Charged Higgs Bosons in $B \to D\tau\nu$: Differential Distributions

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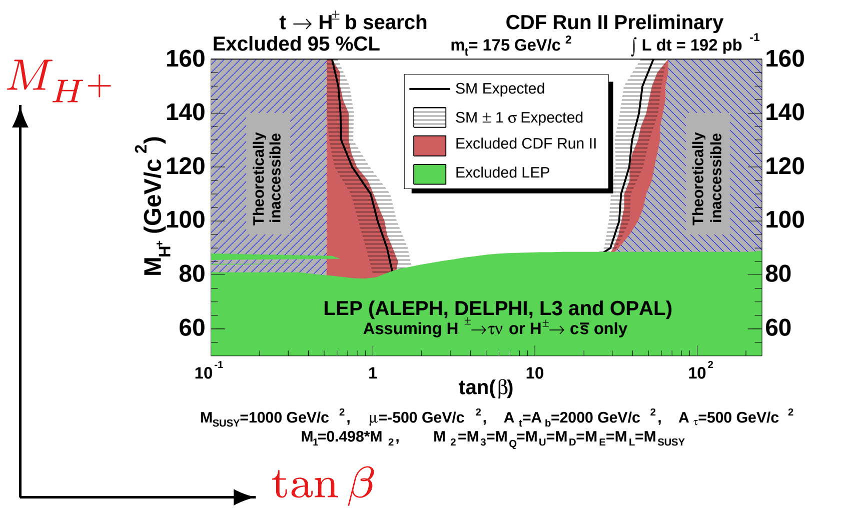
Search for Charged Higgs Bosons

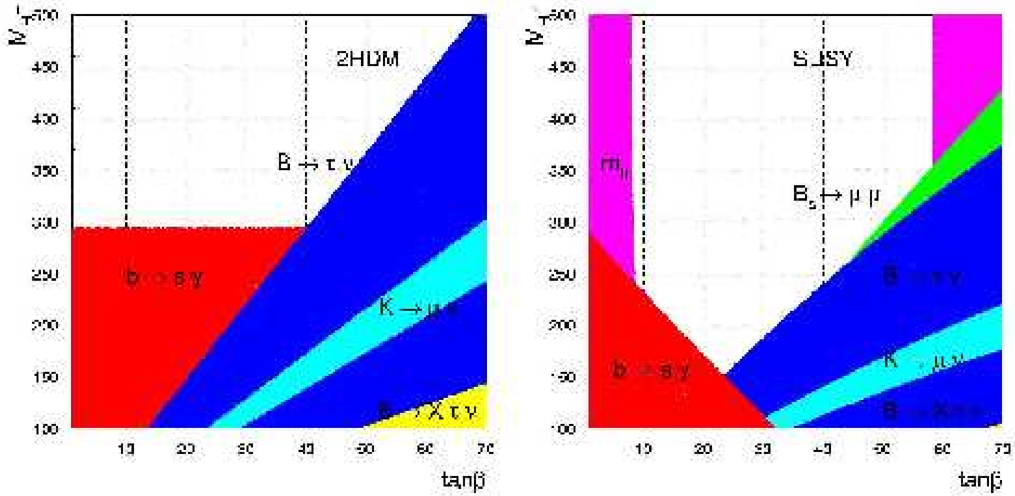
$\boxed{H^+}$...

- H^+ occurs in any 2-Higgs-Doublet Model (2HDM).
- 2 parameters $\tan\beta = v_u/v_d$ and M_{H^+}.
- 5 Higgs bosons $h^0, H^0, A^0, H^{\pm}$.
- Charged-Higgs effects at tree level.

Constraints on $\tan\beta/M_{H^+}$ from flavour and collider physics



[CDF, LEP]

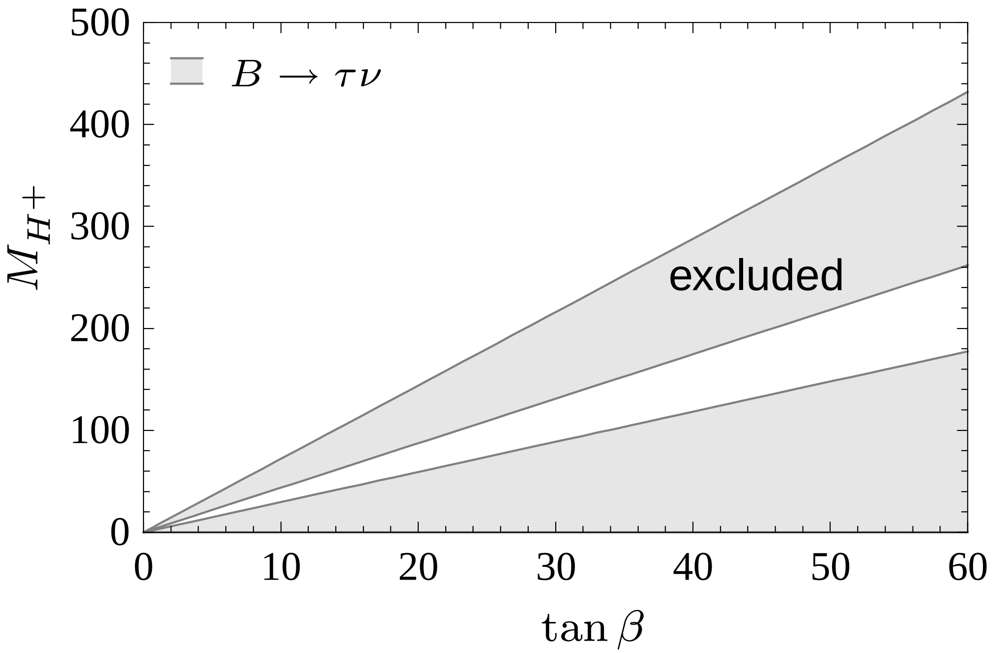


[Paradisi et al. ’08]

Constraints from Leptonic Meson Decays: $B \to \tau\nu$

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

excluded at 95% C.L.



