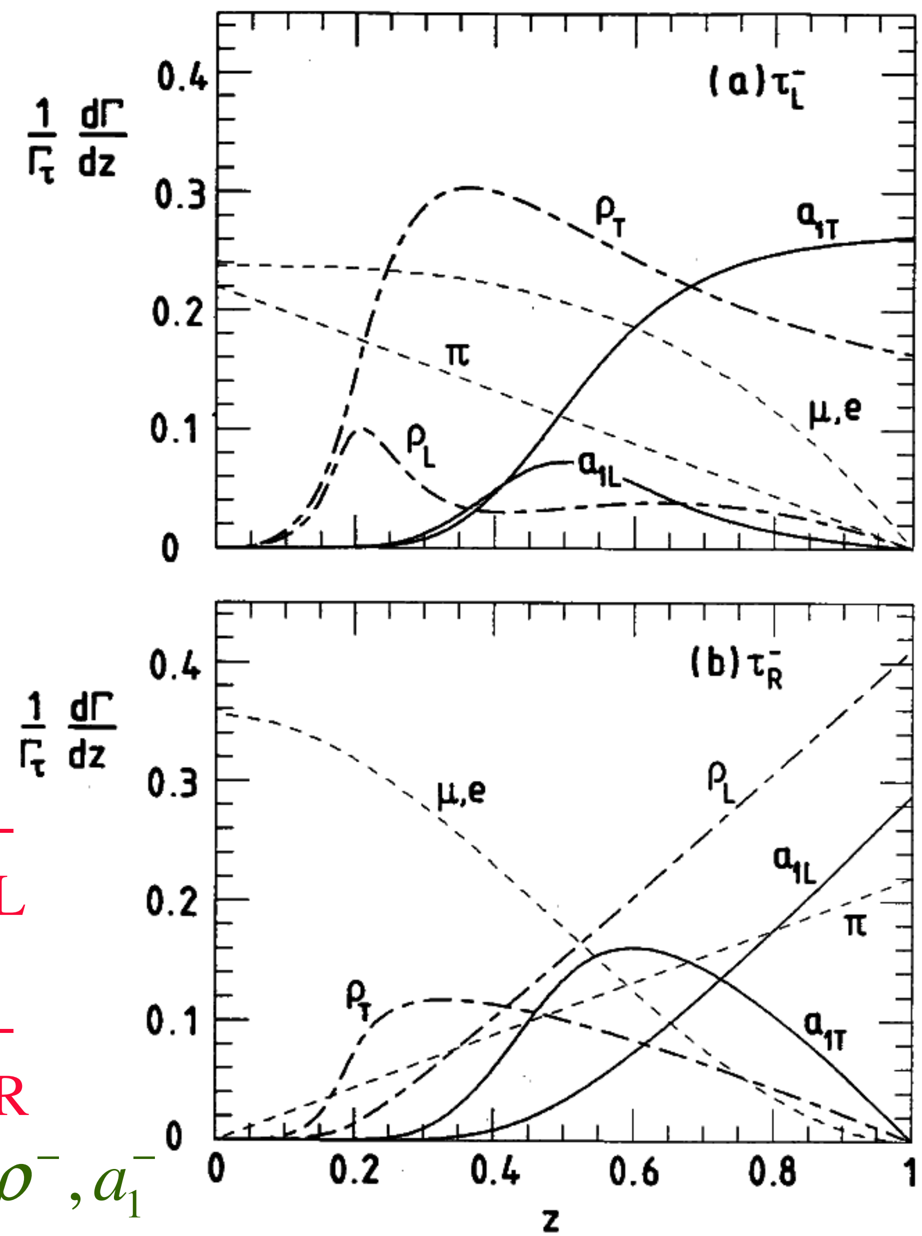
In the colinear limit $E_\tau / m_\tau >> 1$

$$\frac{1}{\Gamma_\tau}\frac{d\Gamma_\pi}{dz} \approx BR_\pi[1+P_\tau\,(2z-1)]; \qquad z = \frac{E_\pi}{E_\tau}$$

