Charged-Higgs effects in $B \to D\tau\nu$

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Charged Higgs boson search

Extension of the standard-model Higgs sector:

Two-Higgs-Doublet Model (2HDM)

- five physical Higgs bosons: neutral h^0, H^0, A^0 and charged $H^\pm$
- two parameters $\tan\beta = v_u/v_d$ and m_H at tree level

Direct $H^\pm$ search: colliders (LHC)

dominant $H^\pm$ production for

$$m_H < m_t:\ gg \to t\bar{t}[\to \bar{b}H^-][\to \tau\bar{\nu}]$$

$$m_H > m_t:\ gg \to t\bar{b}H^-$$
$$gb \to tH^-$$

- difficult for small H^- couplings ($\tan\beta \sim 10$)

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$[\to \tau\bar{\nu}]$

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$gb \to tH^-$

- difficult for small H^- couplings ($\tan\beta \sim 10$)

Indirect search: flavour (B factories)

$H^\pm$ contribute to weak transitions

at tree level:

(semi-)leptonic $B \to (D)\tau\nu$

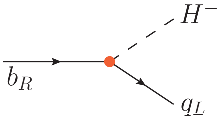
at loop level:

$B \to X_s\gamma$, ΔM_s, ...

- complementary access to H^- couplings

Charged-Higgs couplings

H^- couplings to down-type fermions

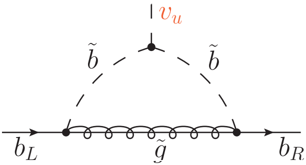


in a 2HDM type II:

$$\mathcal{L}_{H\bar{f}f'} \supset \frac{g_2}{\sqrt{2}} \frac{m_b}{m_W} \tan\beta\, V_{qb}^* \, \bar{b}_R q_L H^- + \frac{g_2}{\sqrt{2}} \frac{m_\tau}{m_W} \tan\beta\, \bar{\tau}_R \nu_L H^-$$

in the MSSM:

$$\mathcal{L}_{H\bar{b}q} = \frac{g_2}{\sqrt{2}} \frac{m_b}{m_W} \frac{\tan\beta}{1+\epsilon_b \tan\beta} V_{qb}^* \, \bar{b}_R \, q_L H^-$$

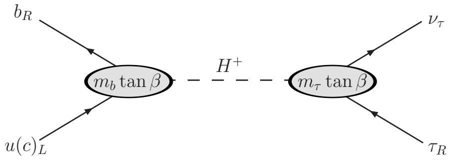


Large $\tan\beta$:

- enhanced H^- couplings to b quarks and τ leptons
- $|\epsilon_b| \tan\beta$ of $\mathcal{O}(1)$, possibly complex

Charged Higgs in (semi-)leptonic B decays

- Branching ratios $\mathcal{B}(B \to (D)\tau\nu)$
- Theoretical limitations:
  decay constant, form factors
- $B \to D\tau\nu$
  differential distributions
- Prospects for SuperB



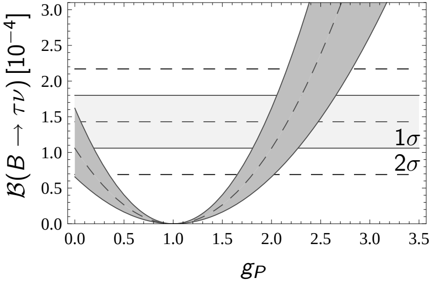
Effective Hamiltonian for $bu \to \tau\nu$ and $b \to c\tau\nu$ transitions ($q = u, c$)

$$\mathcal{H}^{\text{eff}} = 2\sqrt{2}\, G_F\, V_{qb}\Big\{(\overline{b}_L\, \gamma^\mu\, q_L)\,(\overline{\nu}_L\, \gamma_\mu\, \tau_L) - \frac{m_b m_\tau}{m_B^2}\,(\overline{b}_R\,[g_S + g_P\gamma_5]\, q_L)\,(\overline{\nu}_L\, \tau_R)\Big\}$$

$$\text{MSSM}: \quad g_S = g_P \equiv \frac{m_B^2}{m_H^2}\, \frac{\tan^2\beta}{(1+\epsilon_b \tan\beta)(1+\epsilon_\tau \tan\beta)}$$

