Status of $B \to D^{(*)} \tau \nu$ decays in two-Higgs-doublet models

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work in collaboration with A. Pich, M. Jung and Xin-Qiang Li

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arXiv:1302.5992

arXiv:1210.8443

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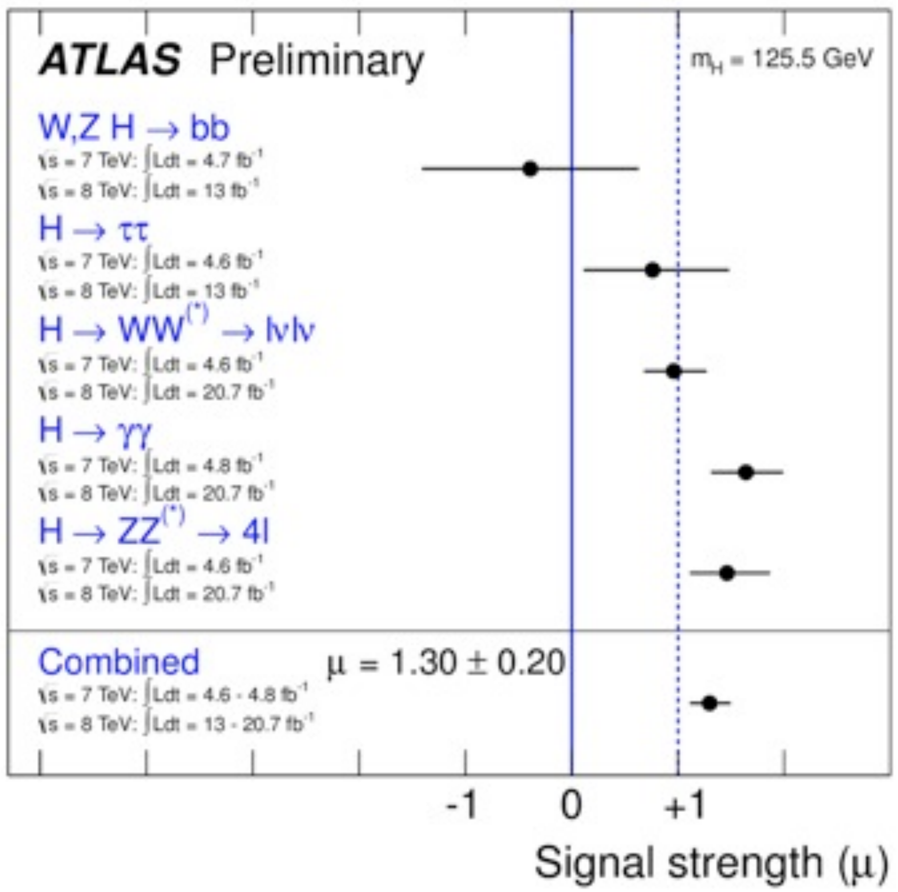
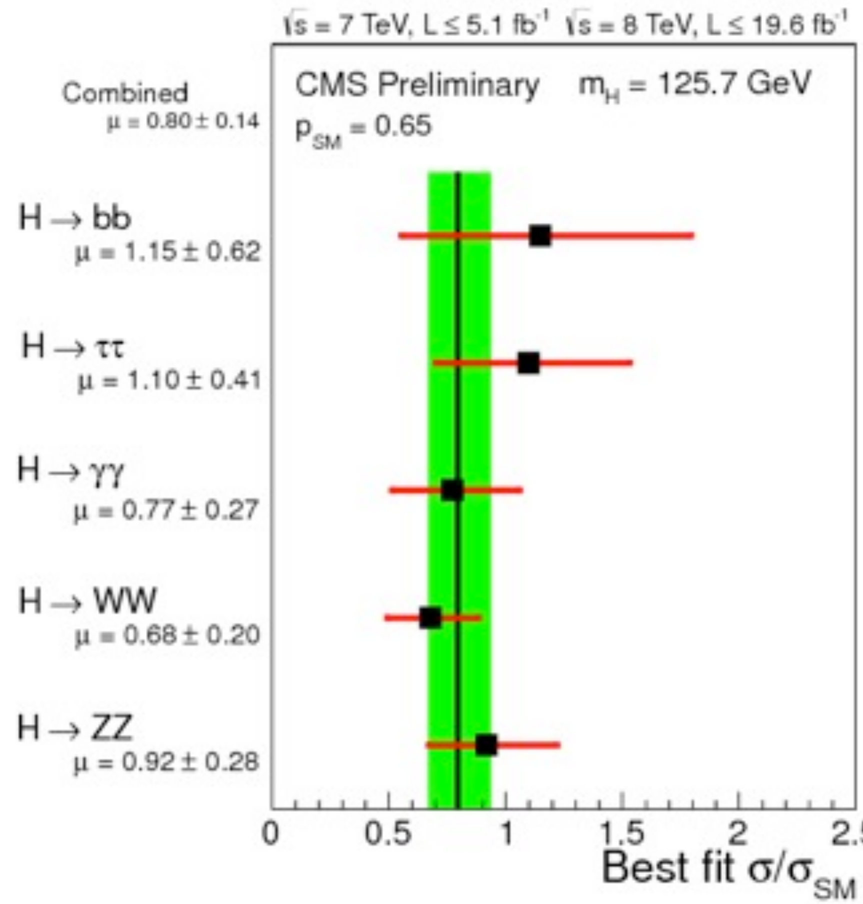
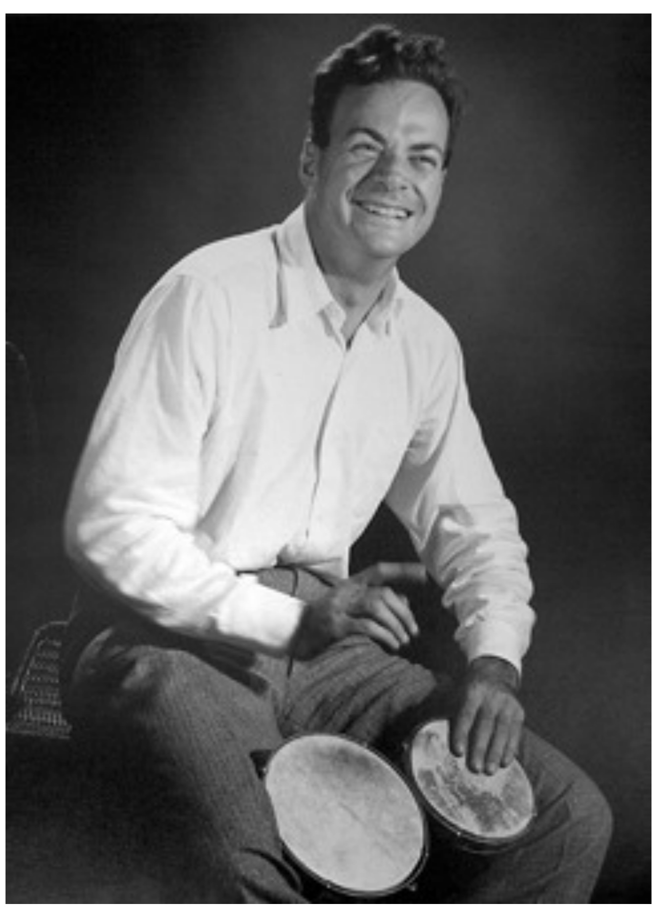