Energy distributions arising from $W^- \rightarrow \tau_L^- \rightarrow h^-$ are significantly different from $H^- \rightarrow \tau_R^- \rightarrow h^-$ decays

- Most energetic particles from τ_L^- decays ➔ transv. polarized ρ^-, a_1^-
- Most energetic particles from τ_R^- decays ➔ π^- & long. polarized ρ^-, a_1^-

Bullock, Hagiwara, Martin



Energetic pions favour charged Higgs over W's

Charged Higgs searches at the ILC: the impact of tau Polarization

- We consider $e^+e^- \to t\bar{t} \to W^{\pm}b\,H^{\mp}\bar{b}$
  - ➔ with $W \to 2\,\mathrm{jets}$
  - ➔ and $H^{\mp} \to \tau^{\mp}\nu$

$\sqrt{s} = 500\,\mathrm{GeV}$ and $500\,\mathrm{fb}^{-1}$

Main background: both tops decay into Wb and $W^{\mp} \to \tau^{\mp}\nu$

- Simulations done with CompHEP, including ISR and beamstrahlung with polarized τ
- Polarized τ decays with TAUOLA, using new CompHEP-TAUOLA interfase (E. Boos et al.)
- All other stages done with CompHEP-Pythia interface
- Energy distributions are given in the reconstructed top rest frame using the recoil mass technique

Systematic Effects

- It is clear that, since we will rely on the recoil mass technique to determine the top quark mass rest frame, there will be a systematic effect, related to the uncertainty in the determination of the energy and momentum of the decaying top-quarks.

- Since one of the top-quarks decays into jets and bottom quarks one should hope that this error will be small and we shall ignore in the following analysis. However, it is important to determine what would be the size of this systematic effect in a realistic case.

- In the top rest frame:

$$t \to bR \to b\tau\nu_\tau \to b\nu_\tau\bar{\nu}_\tau\pi$$

where the resonance R is either the W boson or the charged Higgs

$$\frac{1}{\Gamma_R}\frac{d\Gamma_R}{dy_\pi} = \frac{1}{(x_{\max} - x_{\min})}\times$$

$$\begin{cases} (1-P_\tau)\log\dfrac{x_{\max}}{x_{\min}} + 2P_\tau y_\pi\left(\dfrac{1}{x_{\min}} - \dfrac{1}{x_{\max}}\right), & \text{if } 0 < y_\pi < x_{\min} \\ (1-P_\tau)\log\dfrac{x_{\max}}{y_\pi} + 2P_\tau\left(1 - \dfrac{y_\pi}{x_{\max}}\right), & \text{if } x_{\min} < y_\pi \end{cases}$$

where:

$$y_\pi = \frac{E_\pi^{top}}{m_{top}}, \quad x_{\min} = \frac{E_\tau^{\min}}{m_{top}}, \quad x_{\max} = \frac{E_\tau^{\max}}{m_{top}}, \quad E_\tau^{\min} = \frac{M_R^2}{2m_{top}}, \quad E_\tau^{\max} = \frac{m_{top}}{2}$$