Branching ratio $\mathcal{B}(B \to \tau\nu)$

$$\mathcal{B}(B \to \tau\nu) = \frac{G_F^2}{8\pi}\tau_B |V_{ub}|^2 f_B^2\, m_B\, m_\tau^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 |1 - g_P|^2$$



$\mathcal{B}(B \to \tau\nu)^{\rm exp} = (1.43 \pm 0.37) \cdot 10^{-4}$

[HFAG '09]

$|V_{ub}| = (3.87 \pm 0.09 \pm 0.46) \cdot 10^{-3}$

[CKMfitter '09]

$f_B = (200 \pm 20)$MeV

[Lubicz,Tarantino '08]

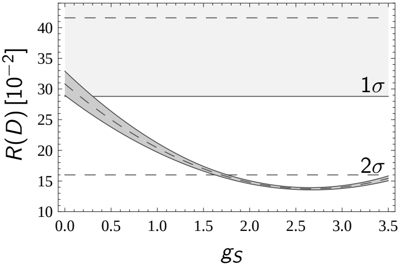
$g_P < 0.34 \;\cup\; 1.66 < g_P < 2.81$ @95% CL

- alternative standard-model prediction of $\mathcal{B}(B \to \tau\nu)$ from UT fit

[UTfit '09 → M. Ciuchini's talk, thursday]

Branching ratio $\mathcal{B}(B \to D\tau\nu)$

$$R(D) \equiv \frac{\mathcal{B}(B \to D\tau\nu)}{\mathcal{B}(B \to D\ell\nu)} = f(F_S/F_V, g_S), \qquad \ell = e, \mu$$



$$R(D)^{\text{exp}} = (41.6 \pm 11.7 \pm 5.2) \cdot 10^{-2}$$

[BaBar '09]

$$|V_{cb}| = (41.6 \pm 0.6) \cdot 10^{-3}$$

[PDG '08]

$$\delta|V_{cb}|F_V = 3.5\%,\ \delta|V_{cb}|F_S = 6.4\%$$

$$g_S < 1.66 \ \cup \ 3.63 < g_S \qquad @95\%\,\text{CL}$$

$R(D)$ is less sensitive to $H^{\pm}$ than $\mathcal{B}(B \to \tau\nu)$, but

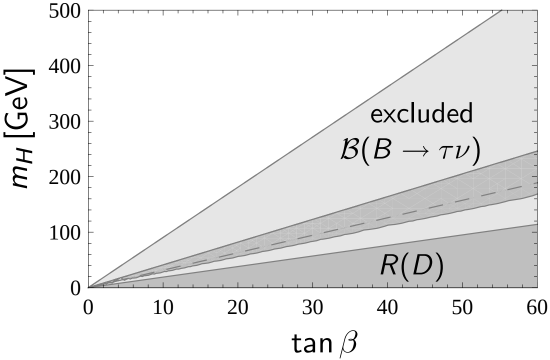
- inputs V_{cb} and F_V, F_S are known to better precision
- $\mathcal{B}(B \to D\tau\nu) \approx 50 \cdot \mathcal{B}(B \to \tau\nu)$ (SM)

Constraints on $\tan\beta - m_H$

Combined constraints from $\mathcal{B}(B \to \tau\nu)$ and $R(D)$

$g_P = g_S < 0.34$ @95% CL

2HDM II: $g_S = \frac{m_B^2}{m_H^2}\tan^2\beta$



- $m_H \lesssim 120\,\mathrm{GeV}$ excluded by LEP and TeVatron searches

$B \to D$ form factors

$$W^+ : \langle D(p_D)|\bar{c}\,\gamma^\mu b|\bar{B}(p_B)\rangle = F_V(q^2)\big(p_B^\mu + p_D^\mu - \frac{m_B^2 - m_D^2}{q^2} q^\mu\big) + F_S(q^2)\frac{m_B^2 - m_D^2}{q^2} q^\mu; \qquad q = p_B - p_D$$

$$H^+ : \langle D(p_D)|\bar{c}\, b|\bar{B}(p_B)\rangle = \frac{m_B^2 - m_D^2}{m_b - m_c} F_S(q^2) \qquad \boxed{F_S(q^2 = 0) = F_V(0)}$$