- $\mathcal{B}^{\text{exp}}(B \to \tau\nu) = (1.41 \pm 0.43) \cdot 10^{-4}$

  [combined BELLE '06 and BaBar '07]

  $f_B = 216 \pm 38$ MeV [HPQCD '05]

$D_s \to \tau\nu$

$$\mathcal{B}(D_s \to \tau\nu) = \frac{G_F^2}{8\pi}\tau_{D_s}|V_{cs}|^2 f_{D_s}^2\, m_{D_s}\, m_\tau^2 \left(1 - \frac{m_\tau^2}{m_{D_s}^2}\right)^2 \left|1 - m_{D_s}^2 \frac{\tan^2\beta}{M_{H^+}^2}\frac{m_s}{m_c + m_s}\right|^2$$

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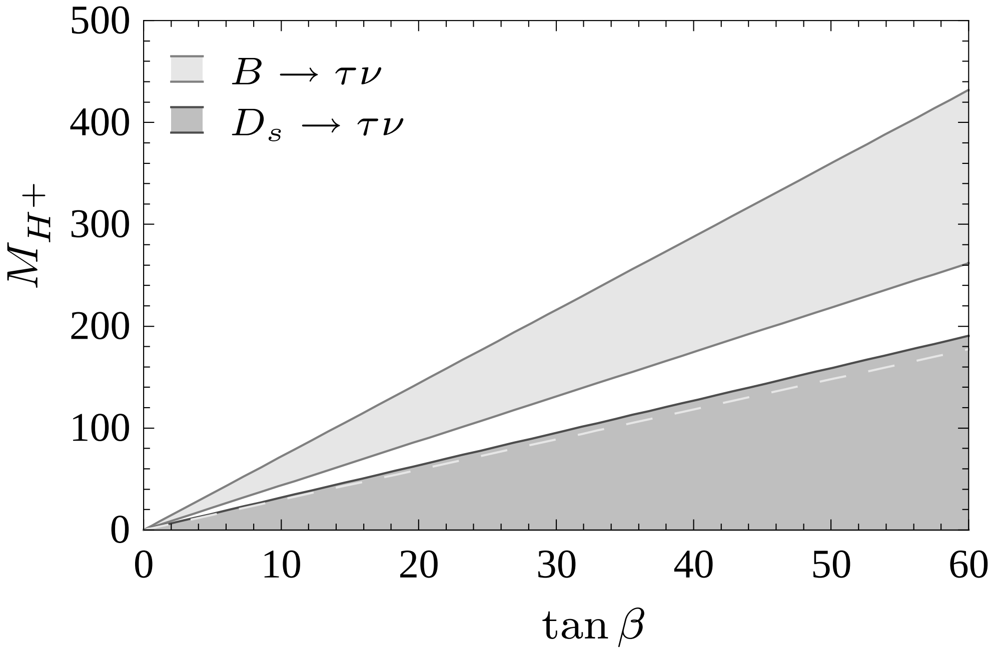

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- $\mathcal{B}^{\text{exp}}(D_s \to \tau\nu) = (6.17 \pm 0.71 \pm 0.34) \cdot 10^{-2}$

  [CLEO '08]

  $f_{D_s} = 241 \pm 3$ MeV **[HPQCD '08]**

$K \to \mu\nu$

$$\mathcal{B}(K \to \mu\nu) = \frac{G_F^2}{8\pi}\tau_K |V_{us}|^2 f_K^2\, m_K\, m_\mu^2 \left(1 - \frac{m_\mu^2}{m_K^2}\right)^2 \left|1 - m_K^2 \frac{\tan^2\beta}{M_{H^+}^2}\right|^2$$

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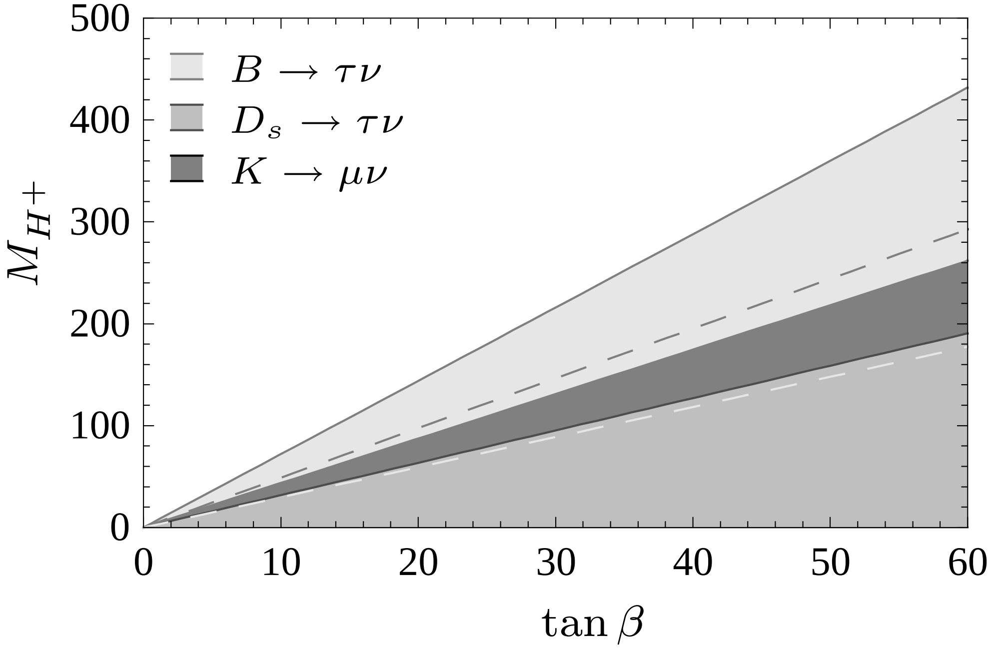

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- $R_{l23} = \frac{V_{us}(K_{l2})}{V_{us}(K_{l3})} \frac{V_{ud}(0^+ \to 0^+)}{V_{ud}(\pi_{l2})} = 1.004 \pm 0.007$ [FlaviaNet WG '08]

  $f_K / f_\pi = 1.189 \pm 0.007$ [HPQCD '08]

