$\bar{B} \to D^{(*)}\tau\bar{\nu}_\tau$ as a probe of a charged Higgs boson

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Based on ZPC 67, 321 (1995)

1. Introduction

Why charged Higgs?

◇ Multi-Higgs-doublet extensions of the Standard Model
# of Higgs doublets ≥ 2 $\rightarrow$ charged Higgs boson(s)

◇ The Minimal Supersymmetric Standard Model is the most poplular model of this kind.

$$N_H = 2 \leftarrow \begin{cases} \text{anomaly cancellation} \\ \text{fermions masses} \end{cases}$$

- Models of CP violation in the scalar sector
$N_H \geq 3$ if NFC is assumed.

Search for a charged Higgs boson

- Direct search: $e^+e^- \to H^+H^- \quad \Longrightarrow \quad m_H \gtrsim 80.5\mathrm{GeV}$
- Indirect search: $b \to s\gamma \quad \Longrightarrow \quad m_H \gtrsim 389\,\mathrm{GeV}$

  in Model II of the two-Higgs-doublet model (MSSM like).

  BUT, in SUSY models, SUSY particle contributions may cancel the charged Higgs contribution.

  $\Rightarrow$ A lighter charged Higgs is possible.

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: propotional to mass

Heavier system $\to$ larger effects

$$\bar{K} \to \pi\mu\bar{\nu} \qquad \sim \quad m_s m_\mu$$

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

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

◇ B factory

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

10^{35} B factory $\Rightarrow$ More events.