A new boson around 126 GeV

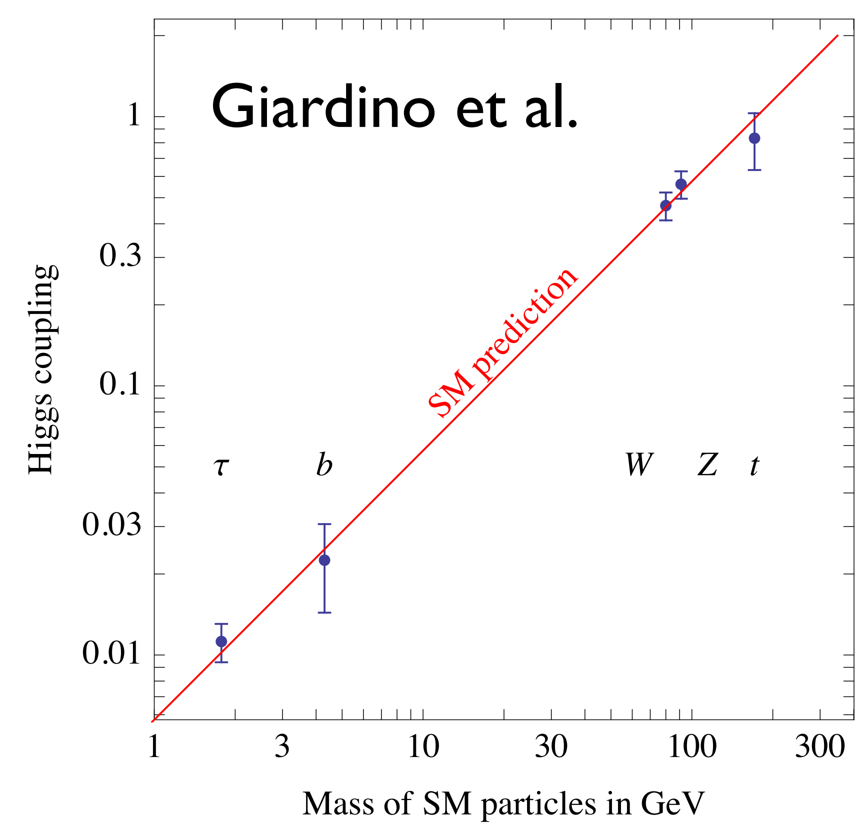
Consistent with SM Higgs



Why does the muon weigh?

R. Feynman

Fit to Higgs couplings



Adding a second Higgs doublet to the SM

3 Goldstone bosons
+
3 neutral Higgs
+
a charged scalar

Scalar spectrum $\longrightarrow$ $\{h, H, A, H^{\pm}\}$

Aligned 2HDM

Pich, Tuzon ´09

no tree-level FCNCs

$$\mathcal{L}_Y \supset -\frac{\sqrt{2}}{v} H^+ \{\bar{u} [\varsigma_d V M_d \mathcal{P}_R - \varsigma_u M_u^\dagger V \mathcal{P}_L] d + \varsigma_l \bar{\nu} M_l \mathcal{P}_R l\}$$

ς_f $\longrightarrow$ new sources of CP violation
Flavor Universal (the same for each family)

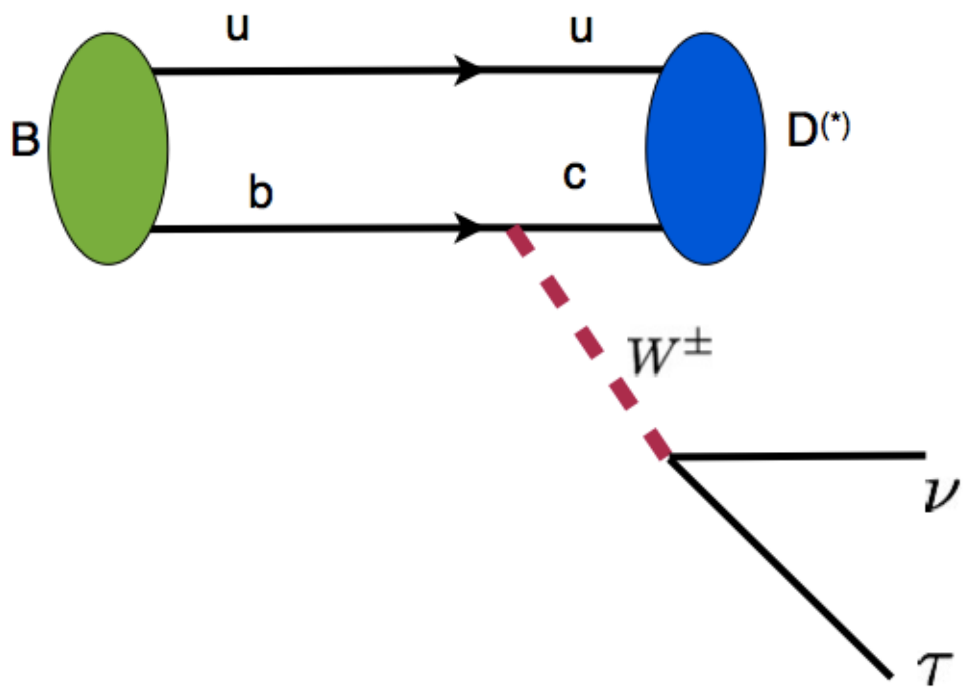
2HDMs with
natural flavor conservation

Model	ς_d	ς_u	ς_l
Type I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type II	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
Type X	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type Y	$-\tan\beta$	$\cot\beta$	$\cot\beta$
Inert	0	0	0