Constraints from Leptonic Meson Decays

$$\mathcal{B}(M_{ij} \to l\nu) = \frac{G_F^2}{8\pi} \tau_M |V_{u_i d_j}|^2 f_M^2 \, m_M \, m_l^2 \left(1 - \frac{m_l^2}{m_M^2}\right)^2 \left|1 - m_M^2 \frac{\tan^2\beta}{M_{H^+}^2} \frac{m_{d_j}}{m_{u_i} + m_{d_j}}\right|^2$$

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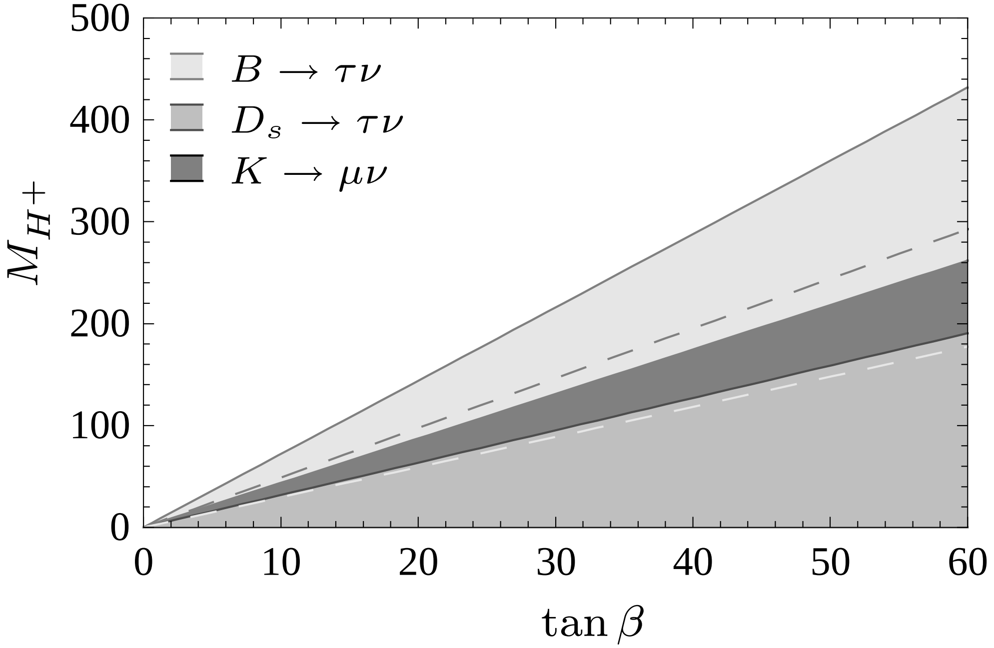

- $B \to \tau\nu$

  $r_B = m_B^2 \frac{\tan^2\beta}{M_{H^+}^2}$

- $D_s \to \tau\nu$

  $r_{D_s} = m_{D_s}^2 \frac{\tan^2\beta}{M_{H^+}^2} \frac{m_s}{m_c + m_s} = 0.002\, r_B$

- $K \to \mu\nu$

  $r_K = m_K^2 \frac{\tan^2\beta}{M_{H^+}^2} = 0.009\, r_B$

Higgs-Fermion Couplings in the 2HDM

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 + v_u \end{pmatrix}; \quad H_d = \begin{pmatrix} H_d^0 + v_d \\ H_d^- \end{pmatrix}; \qquad \tan\beta = \frac{v_u}{v_d}; \quad v = \sqrt{v_u^2 + v_d^2} = 174\,\text{GeV}$$

- 2HDM type II: U and D, E couple separately to H_u and H_d

$$\mathcal{L}_{H\bar{f}f'} = \bar{U} Y_u Q H_u + \bar{D} Y_d Q H_d + \bar{E} Y_e L H_d$$

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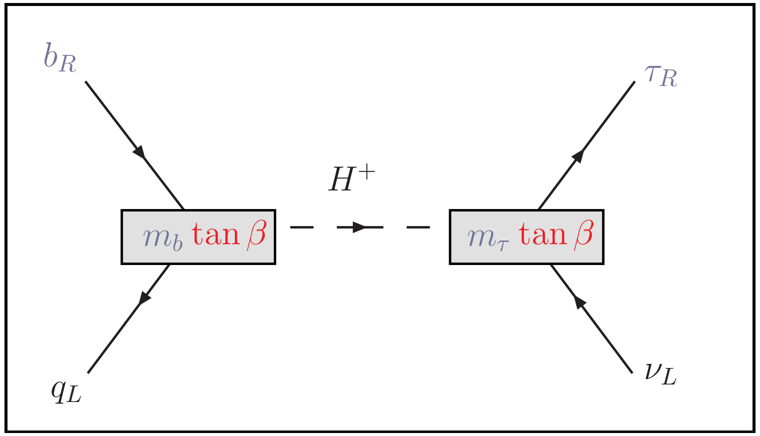
- Higgs mass eigenstates

$$\begin{pmatrix} H_u^{+*} \\ H_d^- \end{pmatrix} = \begin{pmatrix} \sin\beta & \cos\beta \\ -\cos\beta & \sin\beta \end{pmatrix} \begin{pmatrix} G^- \\ H^- \end{pmatrix}$$

- Large $\tan\beta$: enhanced couplings



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

H^+ Couplings in the MSSM with Large $\tan\beta$

$$\mathcal{L}_{H\bar{d}q} \supset \bar{D} Y_d Q H_d + \bar{D}(Y_d \epsilon_u) Q H_u^c$$

$$\epsilon_u = \epsilon_0 + \epsilon_Y Y_u^\dagger Y_u$$

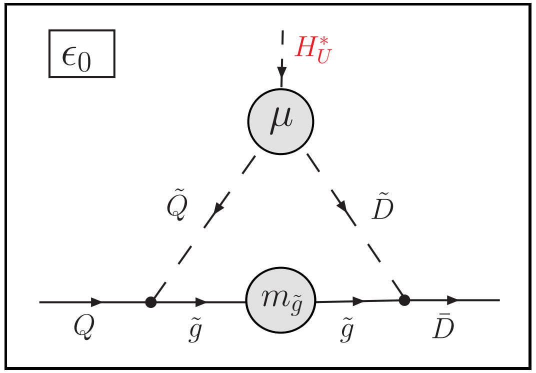
(minimal flavour violation, universal squark masses)

