$\bar{B} \to D\tau\bar{\nu}_\tau$ によるヒッグスセクターの探索

田中 実 (阪大)

in collaboration with T. Miura (Osaka)

1. Introduction
2. The MSSM Higgs Sector
3. $\bar{B} \to D\tau\bar{\nu}_\tau$ in the MSSM
4. Hadronic form factors
5. Numerical results
6. Conclusion

Ref. hep-ph/0109244.

1. Introduction

- The Minimal Supersymmetric Standard model (MSSM)

  The most promising candidate of “new physics”

- Features of the MSSM

◇ Superpartners:

New particle search at the energy frontiers

(Nojiri, Komamiya)

LSP as a candidate of the dark matter (Kishimoto)

◇ Two Higgs doublets: ($\Leftarrow$ anomaly cancellation, fermion masses)

5 physical Higgs boson including a pair of charged Higgs boson

(Okada)

◇ New sources of flavor and CP physics: Soft SUSY breaking terms

Sfermion mass terms, A terms ⇒ Flavor mixing, CP violation

○ Lepton flavor violation

⇒ can be studied at both the energy and luminosity frontiers.

(Hisano, Aoki)

⇒ related to neutrino physics.

(Nishikawa, Takasugi, Yoshimura, Sato, Nakaya, Ejiri, Ishihara)

○ Quark flavor mixing

⇒ Hard to study at the energy frontiers.

Low energy factories (B,K,D) are the venues.

(Hazumi, Yamanaka)

○ CP violation

⇒ EDM's, B decays, K decays

Can B factories do SUSY physics

other than the flavor physics?

YES, Higgs physics.

Through $\bar{B} \to D\tau\bar{\nu}_\tau$.

Why $\bar{B} \to D\tau\bar{\nu}_\tau$?

◇ Tree level processes

Less dependent on the other sectors of the model

◇ Charged Higgs couplings to fermions: proportional to mass

Heavier system $\to$ larger effects

$$\text{Amp}(\bar{K} \to \pi\mu\bar{\nu}) \quad \sim \quad m_s m_\mu$$

$$\Downarrow \quad \sim 500 \text{ times enhancement}$$

$$\text{Amp}(\bar{B} \to D\tau\bar{\nu}) \quad \sim \quad m_b m_\tau$$

◇ B factory

# of B		BR$(b \to c\tau\bar{\nu}_\tau)$	
$\sim 10^8$	$\times$	~ 0.01	$\sim O(10^6)$ events !

Super B factory $\Rightarrow$ More events.

Search for a charged Higgs boson

- Direct search: $e^+e^- \to H^+H^- \quad \Longrightarrow \quad m_{H^\pm} \gtrsim 78.5\mathrm{GeV}$
- Indirect search: $b \to s\gamma \quad \Longrightarrow \quad m_{H^\pm} \gtrsim 389\,\mathrm{GeV}$
  in Model II of the two-Higgs-doublet model (MSSM like).

  BUT, in SUSY models, SUSY particle contributions strongly depend the soft breaking terms and may cancel the charged Higgs contribution.

  $\Rightarrow$ A lighter charged Higgs is possible.

2. The MSSM Higgs Sector

- Potential: $V = V_{\text{tree}} + V_{\text{1-loop}}$

  $V_{\text{tree}} = m_1^2 h_1^\dagger h_1 + m_2^2 h_2^\dagger h_2 + (m_3^2 h_1 h_2 + \text{h.c.}) + (\text{D terms})$

  3 parameters $(m_1^2, m_2^2, m_3^2) \Leftrightarrow (m_Z,\ m_A\ ,\ \tan\beta\ )$

  m_A =pseudo scalar mass, $\tan\beta = v_2/v_1$

  $V_{\text{1-loop}}$ depends on other parameters, stop mass, A term, etc.