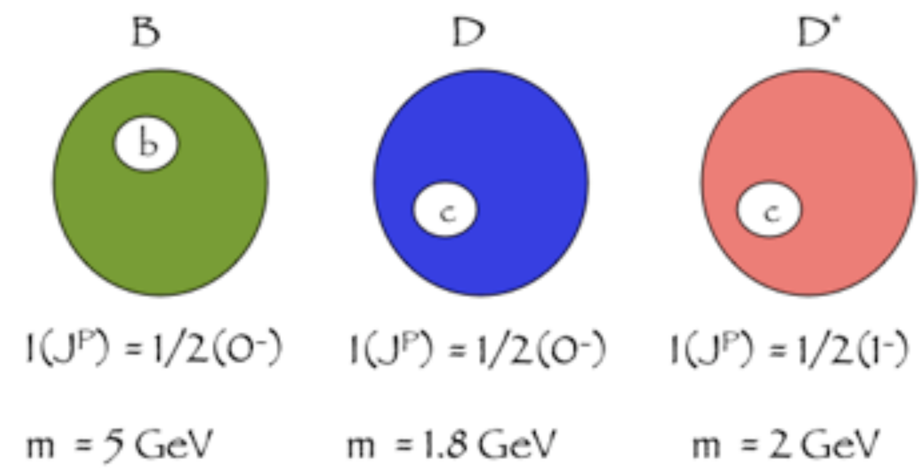
★ See A. Crivellin talk for the Type III 2HDM

Flavor physics tests indirectly the mechanism of EWSB.

b, c, τ : heaviest fermions produced at flavor factories



Charged Higgs enters at tree level



$$R(D^{(*)}) = \frac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}l\nu)}$$

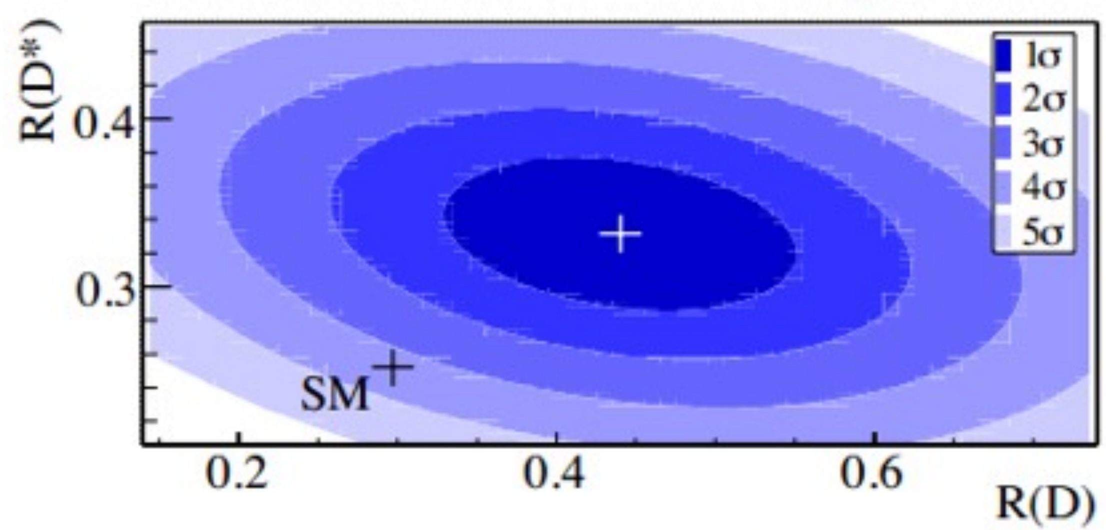
SM predictions

Kamenik, Mescia [Phys.Rev. D78 (2008) 014003]

Fajfer, Kamenik, Nisandzic [Phys.Rev. D85 (2012) 094025]

BaBar [Phys. Rev. D86 (2012) 032001]

$$\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau$$



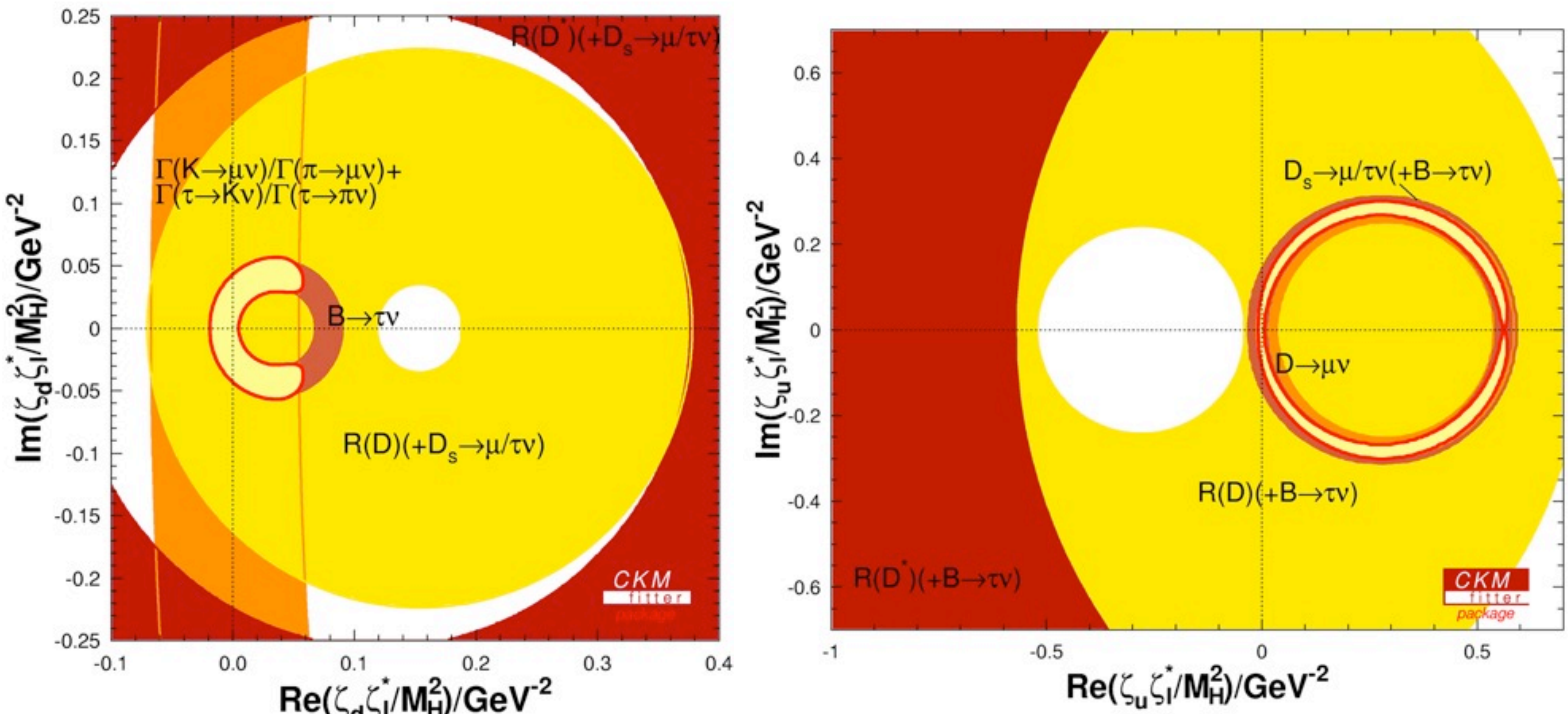
$$R(D) = \begin{cases} 0.440 \pm 0.072 & \text{BABAR} \\ 0.297 \pm 0.017 & \text{SM} \end{cases} \quad 2.0\sigma$$