$\tan\beta$–enhanced H^+ couplings to b_R

2HDM type II: $$\frac{g_2}{\sqrt{2}} \frac{m_b}{M_W} \tan\beta \, V_{qb}^* \, \bar{b}_R \, q_L \, H^-$$

MSSM: $$\frac{g_2}{\sqrt{2}} \frac{m_b}{M_W} \frac{\tan\beta}{1 + \epsilon_0 \tan\beta} V_{qb}^* \, \bar{b}_R \, q_L \, H^-$$

Large $\tan\beta$: $|\epsilon_0| \tan\beta \approx \mathcal{O}(1)$



[Hall et al. ’94] [Blazek et al. ’95]

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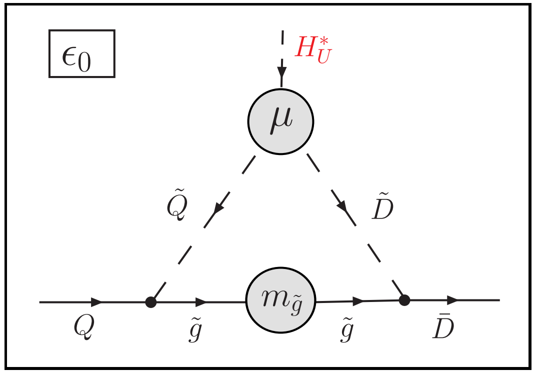


[Hall et al. '94] [Blazek et al. '95]

Large $\tan\beta$: $\quad |\epsilon_0| \tan\beta \approx \mathcal{O}(1)$

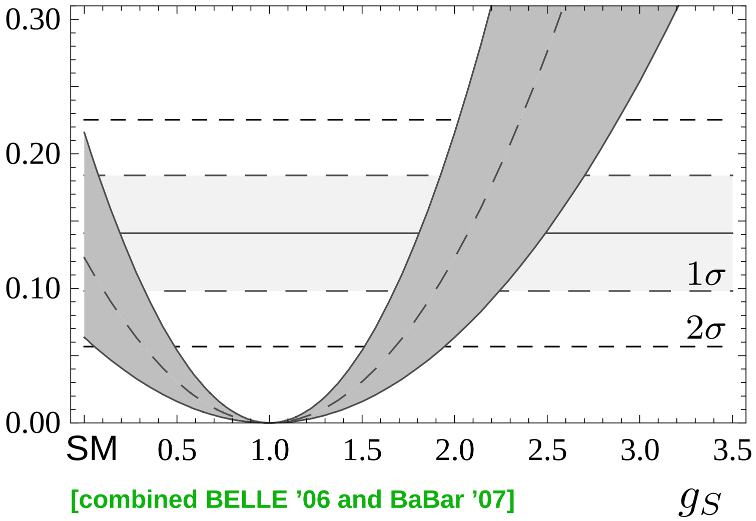
$b \to \tau$ transitions:

$$\mathcal{H}^{\text{eff}} = 2\sqrt{2}\, G_F \, V_{qb} \Big\{ (\bar{b}_L \, \gamma^\mu \, q_L)\, (\bar{\nu}_L \, \gamma_\mu \, \tau_L) - \frac{m_b m_\tau}{m_B^2} g_S \, (\bar{b}_R \, q_L)\, (\bar{\nu}_L \, \tau_R) \Big\}; \qquad q = u, c$$

$$g_S \equiv \frac{m_B^2}{M_H^2} \frac{\tan^2\beta}{(1 + \epsilon_0 \tan\beta)(1 + \epsilon_\tau \tan\beta)}$$

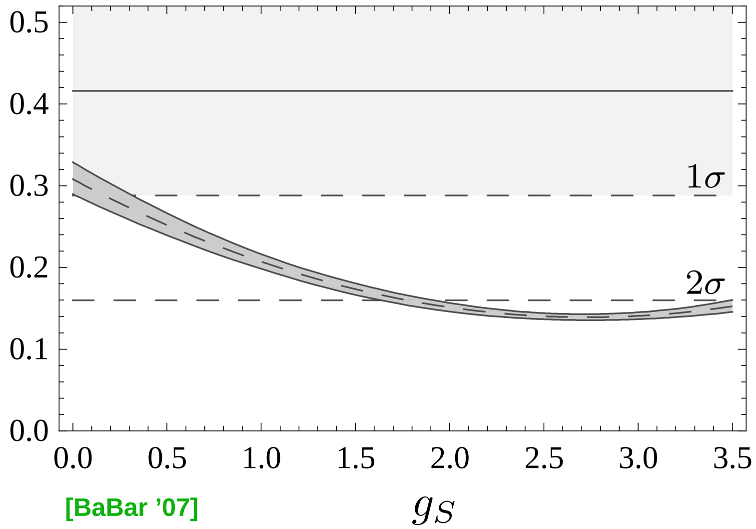
Branching Ratios $\mathcal{B}(B \to \tau\nu)$ and $\mathcal{B}(B \to D\tau\nu)$

$\boxed{\mathcal{B}(B \to \tau\nu)}$ $[10^{-3}]$



[combined BELLE '06 and BaBar '07]

$\boxed{R = \mathcal{B}(B \to D\tau\nu)/\mathcal{B}(B \to D\ell\nu)}$



[BaBar '07]

$$\mathcal{B}(B \to \tau\nu) \propto |V_{ub}|^2 f_B^2 \cdot |1 - g_S|^2$$

SM: $\mathcal{B}(B \to \tau\nu) = (1.23\,^{+0.93}_{-0.59}) \cdot 10^{-4}$

$|V_{ub}| = (3.86 \pm 0.09 \pm 0.47) \cdot 10^{-3}$ [HFAG '07]

$\delta\,|V_{ub}| \approx 12\%, \quad \delta f_B \approx 18\%$

$$\mathcal{B}(B \to D\tau\nu) \propto |V_{cb}|^2 \cdot f(F_V, F_S, g_S)$$

SM update: $R(g_S = 0) = 0.31 \pm 0.02$

$|V_{cb}| = (41.6 \pm 0.7) \cdot 10^{-3}$ [PDG '08, incl.]