Recall: $P_\tau^W = -1$ and $P_\tau^H = 1$

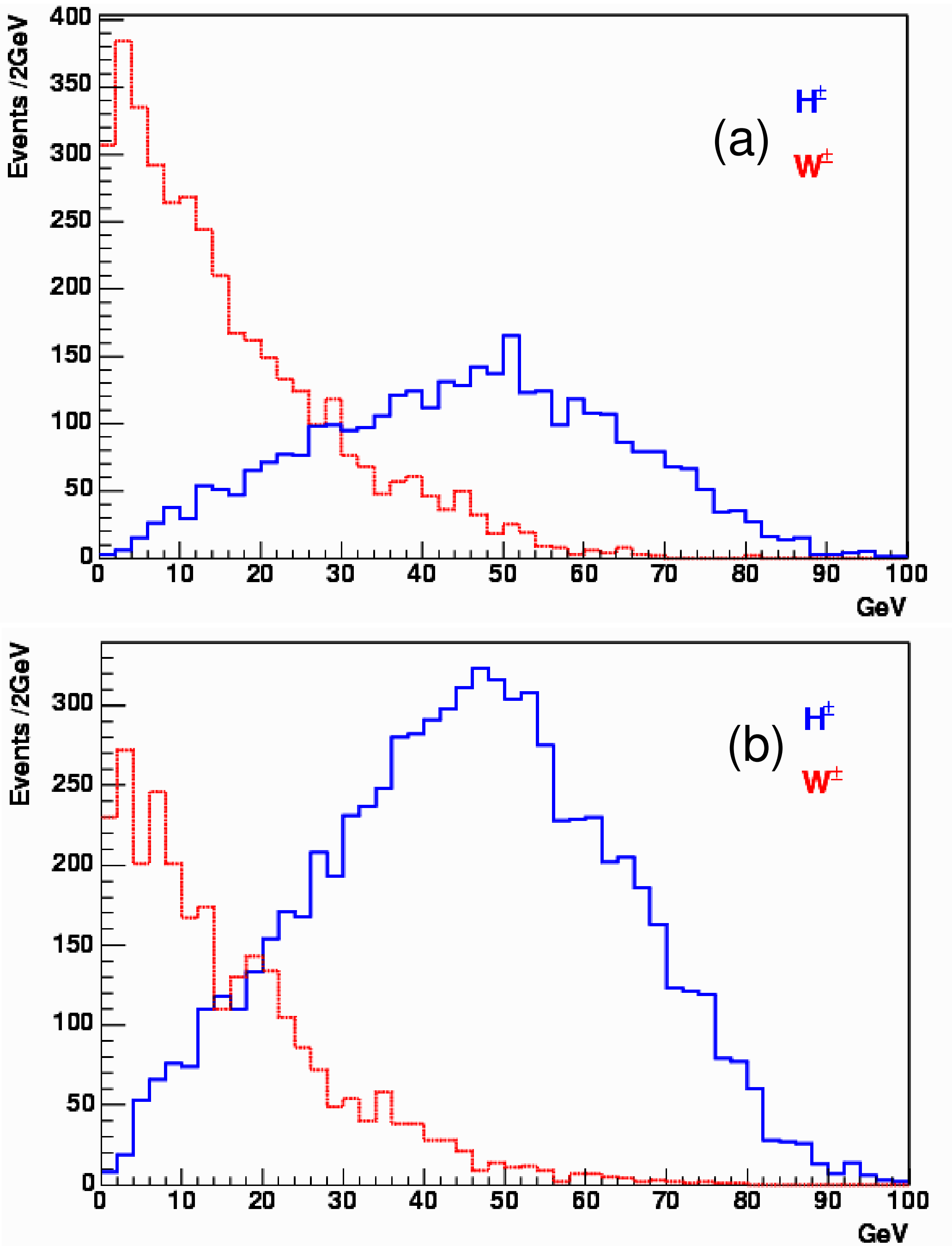
M. Nojiri: Boos, Martyn, Moortgat-Pick, Sachwitz, Sherstnev and Zerwas

for stau pair production: (R equiv. stau)

Top Quark Mass Error

- All energy distributions depend on the top-quark mass and the charged Higgs mass.
- The top quark mass will be independently determined at the ILC, via, for instance, top-quark production threshold scans.
- We will assume that the error on the top quark mass is much smaller than 1 GeV.