  Charged Higgs mass $m_{H^\pm}^2 = m_W^2 + m_A^2$

- Yukawa couplings (Charged Higgs couplings to fermions)

$$\mathcal{L}_H = (2\sqrt{2}G_F)^{1/2}[\tan\beta\,\overline{u}_L V_{KM} M_d d_R + \cot\beta\,\overline{u}_R M_u V_{KM} d_L + \tan\beta\,\overline{\nu}_L M_l l_R]\; H^+ + \text{h.c.}$$

M's= Diagonal fermion mass matrices

$$\text{Amp}(\bar{B} \to D\tau\bar{\nu}) \sim m_b m_\tau \tan^2\beta$$

3. $\bar{B} \to D\tau\bar{\nu}_\tau$ in the MSSM

3.1 Helicity amplitudes

◇ $W^\pm$ exchange Hagiwara *et al.*(1989)

$$\mathcal{M}_s^{\lambda_\tau}(q^2, x)_W = \frac{G_F}{\sqrt{2}} V_{cb} \sum_{\lambda_W} \eta_{\lambda_W} L_{\lambda_W}^{\lambda_\tau} H_{\lambda_W}^s$$

$$q^2 = (p_B - p_D)^2 \,, \quad x = p_B \cdot p_\tau / m_B^2 \,,$$

$$\lambda_\tau = \pm 1 : \quad \tau \text{ helicity} \,,$$

$$\lambda_W = \pm 1,\, 0,\, s : \quad \text{virtual W helicity} \,, \quad \eta_{\pm 1} = \eta_0 = 1,\, \eta_s = -1.$$

- Hadronic amplitude: $\bar{B} \to D\, W^*$

$$H^s_{\lambda_W}(q^2) \equiv \epsilon^*_\mu(\lambda_W)\langle D(p_D)|\bar{c}\gamma^\mu(1-\gamma_5)b|\bar{B}(p_B)\rangle$$

$\epsilon_\mu =$ polarization vector of the virtual W

- Leptonic amplitude: $W^* \to \tau\bar{\nu}$

$$L^{\lambda_\tau}_{\lambda_W}(q^2, x) \equiv \epsilon_\mu(\lambda_W)\langle \tau(p_\tau, \lambda_\tau)\bar{\nu}_\tau(p_\nu)|\bar{\tau}\gamma^\mu(1-\gamma_5)\nu_\tau|0\rangle$$

◇ $H^{\pm}$ exchange M.T. ZPC 67, 321 (1995)

$$\mathcal{M}_s^{\lambda_\tau}(q^2,x)_H = \frac{G_F}{\sqrt{2}}V_{cb}L^{\lambda_\tau}\times \sum_i\Big[\tan^2\beta\frac{m_b m_\tau}{M_{H_i}^2}H_R^s+\frac{m_c m_\tau}{M_{H_i}^2}H_L^s\Big]$$

$$H_{R,L}^s(q^2)\equiv\langle D(p_D)|\bar{c}(1\pm\gamma_5)b|\bar{B}(p_B)\rangle$$

$$L^{\lambda_\tau}(q^2,x)\equiv\langle\tau(p_\tau,\lambda_\tau)\bar{\nu}_\tau(p_\nu)|\bar{\tau}(1-\gamma_5)\nu_\tau|0\rangle$$

$H^s_{R,L}$ and L^{λ_τ} can be written in terms of H^s_s and $L^{\lambda_\tau}_s$:

$$H^s_{R,L} = \frac{\sqrt{q^2}}{m_b - m_c} H^s_s \,, \;\; L^{\lambda_\tau} = \frac{\sqrt{q^2}}{m_\tau} L^{\lambda_\tau}_s \,.$$

Note: The former relation is valid in the heavy quark limit.

3.2 Decay rate

$$\begin{aligned} \frac{d\Gamma}{dq^2} \;=\; & \frac{G_F^2 |V_{cb}|^2 v^4 \sqrt{Q_+ Q_-}}{128\pi^3 m_B^3} \Big[\Big(\frac{2}{3} q^2 + \frac{1}{3} m_\tau^2 \Big) (H_0^s)^2 \\ & + m_\tau^2 \Big(\frac{q^2 \tan^2\beta}{M_{H^\pm}^2} \frac{m_b}{m_b - m_c} + \frac{q^2}{M_{H^\pm}^2} \frac{m_c}{m_b - m_c} - 1 \Big)^2 (H_s^s)^2 \Big] \,, \end{aligned}$$

$$Q_\pm = (m_B \pm m_D)^2 - q^2, v = \sqrt{1 - m_\tau^2/q^2}$$

4. Hadronic form factors

$$\langle D(p_D)|\bar{c}\gamma^\mu b|\bar{B}(p_B)\rangle = \sqrt{m_B m_D}[\xi_+(w)(v+v')^\mu + \xi_-(w)(v-v')^\mu]$$

$$v = p_B/m_B,\ v' = p_D/m_D,\ w \equiv v\cdot v' = (m_B^2 + m_D^2 - q^2)/2m_B m_D$$