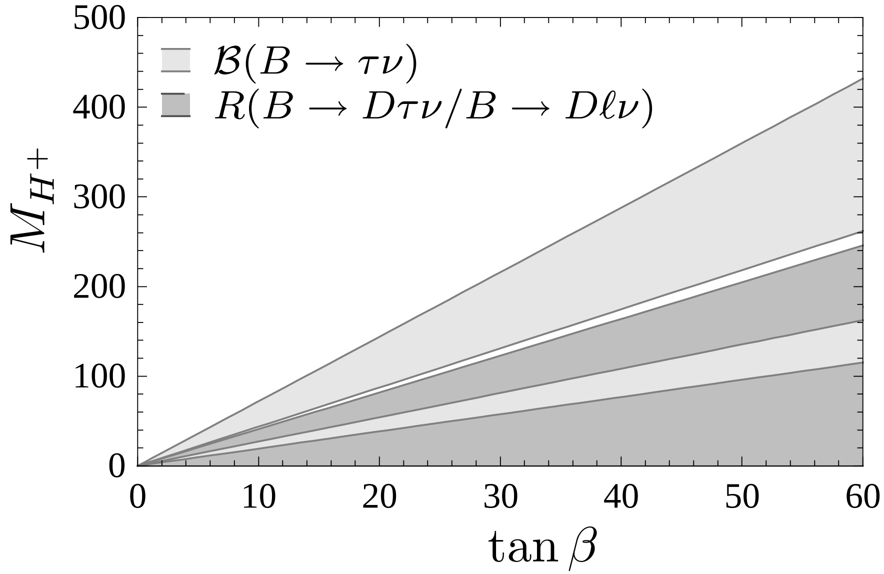
$\delta\,|V_{cb}|F_V \leq 5\%, \quad \delta\,|V_{cb}|F_S \leq 7\%$

with recent fit of $|V_{cb}|F_V$ to data [BaBar '08]

Constraining $\tan\beta / M_{H^+}$ with $\mathcal{B}(B \to \tau\nu)$ and R

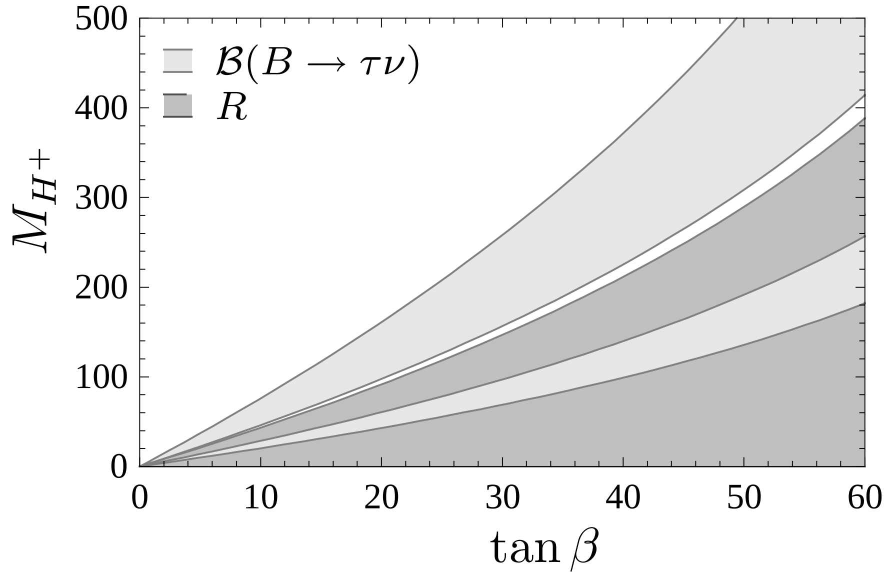
2HDM II, $\epsilon_0 = 0$

excluded at 95% C.L.



MSSM, $\epsilon_0 = -0.01$

excluded at 95% C.L.



$0.5 < g_S < 1.5$ and $g_S > 1.7$ excluded at 95% C.L.

New $\mathcal{B}(B \to \tau\nu)$ measurement by BELLE [ICHEP '08]: Constraints on g_S unchanged.

$B \longrightarrow D$ Form Factors

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

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

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$B \to D$ form factors are linear

after a conformal mapping $w \to z(w)$:

$$w = \frac{m_B^2 + m_D^2 - q^2}{2 m_B m_D}$$

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

[Boyd et al. ’97]

[Hill ’06, et al.]

equivalent parametrization

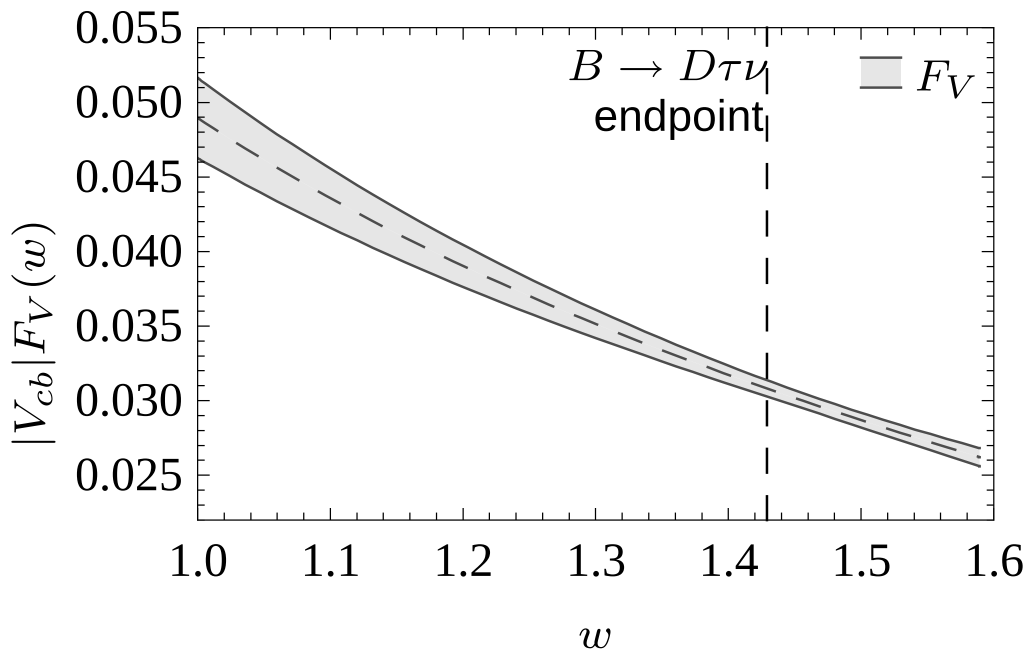
$$F_V(w) = F_V(1)\big(1 - 8\rho^2 z + (51\rho^2 - 10)z^2 - (252\rho^2 - 84)z^3\big)$$