Form factors are linear after conformal mapping [Boyd et al. '97, Hill '06, ...]

$$w \to z(w); \qquad w = \frac{E_D}{m_D} = \frac{m_B^2 + m_D^2 - q^2}{2 m_B m_D}$$

Two parameters describe each vector and scalar form factors

$$F_{V,S}(w) = \frac{1}{P(w)\phi(w)}\left[a^0_{V,S} + a^1_{V,S}\, z(w) + \dots\right]; \qquad |z| < 0.032$$

$B \to D$ form factors

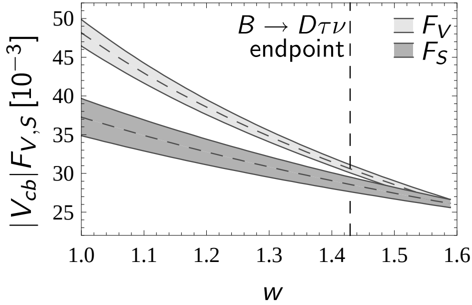
- $|V_{cb}|F_V(w) = |V_{cb}|F_V(a_V^0, a_V^1)$ [BaBar '09, BELLE '02]

  from fit to lepton spectrum $d\Gamma_\ell/dw$ in $B \to D\ell\nu$ ($\ell = e, \mu$).

- $F_S(w) = F_S(a_S^0, a_S^1)$

  from $F_S(q^2 = 0) = F_V(0)$ and Heavy-Quark relation at $w = 1$:

$$\frac{m_B + m_D}{2\sqrt{m_B m_D}} F_S(w = 1) = 1 + \mathcal{O}(\frac{1}{m_{c,b}^2}, \alpha_s) = 1.02 \pm 0.05$$ [using Neubert '92]



$|V_{cb}| = (41.6 \pm 0.6) \cdot 10^{-3}$

[PDG '08]

form factors under control:

$\delta|V_{cb}|F_V(w = 1) = 3.5\%$

$\delta|V_{cb}|F_S(w = 1) = 6.4\%$

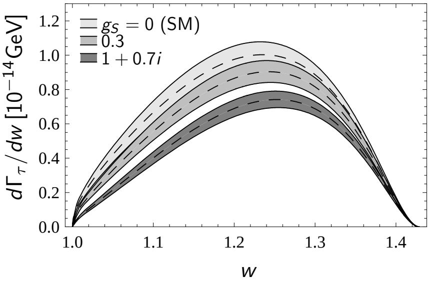
$B \to D\tau\nu$ differential distributions: τ spectrum

Relative q^2 dependence between longitudinal $W_{\parallel}^-$ and H^-:

[Grzadkowski,Hou '92, Kiers,Soni '97]

$$\frac{d\Gamma_\tau(B \to D\tau\nu)}{dw} = \frac{d\Gamma_\ell}{dw}\left\{\bar{\rho}_V(w) + \bar{\rho}_S(w)\left[1 - g_S \frac{q^2/m_B^2}{1 - m_c/m_b}\right]^2 \frac{F_S(w)^2}{F_V(w)^2}\right\}$$

$\to$ determine H^- coupling g_S from shape

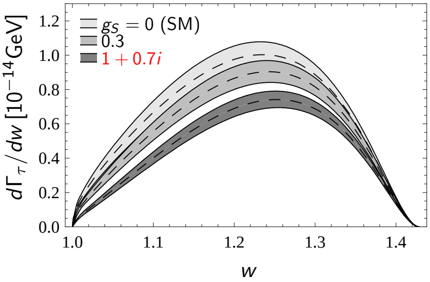


Relative q^2 dependence between longitudinal $W_{\parallel}^{-}$ and H^{-}:

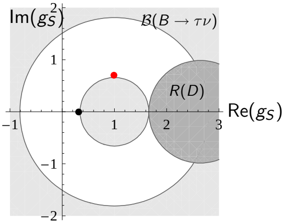
[Grzadkowski,Hou '92, Kiers,Soni '97]

$$\frac{d\Gamma_\tau(B \to D\tau\nu)}{dw} = \frac{d\Gamma_\ell}{dw}\left\{\bar{\rho}_V(w) + \bar{\rho}_S(w)\left[1 - g_S \frac{q^2/m_B^2}{1 - m_c/m_b}\right]^2 \frac{F_S(w)^2}{F_V(w)^2}\right\}$$

$\longrightarrow$ determine H^- coupling g_S from shape



Excluded from branching ratios



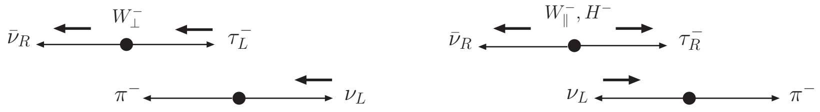
Complex phase of g_S is visible in τ spectrum, not in branching ratios.

$B \to D\tau\nu$ triple differential distribution

Tau polarization distinguishes $W_\perp^-$ (τ_L) from $W_\parallel^-, H^-$ (τ_R).

- not directly accessible at B factories: $\tau \to \ell\bar{\nu}_\ell\nu_\tau,\ \tau \to \pi\nu_\tau, \ldots$
- decay chain $B \to D\bar{\nu}_\tau\tau[\to \pi\nu_\tau]$:

  τ polarization correlated with π momentum



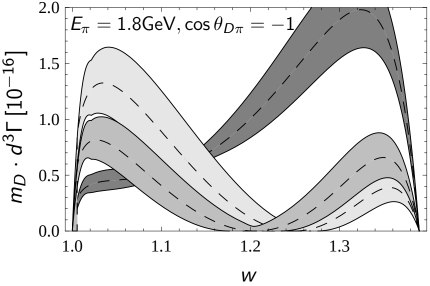
Triple differential distribution: combines q^2 dependence and τ polarization

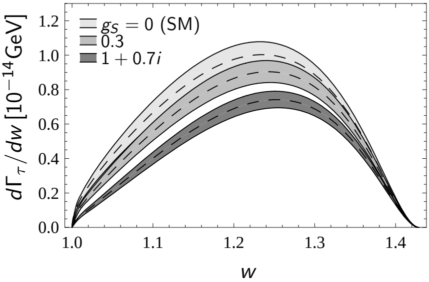
[Nierste,Trine,Westhoff '08]

$$\frac{d^3\Gamma(\bar{B} \to D\bar{\nu}_\tau\tau^-[\to \pi^-\nu_\tau])}{dE_D\, dE_\pi\, d\cos\theta_{D\pi}} =$$

$$G_F^4 f_\pi^2 |V_{ud}|^2 |V_{cb}|^2 \tau_\tau \left[C_W(F_V, F_S) - C_{WH}(F_V, F_S)\mathrm{Re}(g_S) + C_H(F_S)|g_S|^2\right]$$

Triple differential distribution versus τ spectrum





- increased sensitivity to small coupling $|g_S|$ and to phase $\arg(g_S)$
- theoretical precision limited
  by Heavy-Quark corrections to the scalar form factor $F_S(w = 1)$
- possible improvement: $\Delta(w) = F_S/F_V$ from lattice calculations;
  status: $\Delta(w) = 0.46(1)$ for $w \in [1, 1.2]$ (quenched) [de Divitiis et al. '07]
  [Kamenik,Mescia '08]

SuperB prospects for $B \to D\tau\nu$ and summary

- $B \to D\tau\nu$ differential distributions are sensitive to the magnitude and phase of a charged-Higgs coupling g_S.
- At today's B factories one is statistically limited to (at best) a fit of the τ spectrum.
- SuperB would provide enough data to fit differential distributions.
- Need simultaneous progress in form factor precision, e.g. improved lattice calculations of F_S/F_V.

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