In the HQL and the LLA,

$$\xi_+(w) = \xi(w)\ ,\quad \xi_-(w) = 0$$

$\xi(w)$: the universal form factor (Isgur-Wise function)

$\xi(w)$ is constrained strongly by the dispersion relations:

Caprini et al.

$$\xi(w) \simeq 1 - 8\rho_1^2 z + (51.\rho_1^2 - 10.)z^2 - (252.\rho_1^2 - 84.)z^3$$

$$z = (\sqrt{w+1} - \sqrt{2})/(\sqrt{w+1} + \sqrt{2})$$

Fitting experimental data of $\bar{B} \to D^* l\bar{\nu}$, the slope parameter is given:

$$\rho_1^2 = 1.33 \pm 0.22$$

$\Rightarrow$ Dominant uncertainty in the calculation of the decay rate

5. Numerical results

The decay rate depends on the Higgs parameter mostly through $R \equiv m_W \tan\beta / m_H^{\pm}$.

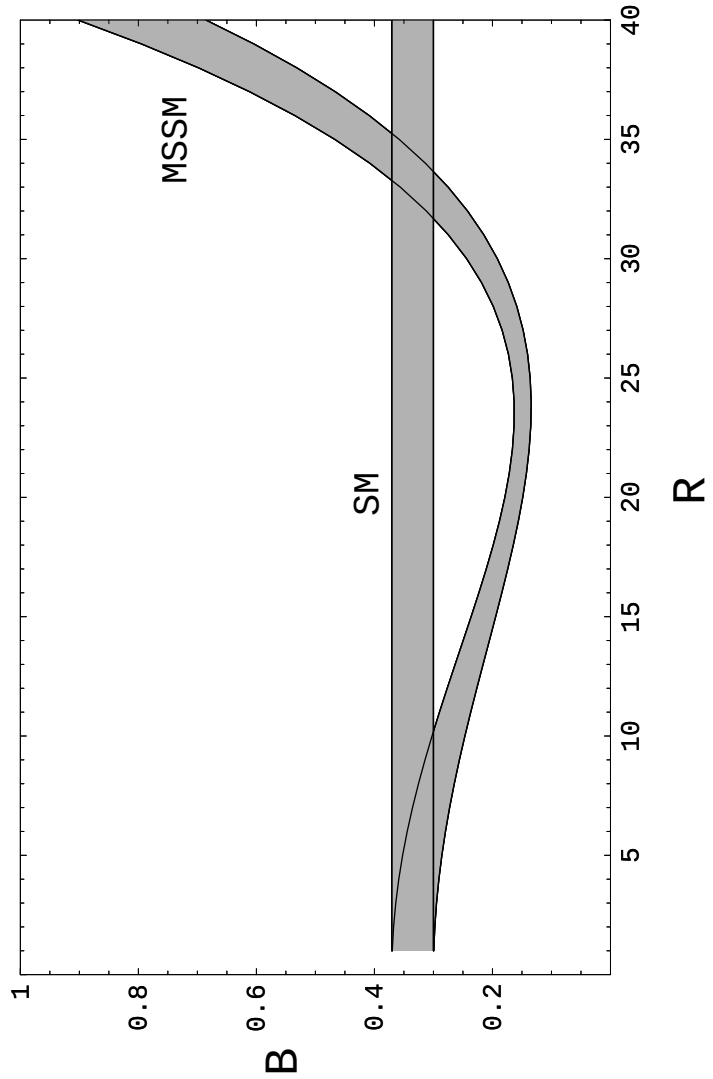
- Ratios of decay rates:

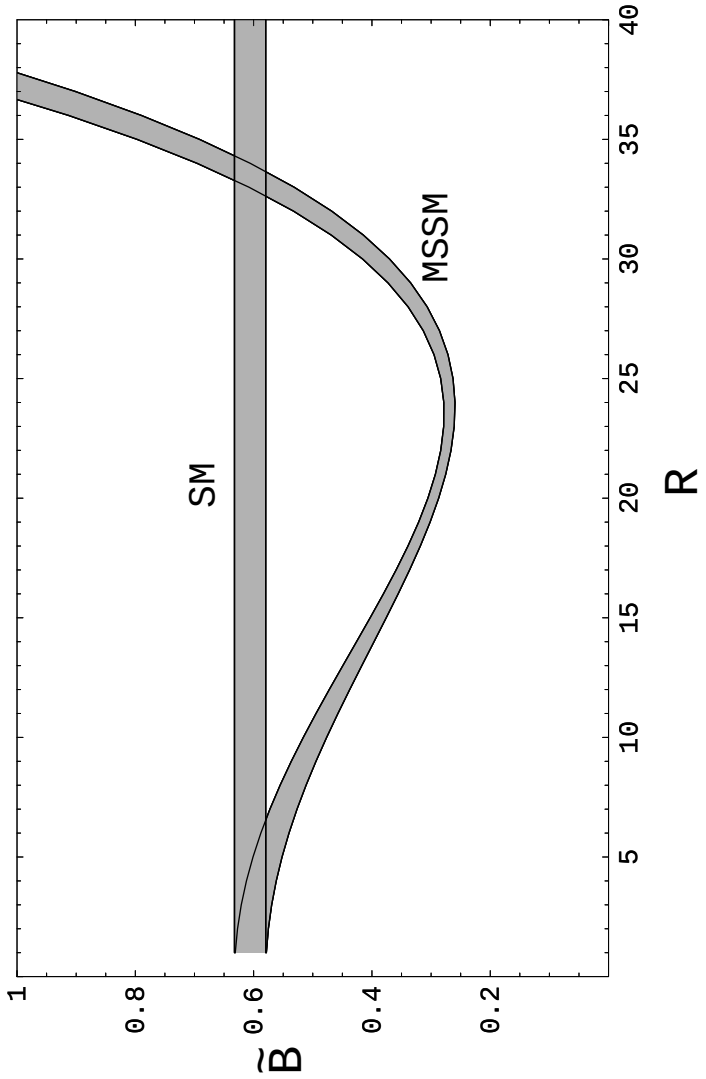
$$B(R) \equiv \frac{\Gamma(\bar{B} \to D\tau\bar{\nu}_\tau)}{\Gamma(\bar{B} \to D\mu\bar{\nu}_\mu)_{SM}}$$

$$\tilde{B}(R) \equiv \frac{\Gamma(\bar{B} \to D\tau\bar{\nu}_\tau)}{\tilde{\Gamma}(\bar{B} \to D\mu\bar{\nu}_\mu)_{SM}}$$

$\tilde{\Gamma}$: integrated over $m_\tau^2 \le q^2 \le (m_B - m_D)^2$

(to reduce the uncertainty)