[Caprini et al. ’98]

$F_V(w)$ from $B \to D\ell\nu$ Data $(\ell = e, \mu)$

$$G(w) = G(1)\big(1 - 8\rho^2 z + (51\rho^2 - 10)z^2 - (252\rho^2 - 84)z^3\big); \quad z(w) = \frac{\sqrt{w+1} - \sqrt{2}}{\sqrt{w+1} + \sqrt{2}}$$

$$G(w) = 2\frac{\sqrt{m_B m_D}}{m_B + m_D} F_V(w)$$



Recent fit to $B^{0,+} \to D\ell\nu$ data

$$|V_{cb}|G(1) = (43.0 \pm 1.9 \pm 1.4) \cdot 10^{-3}$$

$$\rho^2 = 1.20 \pm 0.09 \pm 0.04$$ [BaBar '08]

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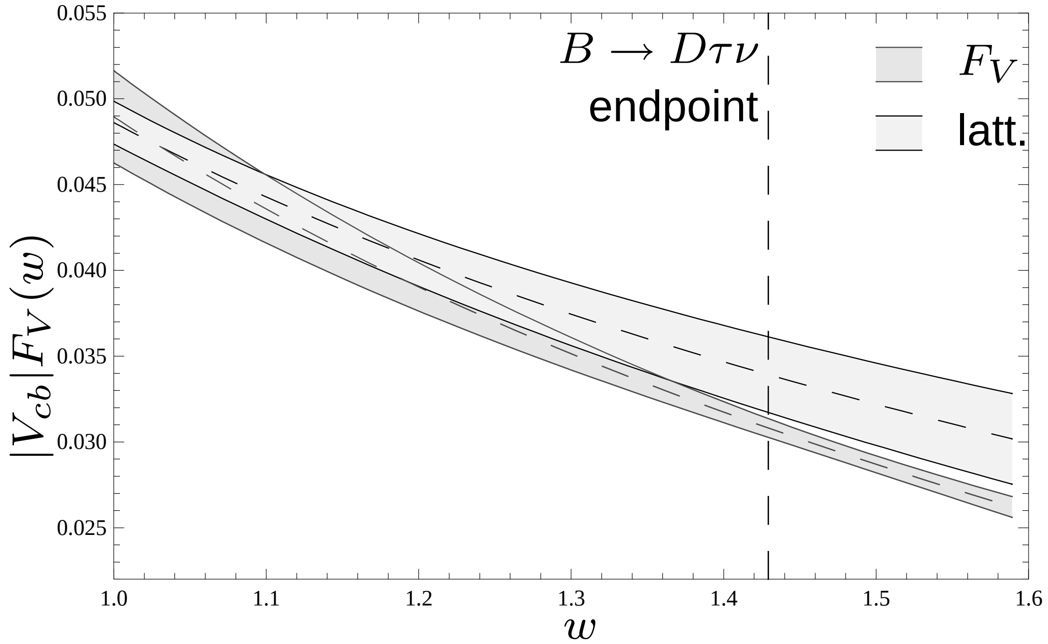

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$$\rho^2 = 1.20 \pm 0.09 \pm 0.04$$ [BaBar '08]

Compare with lattice form factor:

$$|V_{cb}|G(1) = (42.7 \pm 1.1) \cdot 10^{-3}$$

$$\rho^2 = 0.97 \pm 0.14$$ [Divitiis et al. '07]

[Kamenik, Mescia '08]

$F_S(w)$ from F_V and Heavy Quark Effective Theory

- Heavy quark limit $m_Q \to \infty$: $S(1) = G(1) = 1$

  Quantum corrections: $S(1) = \frac{m_B+m_D}{2\sqrt{m_B m_D}} F_S(1) = 1 + \mathcal{O}(1/m_Q, \alpha_s)$

- $F_S(w) = F_S(a_S^0, a_S^1)$ from $\begin{cases} w = 1: & F_S(1) = \frac{2\sqrt{m_B m_D}}{m_B+m_D}(1.02 \pm 0.05) \\ w = w_{\text{max}}: & F_S(q^2=0) = F_V(q^2=0) \end{cases}$

  [parametrization as in Hill ’06]