2. Observables

$\bar{B} \to M \tau \bar{\nu}_\tau$ $(M = D, D^*)$

- Decay rates

  tend to suffer from hadronic uncertainties

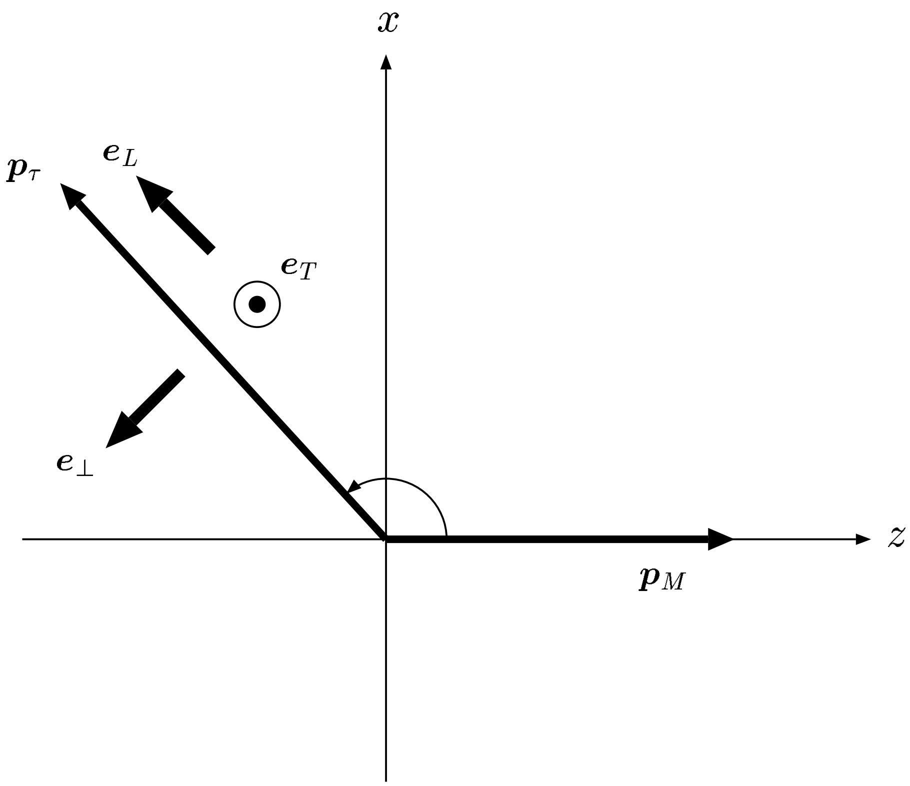
- τ polarizations

  $$\mathbf{e}_L \equiv \frac{\mathbf{p}_\tau}{|\mathbf{p}_\tau|},$$ longitudinal

  $$\mathbf{e}_T \equiv \frac{\mathbf{p}_M \times \mathbf{p}_\tau}{|\mathbf{p}_M \times \mathbf{p}_\tau|},$$ transverse (T violating)

  $$\mathbf{e}_\perp \equiv \mathbf{e}_T \times \mathbf{e}_L,$$ perpendicular

Decay plane


x
$\boldsymbol{p}_\tau$
$\boldsymbol{e}_L$
$\boldsymbol{e}_T$
$\boldsymbol{e}_\perp$
z
$\boldsymbol{p}_M$

3. Charged Higgs couplings to fermions in MHDM

Charged Higgs couplings to fermions in N-Higgs-doublet model

$$\mathcal{L}_H = (2\sqrt{2}G_F)^{1/2} \sum_{i=1}^{N-1} [X_i \overline{u}_L V_{KM} M_d d_R + Y_i \overline{u}_R M_u V_{KM} d_L$$
$$+ Z_i \overline{\nu}_L M_l l_R \quad] H_i^+ + \text{h.c.}$$

M's$=$ Diagonal fermion mass matrices

In the Model II of the two-Higgs-doublet model (MSSM),

$$X_1 = Z_1 = \tan\beta (\equiv \frac{v_2}{v_1}), \ Y_1 = \cot\beta$$

4. $\bar{B} \to M\tau\bar{\nu}_\tau$ in MHDM

4.1 Helicity amplitudes

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

$$\mathcal{M}^{\lambda_\tau}_{\lambda_M}(q^2, x)_W = \frac{G_F}{\sqrt{2}} V_{cb} \sum_{\lambda_W} \eta_{\lambda_W} L^{\lambda_\tau}_{\lambda_W} H^{\lambda_M}_{\lambda_W}$$

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

$$\lambda_\tau = \pm 1 : \quad \tau \text{ helicity} , \quad \lambda_M = \begin{cases} s & \text{for } D \text{ meson,} \\ \pm 1,\ 0 & \text{for } D^* \text{ meson,} \end{cases}$$

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

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

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

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

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

$\diamond$ $H^{\pm}$ exchange

$$\mathcal{M}^{\lambda_\tau}_{\lambda_M}(q^2, x)_H = \frac{G_F}{\sqrt{2}} V_{cb} L^{\lambda_\tau} \times \sum_i \left[X_i Z_i^* \frac{m_b m_\tau}{M^2_{H_i}} H^{\lambda_M}_R + Y_i Z_i^* \frac{m_c m_\tau}{M^2_{H_i}} H^{\lambda_M}_L \right]$$

$$H^{\lambda_M}_{R,L}(q^2) \equiv \langle M(p_M, \lambda_M) | \bar{c}(1 \pm \gamma_5) b | \bar{B}(p_B) \rangle$$

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

$H^{\lambda_M}_{R,L}$ and L^{λ_τ} can be written in terms of $H^{\lambda_M}_{\lambda_W}$ and $L^{\lambda_\tau}_{\lambda_W}$:

$$H^s_{R,L} = \frac{\sqrt{q^2}}{m_b - m_c} H^s_s \ , \quad H^{\pm}_R = 0 \ , \quad H^0_R = \frac{\sqrt{q^2}}{m_b + m_c} H^0_s \ ,$$

$$H^{\pm,0}_L = -H^{\pm,0}_R \ , \quad L^{\lambda_\tau} = \frac{\sqrt{q^2}}{m_\tau} L^{\lambda_\tau}_s \, .$$

Charged Higgs contributes only to $\lambda_M = s, 0$,

i.e. D and D^*_L (not D^*_T).