$$R(D^*) = \begin{cases} 0.332 \pm 0.030 & \text{BABAR} \\ 0.252 \pm 0.003 & \text{SM} \end{cases} \quad 2.7\sigma$$

Combined: 3.4σ

$$\mathcal{L}_Y \supset -\frac{\sqrt{2}}{v}\, H^+ \left\{ \bar{u} \left[\varsigma_d\, V M_d \mathcal{P}_R - \varsigma_u\, M_u^\dagger V \mathcal{P}_L \right] d \,+\, \varsigma_l\, \bar{\nu} M_l \mathcal{P}_R l \right\}$$

LEP limit: $M_{H^\pm} \gtrsim 80$ GeV



95 % CL

★ A departure from family universality of the Yukawa couplings is needed

family universality of Yukawa couplings: $Y_f \sim \varsigma_f\, M_f$

$B \to D$ $B \to D^*$

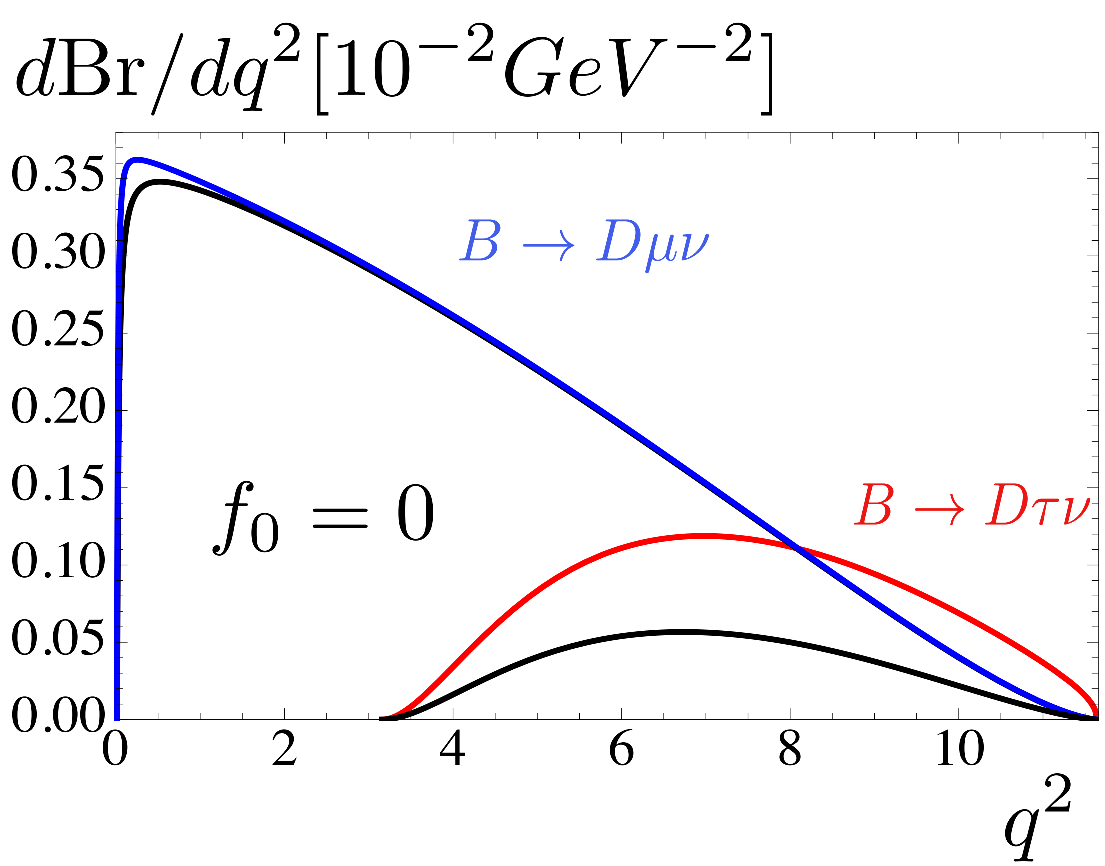
$f_0(q^2)$, $f_+(q^2)$ $A_0(q^2), V(q^2), A_1(q^2), A_2(q^2)$