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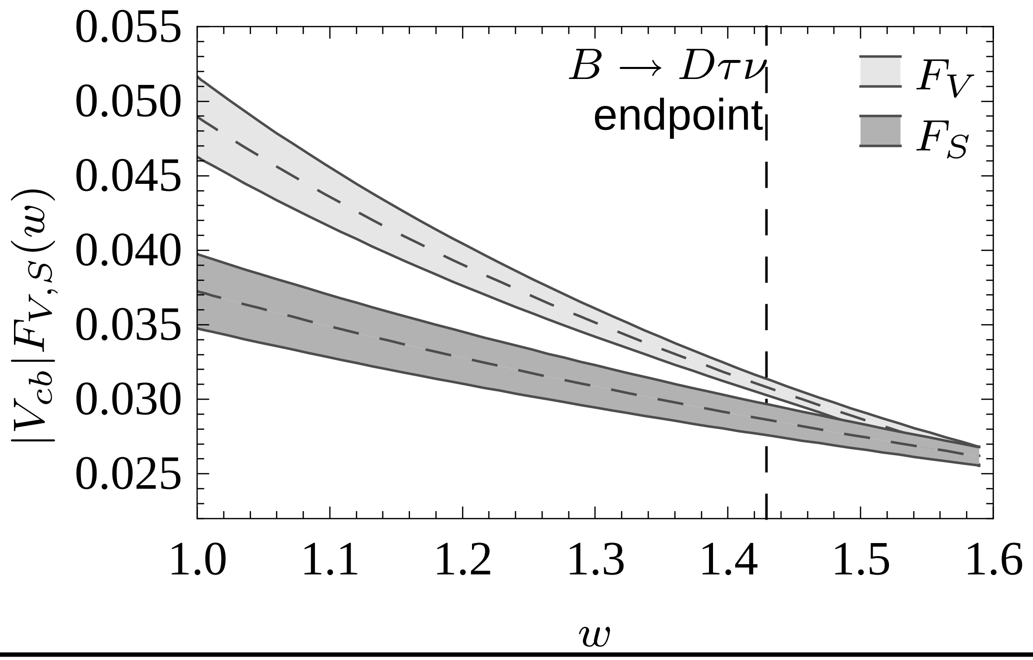


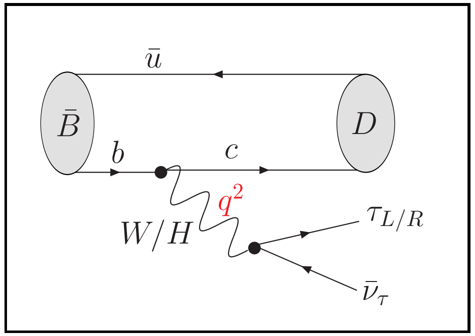
form factors are under control:

$$\delta\,|V_{cb}|F_V(1) = 5.5\%$$

$$\delta\,|V_{cb}|F_S(1) = 6.7\%$$

$B \to D\tau\nu$: q^2 Distribution

$$\frac{d\Gamma(B \to D\tau\nu)}{dw} \propto |V_{cb}|^2 \left\{ (w^2-1) F_V(w)^2 \rho_V(w) + F_S(w)^2 \left[1 - g_s \frac{q^2/m_B^2}{1-m_c/m_b}\right]^2 \rho_S(w) \right\}$$



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

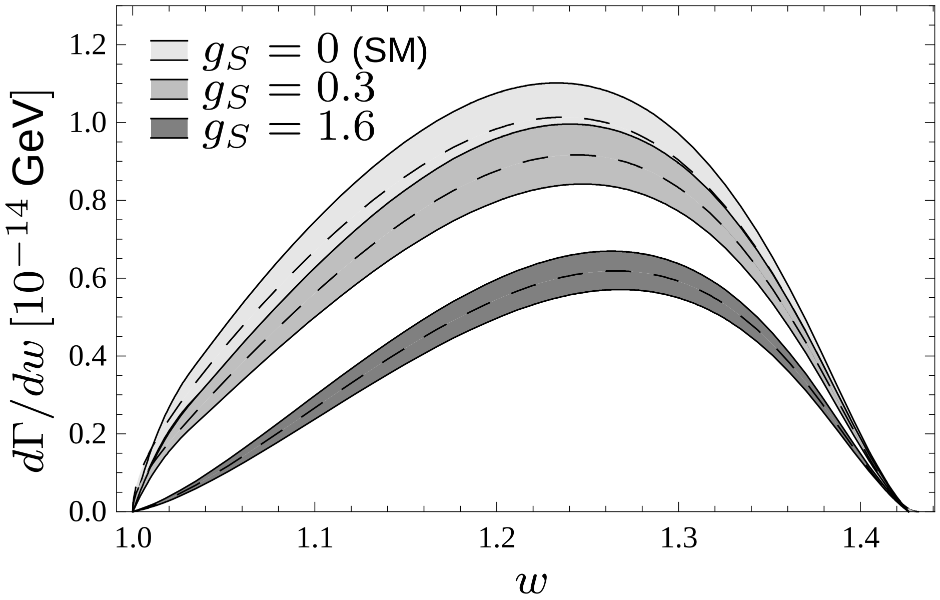
$$w = \frac{E_D}{m_D} = \frac{m_B^2 + m_D^2 - q^2}{2 m_B m_D}$$

$w = 1:$

transversal $W_\perp^+$ modes suppressed

relative $W_\parallel^+$ and H^+ contributions depend on q^2

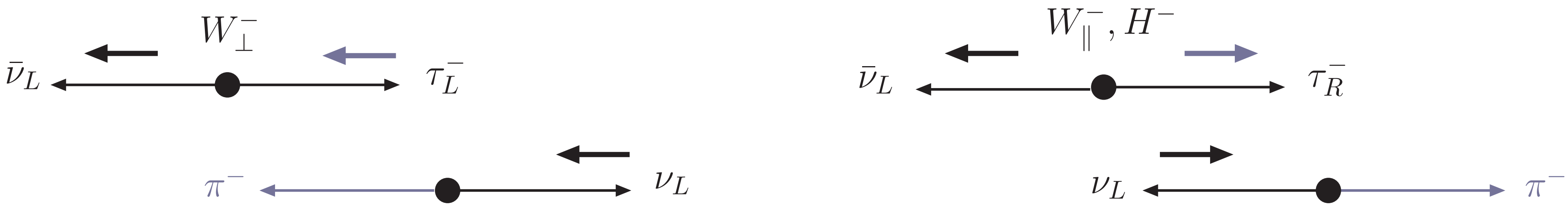
$\to$ determine g_S from shape



$B \to D\nu[\tau \to \pi\nu]$: Triple Differential Distribution

τ polarization to distinguish H^+ (τ_R) from $W_\perp^+$ (τ_L)