$\Rightarrow$ Dilution of signal in the inclusive study.

4.2 Decay rate

$$d\Gamma_{\lambda_M} = \frac{1}{2m_B} \sum_{\lambda_\tau} |\mathcal{M}_{\lambda_M}^{\lambda_\tau}|^2 d\Phi_3$$

$$\mathcal{M}_{\lambda_M}^{\lambda_\tau} = \mathcal{M}_{\lambda_M}^{\lambda_\tau}(q^2, x)_W + \mathcal{M}_{\lambda_M}^{\lambda_\tau}(q^2, x)_H$$

$d\Phi_3 =$ three body phase space

4.3 τ polarizations

$$d\Gamma_{\lambda_M}(\mathbf{s}) = \frac{1}{2}\left[d\Gamma_{\lambda_M} + (d\Gamma^L_{\lambda_M}\mathbf{e}_L + d\Gamma^\perp_{\lambda_M}\mathbf{e}_\perp + d\Gamma^T_{\lambda_M}\mathbf{e}_T)\cdot\mathbf{s}\right]$$

$$d\Gamma^L_{\lambda_M} = \frac{1}{2m_B}\left(|\mathcal{M}^+_{\lambda_M}|^2 - |\mathcal{M}^-_{\lambda_M}|^2\right) d\Phi_3$$

$$d\Gamma^\perp_{\lambda_M} = \frac{1}{m_B}\mathrm{Re}\left(\mathcal{M}^{+*}_{\lambda_M}\mathcal{M}^-_{\lambda_M}\right) d\Phi_3$$

$$d\Gamma^T_{\lambda_M} = \frac{1}{m_B}\mathrm{Im}\left(\mathcal{M}^{+*}_{\lambda_M}\mathcal{M}^-_{\lambda_M}\right) d\Phi_3$$

$$P_L = \frac{d\Gamma^L}{d\Gamma},\quad P_\perp = \frac{d\Gamma^\perp}{d\Gamma},\quad P_T = \frac{d\Gamma^T}{d\Gamma}$$

Note

1. $P_L^2 + P_\perp^2 + P_T^2 = 1$ at an arbitrary point in the phase space.
2. P_L and $P_\perp$ depend on the frame in which the τ helicity is defined.
3. P_T is independent of the frame.

4.4 Comparison between the D mode and the D_L^* mode

	$\bar{B} \to DW^*$	$\bar{B} \to DH^*$	$\bar{B} \to D_L^* W^*$	$\bar{B} \to D_L^* H^*$
$L=0$	H_s^s	H_s^s	H_0^0	
$L=1$	H_0^s		H_s^0	H_s^0

$$H_0^s,\ H_s^0 \quad \propto \quad \sqrt{(m_B - m_M)^2 - q^2}$$

$$\longrightarrow \quad 0 \qquad \text{as} \quad q^2 \to q^2_{max} = (m_B - m_M)^2$$

$\boxed{D \text{ is more sensitive than } D_L^*.}$

5. Hadronic form factors

5.1 Heavy quark limit (and LLA)

All form factors are proportional to a universal form factor $\xi(y)$.

$$H_{\lambda_W}^{\lambda_M}(q^2) \propto \xi(y)\,, \quad y \equiv v \cdot v' = (m_B^2 + m_M^2 - q^2)/2m_B m_M$$

Assuming

$$\xi(y) = \left(\frac{2}{y+1}\right)^{2\rho^2},$$

we obtain

$$\rho = 1.08 \pm 0.11$$

from the experimental data of CLEO. (1.21 ± 0.10, CLEO2001)