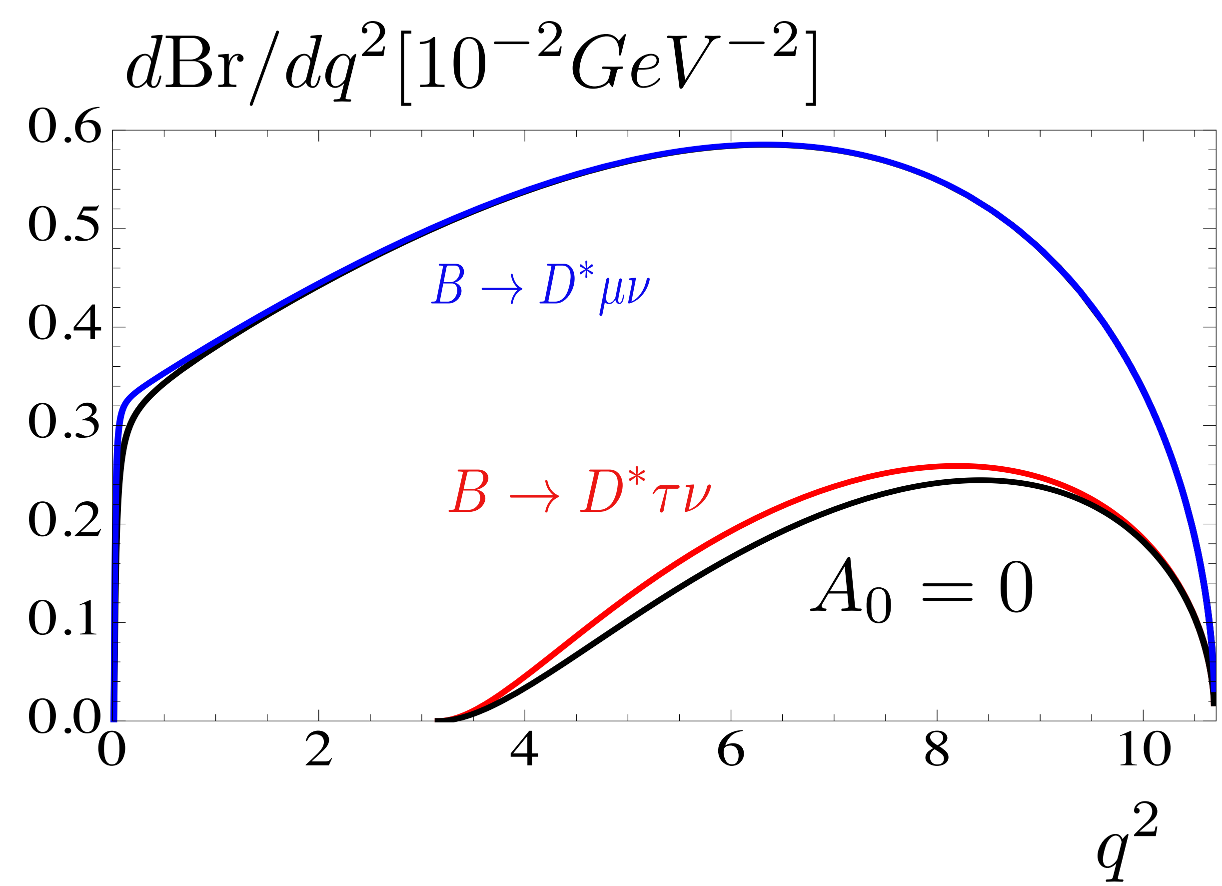
$q^2 = (p_B - p_{D^{(*)}})^2$

Type II: -1 $\tan^2 \beta$

$$\tilde{f}_0(q^2) = f_0(q^2) \left[1 + \frac{q^2}{m^2_{H^\pm}} \left(\frac{m_c\, \varsigma_u \varsigma_l^* - m_b\, \varsigma_d \varsigma_l^*}{m_b - m_c}\right)\right]$$

$$\tilde{A}_0(q^2) = A_0(q^2) \left[1 - \frac{q^2}{m^2_{H^\pm}} \left(\frac{m_c\, \varsigma_u \varsigma_l^* + m_b\, \varsigma_d \varsigma_l^*}{m_b + m_c}\right)\right]$$