π -meson energy spectrum in the top rest frame



Two MSSM benchmark MSSM scenarios:

common parameters:

$$M_Q = M_U = M_D = M_{\tilde{g}} = M_2 = 1\,\text{TeV}$$

$$A_t = 500\,\text{GeV}$$

$$\tan\beta = 50 \qquad m_{H^{\mp}} = 130\,\text{GeV}$$

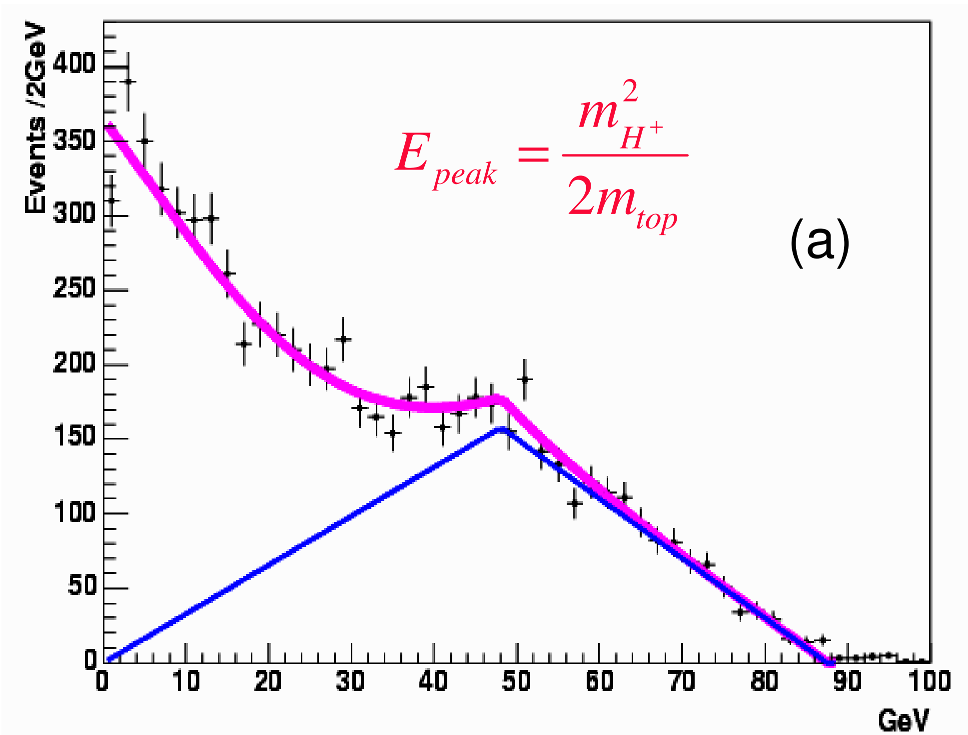
a) $\mu = 500\,\text{Gev}$

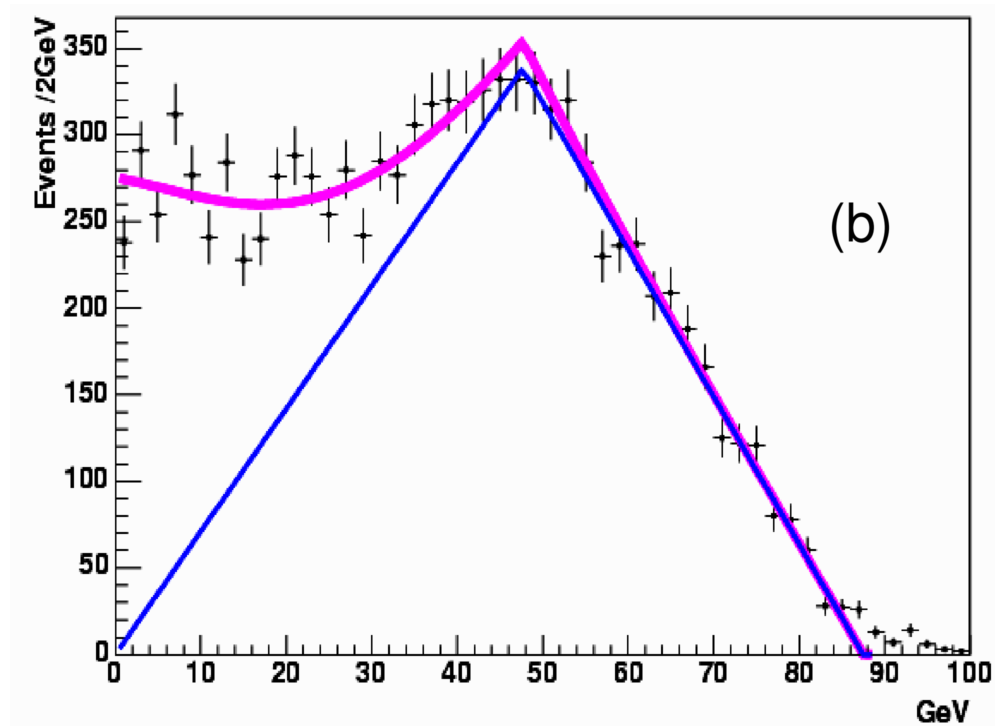
$\Rightarrow BR(t \to H^+ b) = 10\,\%$

b) $\mu = -500\,\text{Gev}$

$\Rightarrow BR(t \to H^+ b) = 24\,\%$

Performing a fit to the simulated signal + background





one can determine the value of

In particular we obtain:

(no systematics/detector effects)

$$a)\ \ m_{H^{\mp}} = (129.4 \pm 0.9)\ \mathrm{GeV}$$

$$b)\ \ m_{H^{\mp}} = (129.7 \pm 0.5)\ \mathrm{GeV}$$

Charged Higgs Mass Determination

- The example provided above shows that the systematics may be under control, the charged Higgs mass may be determined with high accuracy.
- Observe that, due to the missing energy in the charged Higgs decay, this is probably a much better determination than the one coming from charged Higgs pair production. This, of course, must be studied in detail.
- We have used only one of the possible one-prong tau decays.
  Other decays should be helpful in improving the charged Higgs mass determination and should also be studied. They should partially compensate for the unaccounted systematic and detector errors.