Range of ρ $\Rightarrow$ theoretical uncertainty

5.2 $1/m$ and non-LLA QCD correction

6 form factors: $\xi_+,\ \xi_-,\ \xi_V,\ \xi_{A_1},\ \xi_{A_2},\ \xi_{A_3}$

$$\xi_i(y) = [\alpha_i + \beta_i(y) + \gamma_i(y)]\,\xi(y)$$

$\beta_i(y)$: QCD corrections , $\gamma_i(y)$: $1/m$ corrections

$$\alpha_+ = \alpha_V = \alpha_{A_1} = \alpha_{A_3} = 1,\ \alpha_- = \alpha_{A_2} = 0$$

$\beta_i(y)$: full 1-loop correction

Neubert

$\gamma_i(y)$: QCD sum rule

We obtain

$$\rho = 1.23 \pm 0.09$$

6. Numerical results

In Model II of the two-Higgs-doublet model,

$$X_1 Z_1^* = \tan^2\beta, \quad Y_1 Z_1^* = 1$$

Rates have larger theoretical uncertainties.

The uncertainties in P_L's are smaller.

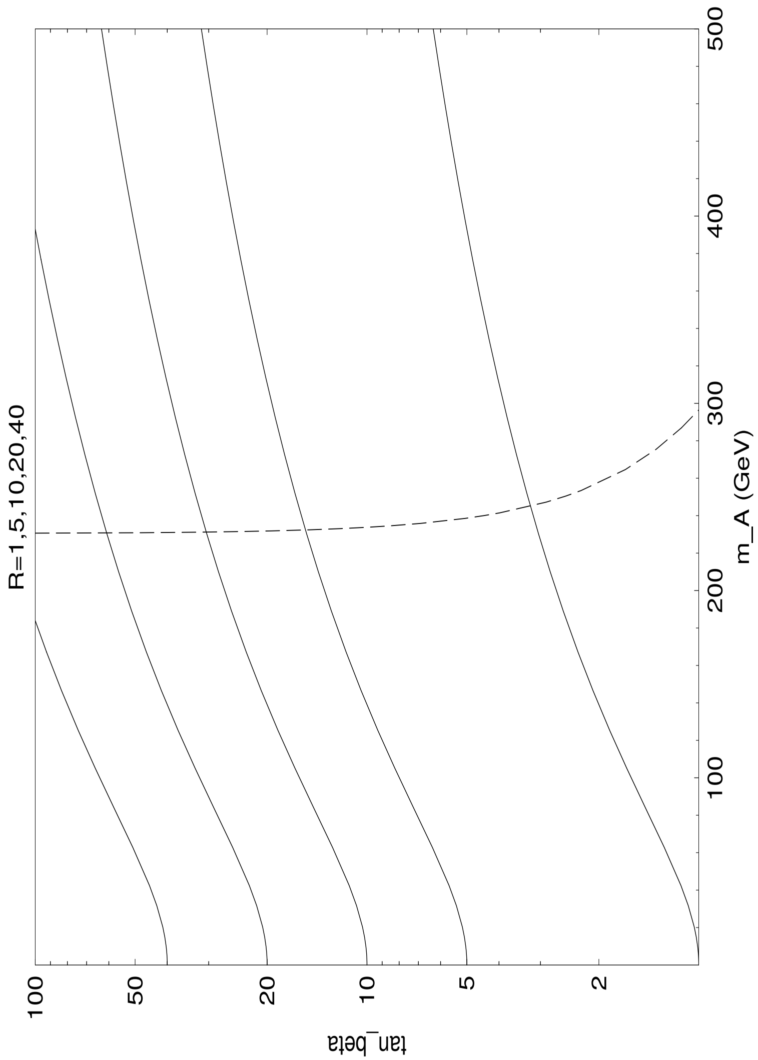
Theoretical reach: $R \equiv \frac{m_W}{m_H} \tan\beta$