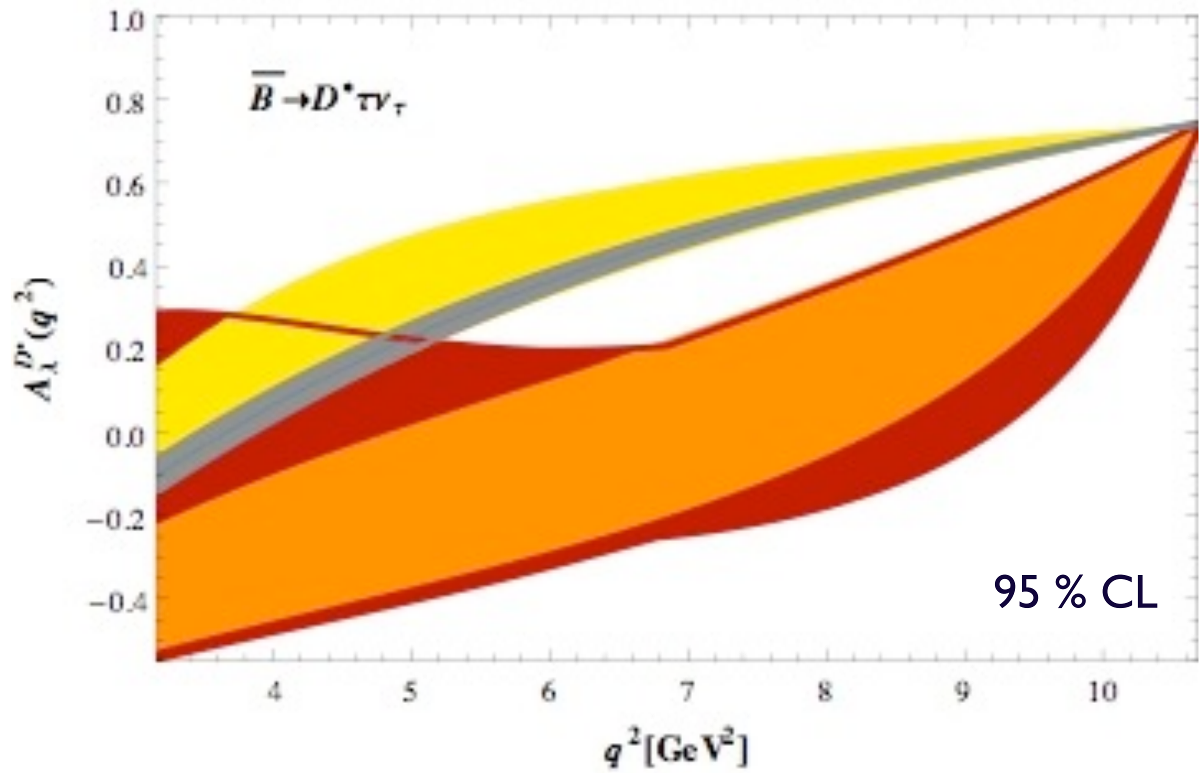


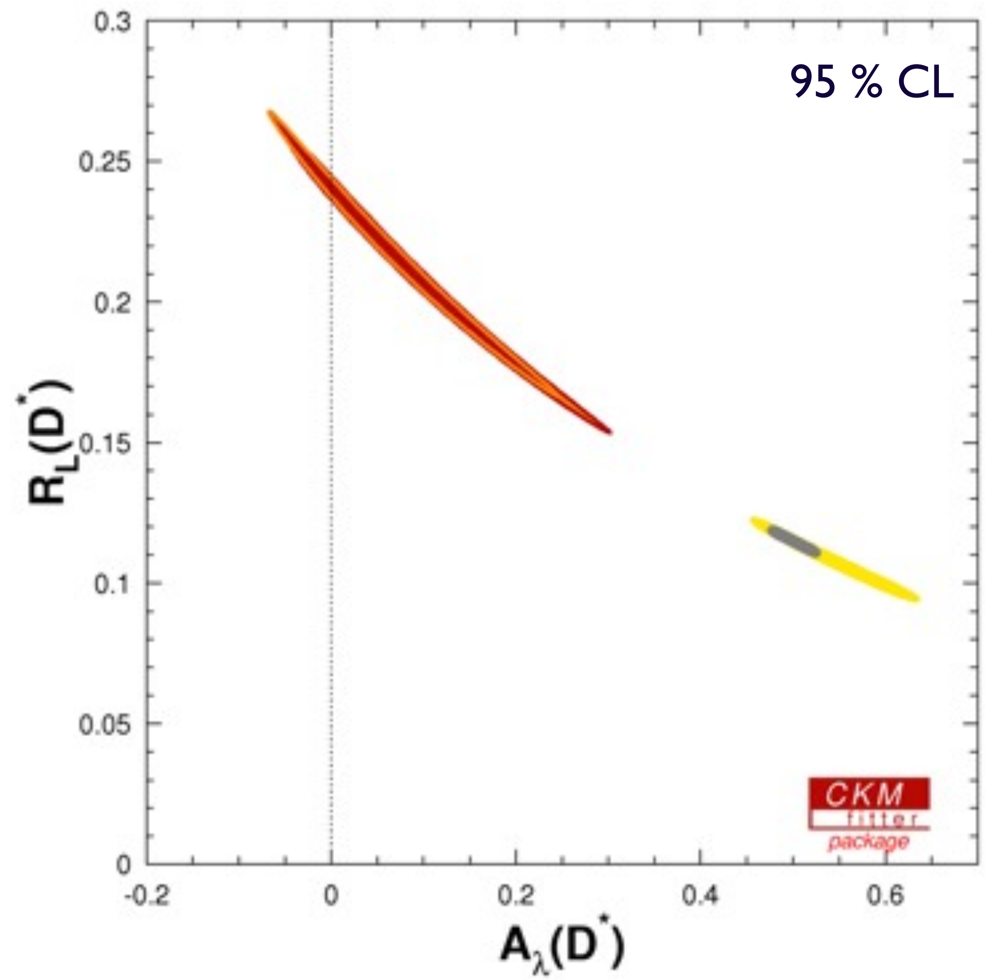


Is it a charged Higgs?

- SM
- $R(D) + R(D^*)$
- $R(D) + R(D^*) + B \to \tau\nu$
- $R(D) + B \to \tau\nu + D \to \ell\nu$

$A_\lambda^{D^*}(q^2)$





$$R_L(D^*) = \frac{\Gamma(B \to D_L^* \tau\nu)}{\Gamma(B \to D_L^* l\nu)}$$

$$A_\lambda^{D^{(*)}}(q^2) = \frac{d\Gamma^{D^{(*)}}[\lambda_\tau = -1/2]/dq^2 - d\Gamma^{D^{(*)}}[\lambda_\tau = +1/2]/dq^2}{d\Gamma^{D^{(*)}}/dq^2}$$

★ $B_c \to \tau\nu$ large enhancement expected arXiv:1302.5992

Summary

$$B \to D^{(*)}\tau\nu$$

provide an interesting laboratory to look for NP effects related to the EWSB mechanism

To accommodate current measurements of R(D*) in 2HDMs, a departure from family universality of the Yukawa couplings is needed.

rich kinematics $\longrightarrow$ interesting prospects for Belle II

Important to improve our understanding of hadronic matrix elements

★ Expected update from Belle.
Can it be measured at LHCb ?

Back-up slides

An incomplete list of references on the topic

apologies for those not included

Fajfer, Kamenik, Nisandzic, Zupan [Phys.Rev.Lett. 109 (2012) 161801]

Fajfer, Kamenik, Nisandzic [Phys.Rev. D85 (2012) 094025]

Kamenik, Mescia [Phys.Rev. D78 (2008) 014003]

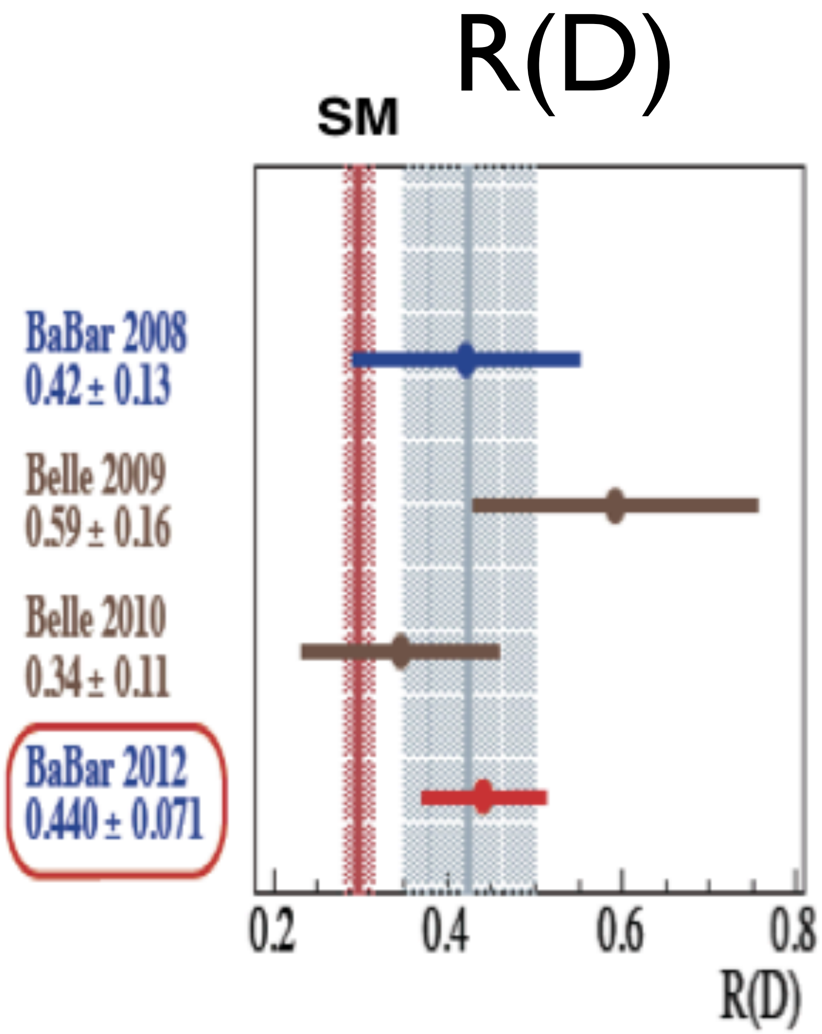
Crivellin, Greub, Kokulu [Phys.Rev. D86 (2012) 054014]