MSSM
SM
R
B
1
0.8
0.6
0.4
0.2
5
10
15
20
25
30
35
40


MSSM
SM
R
B̃
1
0.8
0.6
0.4
0.2
5
10
15
20
25
30
35
40

- Expected experimental reach

$\delta B_{\mathrm{exp}}/B_{\mathrm{exp}}$: Experimental error in B

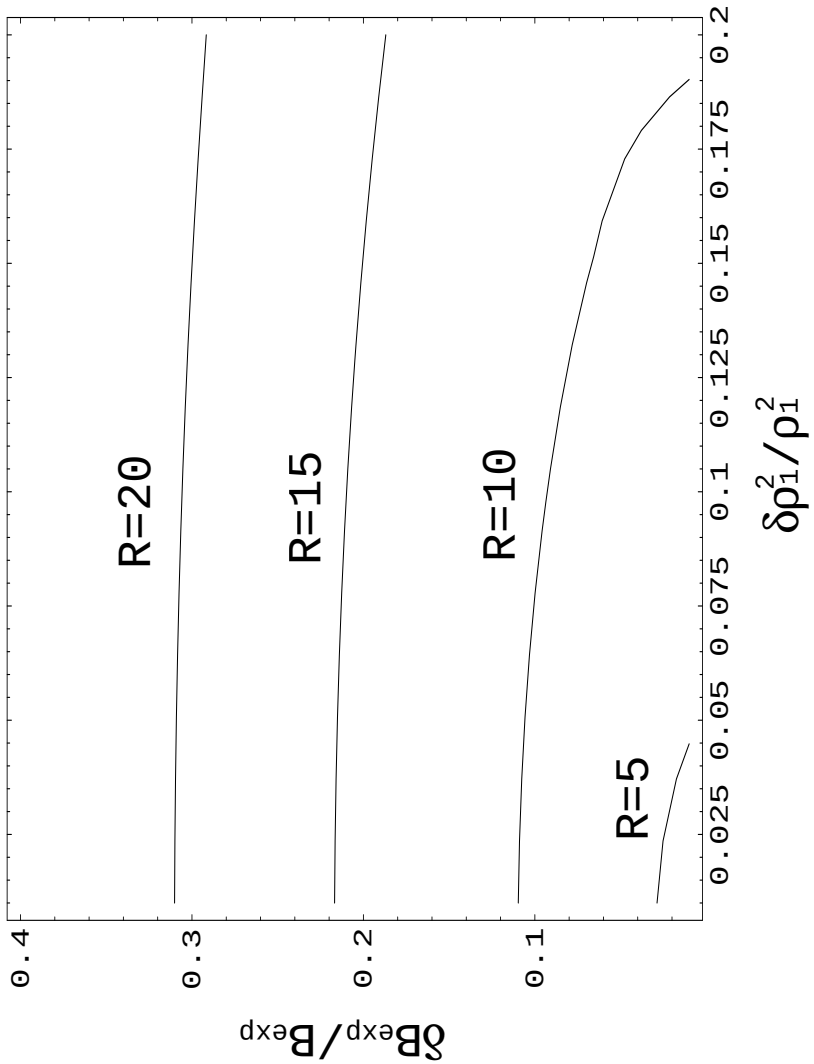
$\delta\rho_1^2/\rho_1^2$: Error in the slope parameter ($\sim 17\%$ at present)

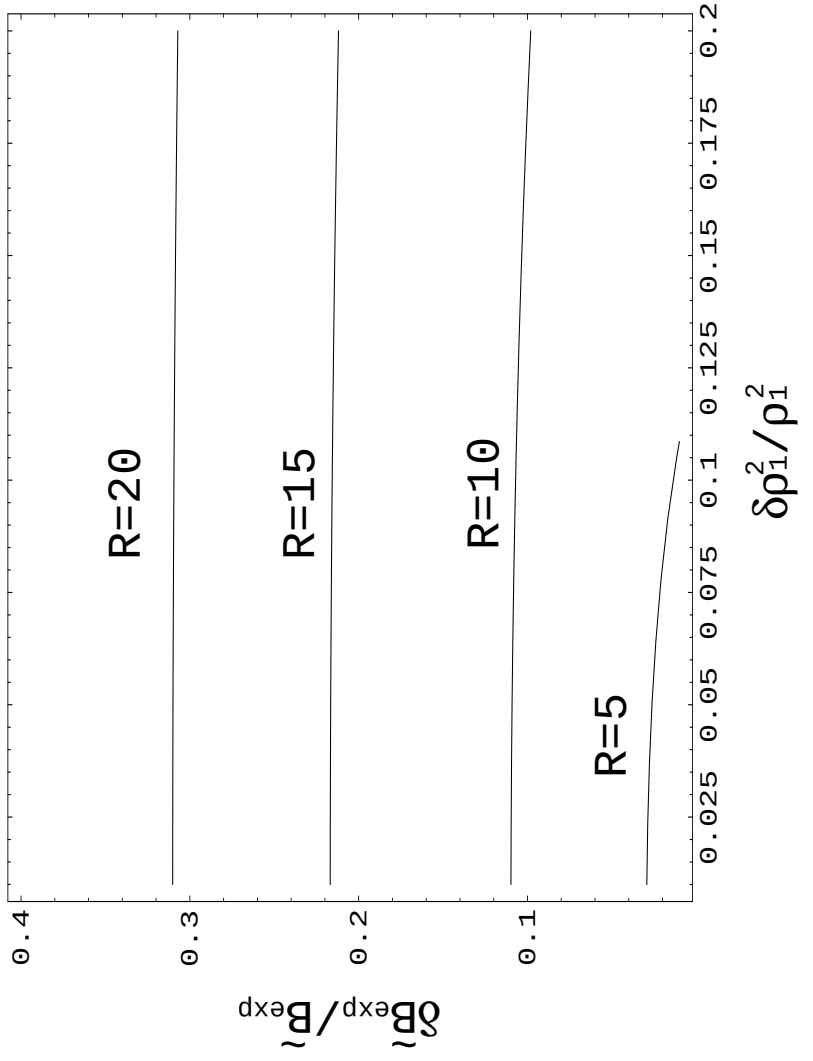
Suppose $B_{\mathrm{exp}} =$ the central value in the standard model.