- not directly accessible: $\tau \to \pi\nu_\tau,\ \ell\bar{\nu}_\ell\nu_\tau,\ \ldots$ inside the detector
- $B \to D\nu[\tau \to \pi\nu]$: correlation of τ polarization and π direction



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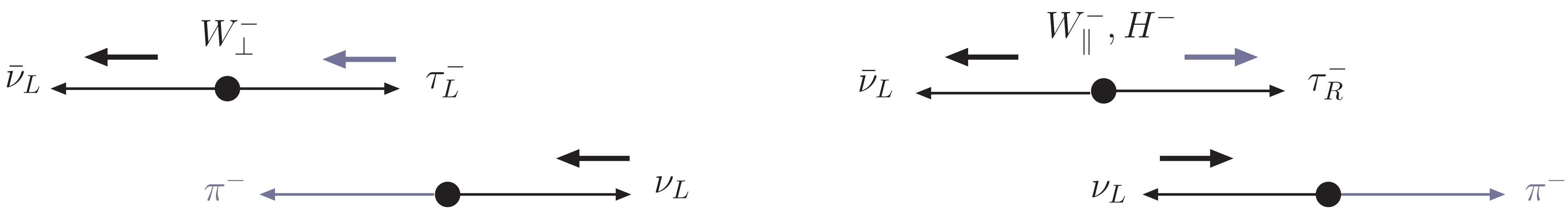


Triple differential distribution

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

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

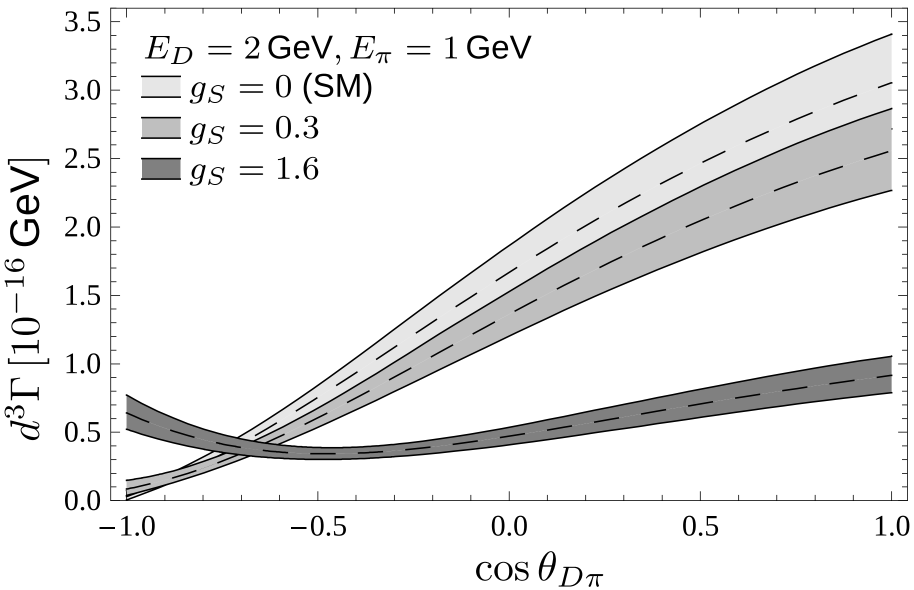
joins H^+ effects in q^2 $(\leftrightarrow E_D)$ dependence and τ polarization

Triple Differential Distribution

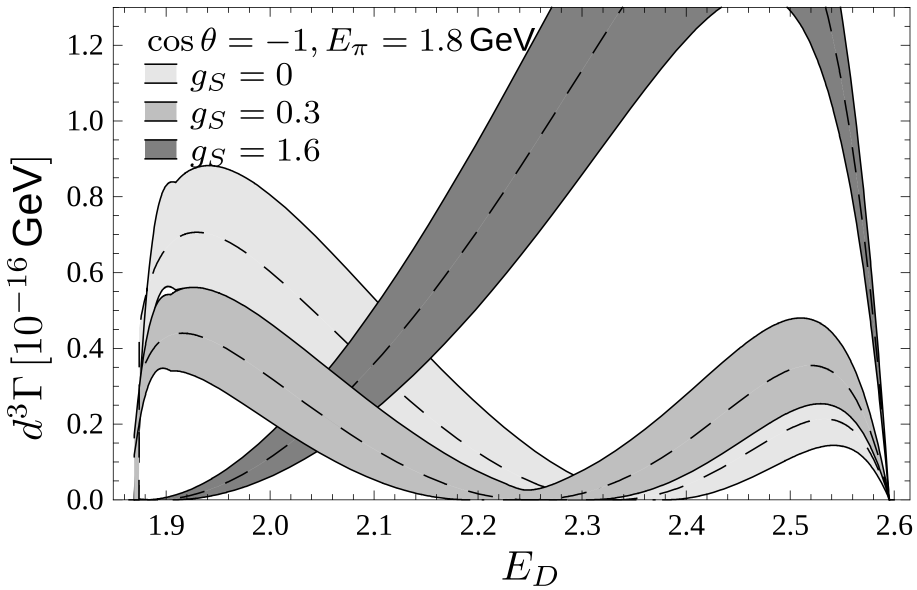
Maximum likelihood fit to $\frac{d^3\Gamma(B \to D\nu[\tau \to \pi\nu])}{dE_D\, dE_\pi\, d\cos\theta_{D\pi}}$ $\Longrightarrow$ $|g_S|, |\arg(g_S)|$

For illustration:

angular spectrum



E_D spectrum



The values for g_S are allowed by $\mathcal{B}(B \to \tau\nu)$ and $\mathcal{B}(B \to D\tau\nu)/\mathcal{B}(B \to D\ell\nu)$.

To Be Taken Home

- The $B \to D$ form factors are improved to $< 7\%$ error thanks to the recent fit by BaBar.

- In $B \to D\nu[\tau \to \pi\nu]$, the triple differential distribution combines the q^2 dependence and the τ polarization.

- $B \to D\tau\nu$ is complementary to $B \to \tau\nu$ in the search for charged Higgs bosons.

$\boxed{H^+}$ . . .

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