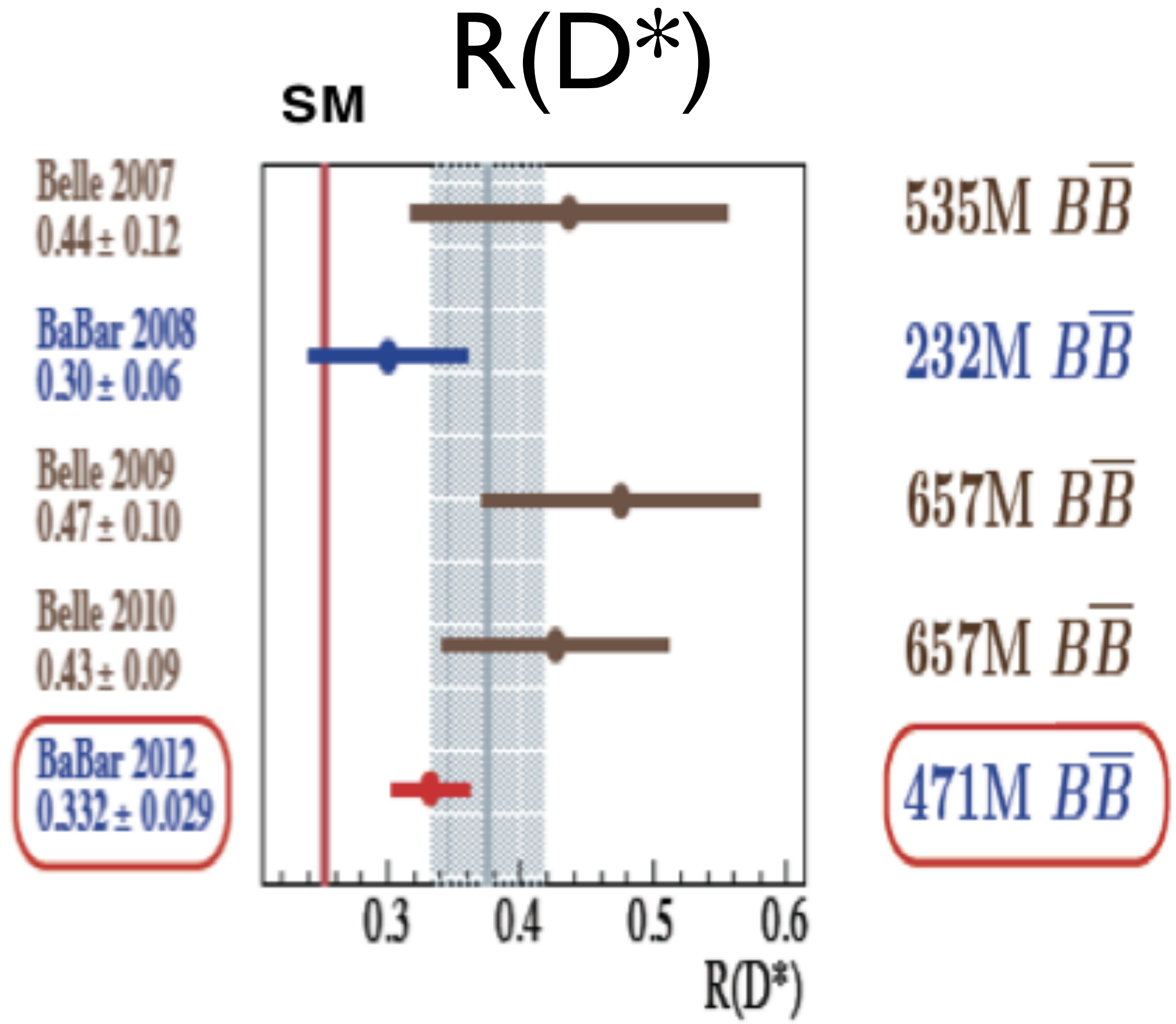
Datta, Duraisamy [Phys. Rev. D86 034027]

AC, Jung, X-Q. Li , Pich [JHEP 1301 (2013) 054]

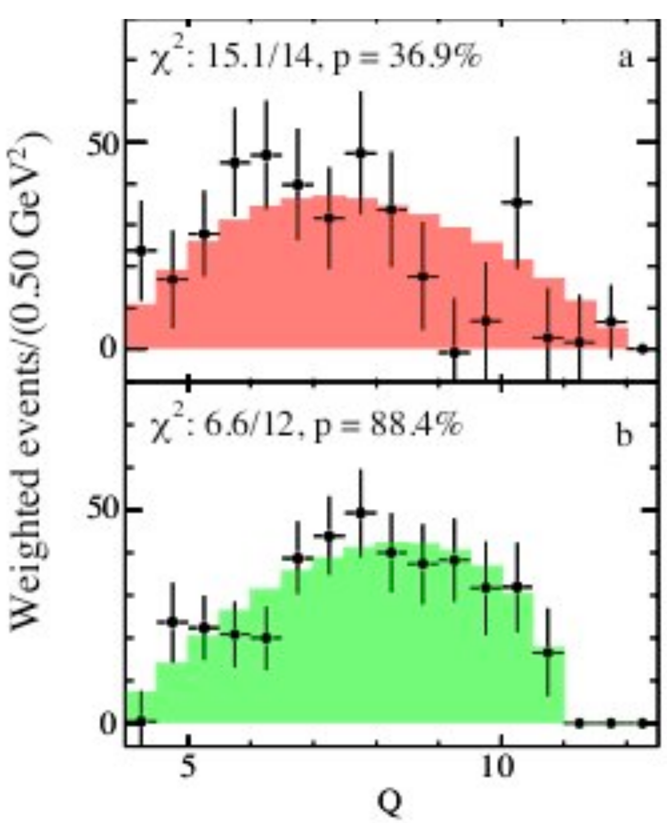
Tanaka, Watanabe [Phys. Rev. D87 (2013) 034028]