$\Rightarrow$ An upper bound of allowed R.

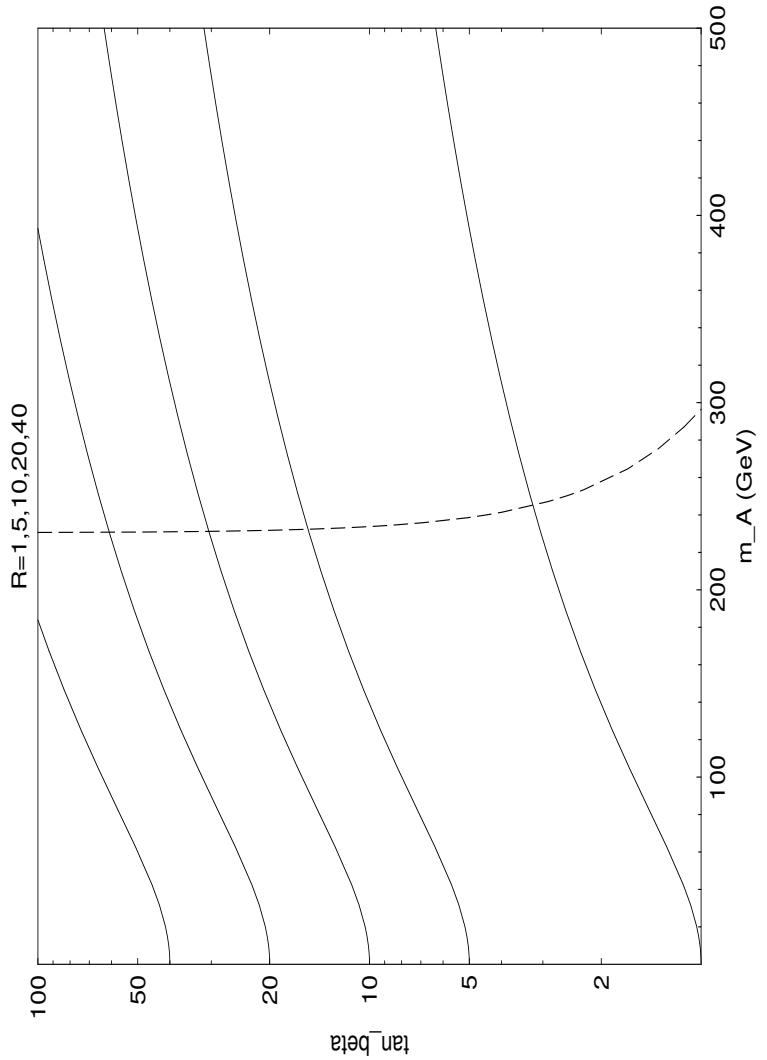
- Comparison with LHC MSSM Higgs search

  Explorable regions in the m_A–$\tan\beta$ plane


R=20
R=15
R=10
R=5
0.4
0.3
0.2
0.1
0.025 0.05 0.075 0.1 0.125 0.15 0.175 0.2
$\delta B_{exp}/B_{exp}$
$\delta\rho_1^2/\rho_1^2$