$$R \sim 6(32) \quad \Leftarrow \quad \text{Rate measurement}$$

$$R \sim 4.5(20) \quad \Leftarrow \quad P_L \text{ measurment}$$

( ) = inclusive analysis by Grossman and Ligeti

Present bound: $R \lesssim 40$ from the inclusive branching ratio

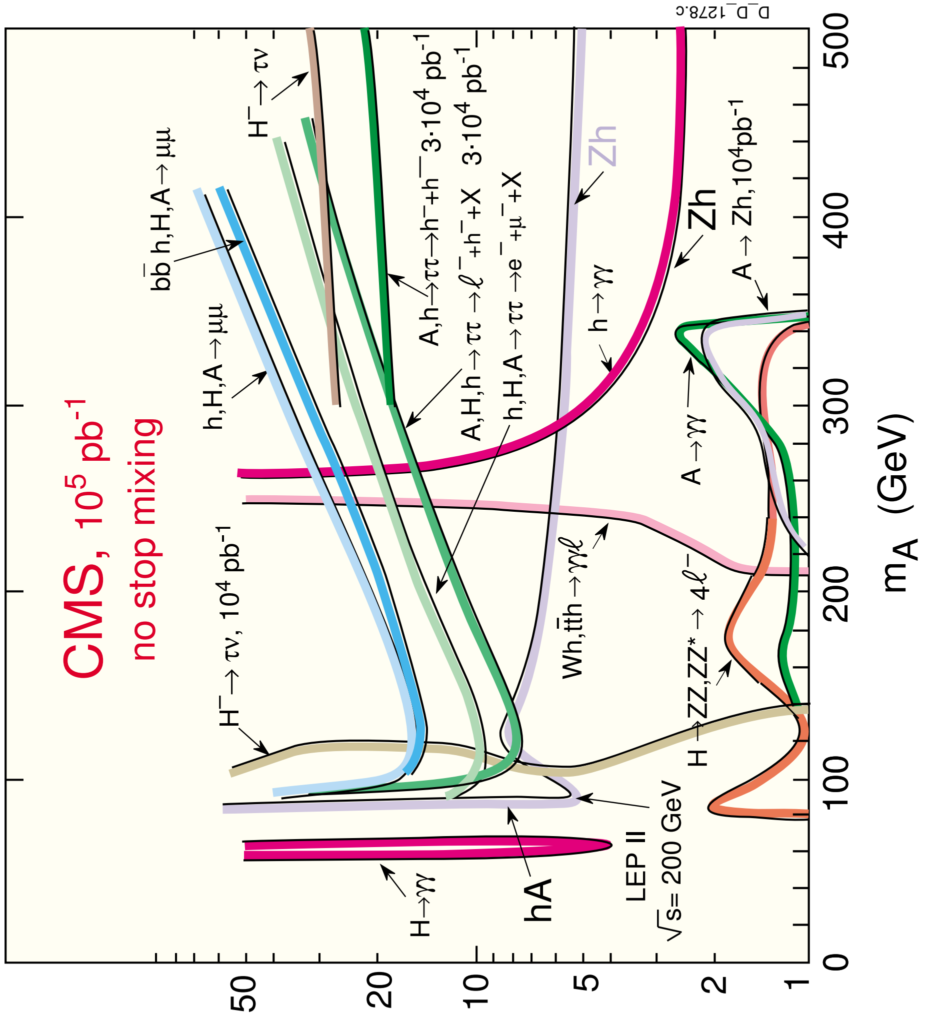

R=1,5,10,20,40
m_A (GeV)
100
200
300
400
500
tan_beta
100
50
20
10
5
2

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

Significance contours for SUSY Higgses

Regions of the MSSM parameter space $(m_A, tg\beta)$ explorable through various SUSY Higgs channels

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



7. Conclusion

The branching ratio and the τ polarizations of $\bar{B} \to D\tau\bar{\nu}_\tau$ are sensitive probes of the MSSM-like Higgs sector.

The major theoretical uncertainties are those in the hadronic form factors.

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

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