- Finally, the error in the determination of top-quark rest frame must be studied.

Conclusions

- Low energy supersymmetry has an important impact on Higgs physics.
  → It leads to definite predictions to the Higgs boson masses and their couplings to fermions and gauge bosons.

- Such couplings, however, are affected by radiative corrections induced by supersymmetric particle loops.

  → QCD and SUSY quantum corrections to $\Gamma(t \to bH^{+})$ lead to crucial effects in the interpretation of $H^{\mp}$ searches from top decays at the Tevatron

- Tau Lepton polarization is a powerful discriminative characteristic to separate charged Higgs signal

- Fit to pion spectra from polarized tau decays allows to extract light charged Higgs masses with $\delta m_{H^{\mp}} \approx 1\,\mathrm{GeV}$

  Theory level study, but only info on P_{τ} from $\tau^{\pm} \to \pi^{\pm} \nu_{\tau}$ has been used

CPsuperH

- Code to compute Higgs spectrum, couplings and decay modes in the presence of CP-violation

  Lee, Pilaftsis, M.C., Choi, Drees,Ellis, Lee,Wagner.'03

- CP-conserving case: Set phases to zero. Similar to HDECAY, but with the advantage that charged and neutral sector treated with same rate of accuracy.

- Combines calculation of masses and mixings by M.C., Ellis, Pilaftsis, Wagner. with analysis of decays by Choi, Drees, Hagiwara, Lee and Song.