R=20
R=15
R=10
R=5
0.4
0.3
0.2
0.1
0.025 0.05 0.075 0.1 0.125 0.15 0.175 0.2
$\delta\tilde{B}_{exp}/\tilde{B}_{exp}$
$\delta\rho_1^2/\rho_1^2$

$$m_{H^\pm}^2 = m_W^2 + m_A^2 , \quad R = \frac{m_W}{m_{H^\pm}} \tan\beta$$

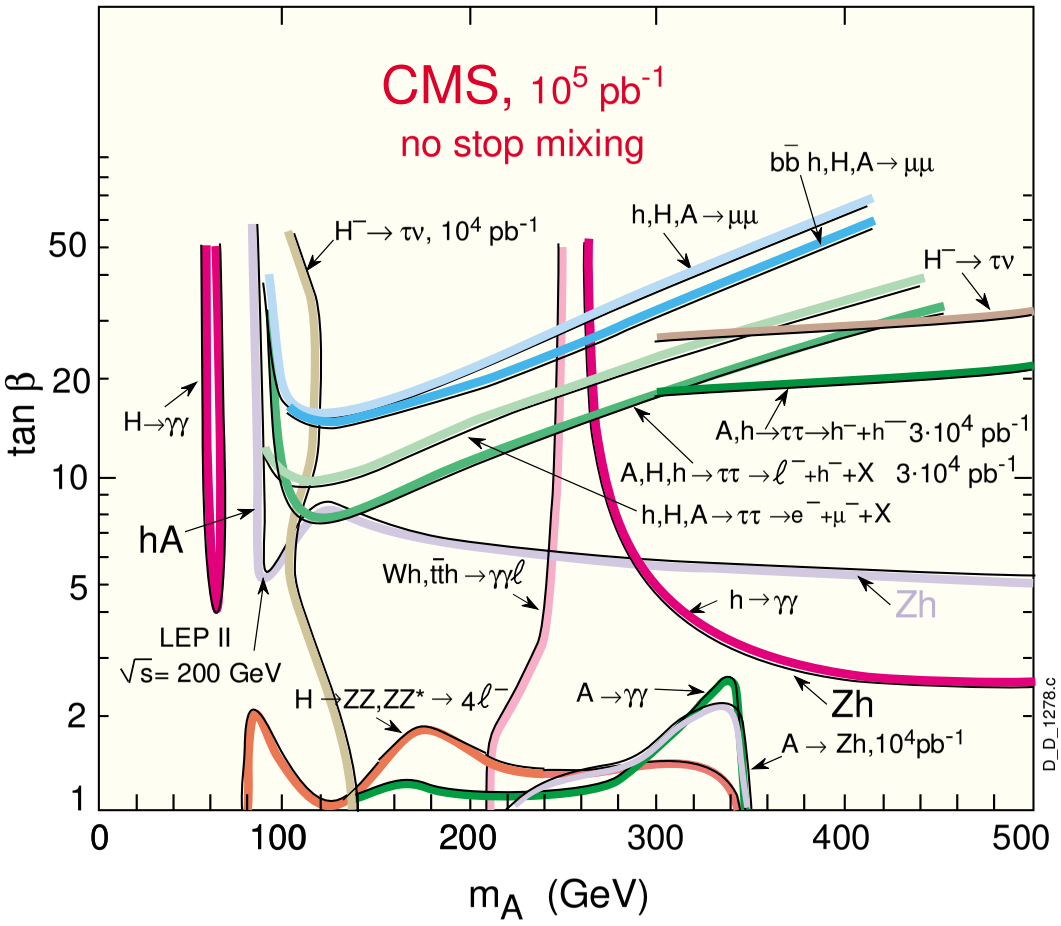


Taken from http://cmsinfo.cern.ch/

Significance contours for SUSY Higgses

Regions of the MSSM parameter space (m_A, tgβ) explorable through various SUSY Higgs channels

- 5 σ significance contours
- two-loop / RGE-improved radiative corrections
- m_{top} = 175 GeV, m_{SUSY} = 1 TeV



6. Conclusion

$\bar{B} \to D\tau\bar{\nu}_\tau$ is a sensitive probe of the MSSM Higgs sector, especially in large $\tan\beta$ case.

The major theoretical uncertainties are in the hadronic form factors.

One of the two relevant form factors (ξ_+) can be determined by $\bar{B} \to D^{(*)} l\bar{\nu}_l$ ($l = e, \mu$). The other form factor (ξ_-) vanishes in the heavy quark limit.

These form factor issues are subject to future experimental and theoretical studies.

NLO QCD correction, $1/m_Q$ correction, q^2 distribution and τ polarization are under study. (T. Miki, T. Miura, M.T.)