- Available at

  http://theory.ph.man.ac.uk/~jslee/CPsuperH.html

Renormalization Group Effects

- tanb enhanced correc. to h_b are not the only universal ones
- Standard QCD corrections to transitions involving $\bar{t}_L b_R H^+$ Yukawa interactions➔ $\log(Q/m_b)$ with: $Q \approx m_t$ or $m_{H^\mp} \Rightarrow \alpha_s \log(Q/m_b) \approx O(1)$

-- Summation to all orders in leading logs $\alpha_s^n \log^n(Q/m_b)$ done evaluating running $h_b(Q) \longleftrightarrow m_b(Q)$ Braaten,Leveille; Drees, Hikasa

-- Full one-loop QCD correc. to decay rates require summation of NLO logs $\alpha_s^{n+1} \log^n(Q/m_b)$ due to non-log α_S terms Czarnecki, Davidson

To consider both effects: using OPE + RG evolution in $\overline{\mathrm{MS}}$

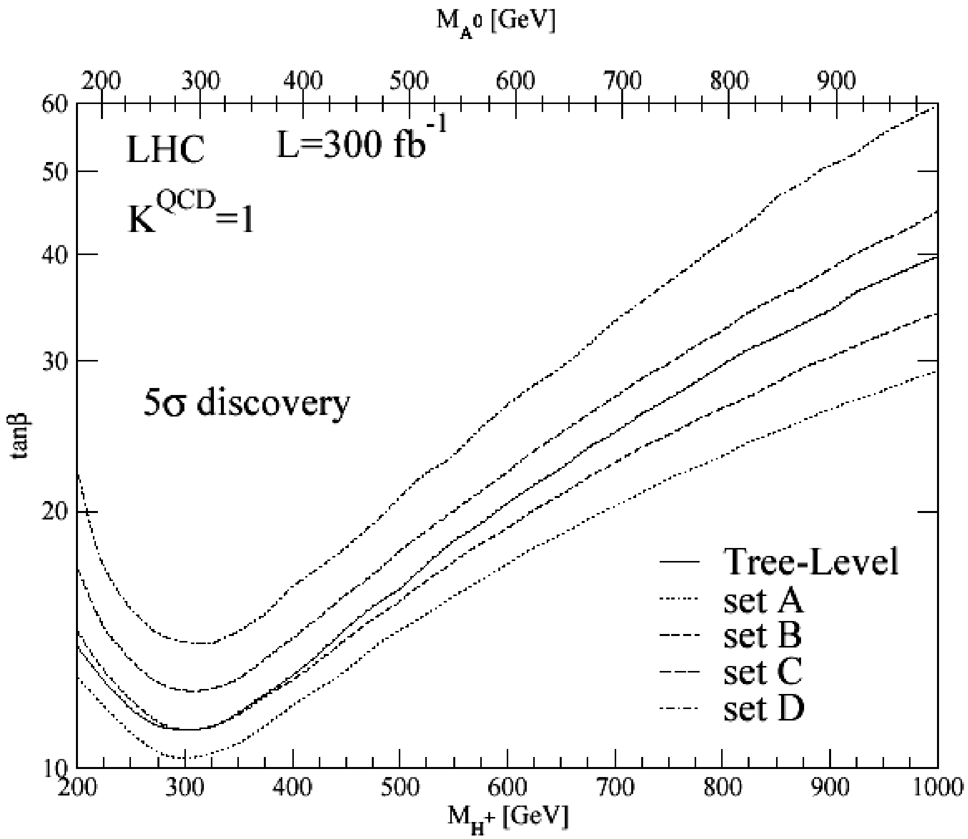
$$\bar{h}_b(Q = m_b) = \frac{\overline{m}_b(Q = m_b)}{v} \frac{1}{1 + \Delta m_b(Q = M_{SUSY})} \tan\beta$$

M.C., Garcia, Nierste, Wagner

The above relation is also valid at the scale Q

➔ the characteristic scale of the process

Similar analysis for $pp \to H^+ tb + X$ at LHC for large $\tan\beta$



Discovery reach at the LHC for different sets of SUSY parameters, which can enhance or suppress the $H^{\pm}tb$ coupling

Discovery reach at LHC with 300 fb^{-1} and $\tan\beta > 30$

- best case scenario: $m_{H^+} \leq 1$ TeV
- worst case scenario: $m_{H^+} \leq 450$ GeV

Belyaev, Garcia, Gausch, Sola