R(D) R(D*)





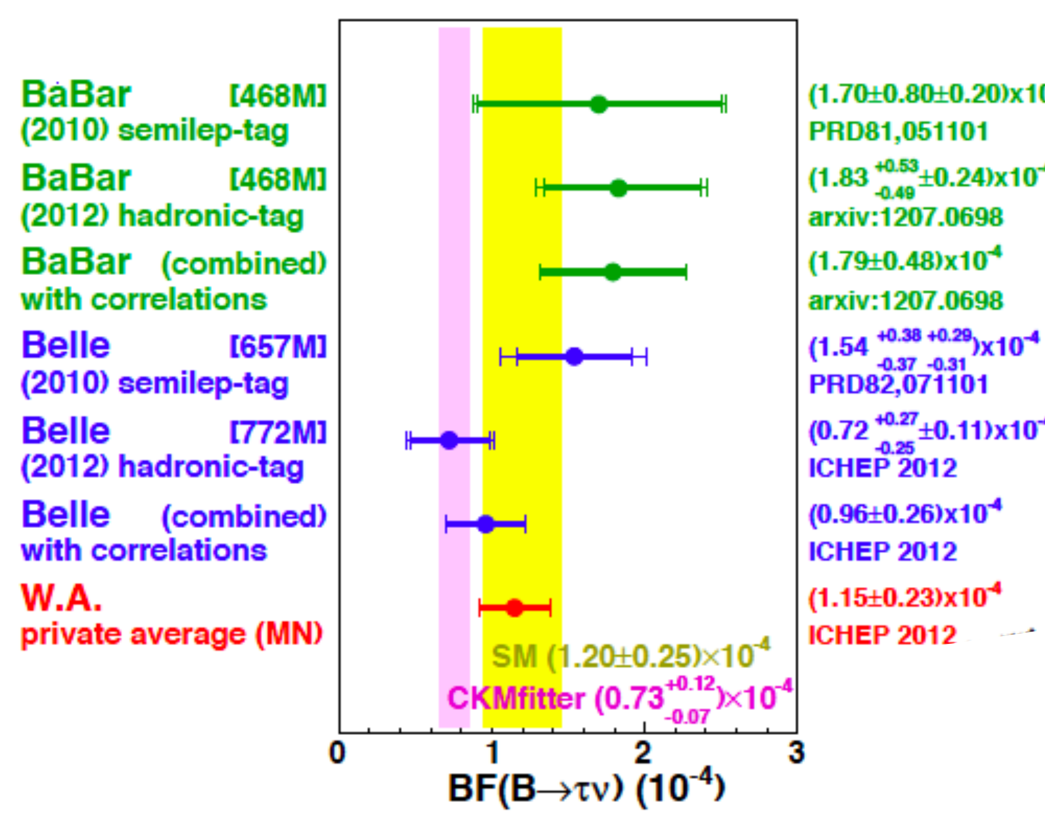
$$B \to \tau\nu$$



Distributions in momentum transfer

BaBar [arXiv:1303.0571]

BaBar [Phys. Rev. D86 (2012) 032001]



Two-Higgs-doublet model (2HDM)

$$\langle 0|\,\phi_a^T(x)|0\rangle = \frac{1}{\sqrt{2}}\left(0\,,\, v_a\, e^{i\theta_a}\right) \quad , \quad \theta_1 = 0 \quad , \quad \theta \equiv \theta_2 - \theta_1$$

Higgs basis: $v \equiv \sqrt{v_1^2 + v_2^2}$, $\tan\beta \equiv v_2/v_1$

$$\begin{pmatrix} \Phi_1 \\ -\Phi_2 \end{pmatrix} \equiv \begin{bmatrix} \cos\beta & \sin\beta \\ \sin\beta & -\cos\beta \end{bmatrix} \begin{pmatrix} \phi_1 \\ e^{-i\theta}\,\phi_2 \end{pmatrix}$$

$$\rightarrow \quad \Phi_1 = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + S_1 + iG^0\right) \end{bmatrix} \quad , \quad \Phi_2 = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}}\left(S_2 + iS_3\right) \end{bmatrix}$$

Mass eigenstates: $H^\pm$, $\varphi_i^0(x) \equiv \{h(x), H(x), A(x)\} = \mathcal{R}_{ij}\, S_j(x)$

Yukawa interactions in the 2HDM

$$\mathcal{L}_Y = -\bar{Q}'_L(\Gamma_1\phi_1+\Gamma_2\phi_2)\,d'_R - \bar{Q}'_L(\Delta_1\tilde{\phi}_1+\Delta_2\tilde{\phi}_2)\,u'_R - \bar{L}'_L(\Pi_1\phi_1+\Pi_2\phi_2)\,l'_R + \text{h.c.}$$

$\downarrow$ **SSB**

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v}\left\{\bar{Q}'_L(M'_d\Phi_1+Y'_d\Phi_2)\,d'_R + \bar{Q}'_L(M'_u\tilde{\Phi}_1+Y'_u\tilde{\Phi}_2)\,u'_R + \bar{L}'_L(M'_l\Phi_1+Y'_l\Phi_2)\,l'_R + \text{h.c.}\right\}$$

M'_f and Y'_f unrelated $\rightarrow$ **FCNCs**

$$\sqrt{2}\,M'_d = v_1\Gamma_1 + v_2\Gamma_2 e^{i\theta} \quad , \quad \sqrt{2}\,M'_u = v_1\Delta_1 + v_2\Delta_2 e^{-i\theta}$$

$$\sqrt{2}\,Y'_d = v_1\Gamma_2 e^{i\theta} - v_2\Gamma_1 \quad , \quad \sqrt{2}\,Y'_u = v_1\Delta_2 e^{-i\theta} - v_2\Delta_1$$

Avoiding large FCNC

- Very large scalar masses ➡ THDM irrelevant at low energies
- Very small scalar couplings
- Type III model: $(Y_f)_{ij} \propto \sqrt{m_i m_j}$ Yukawa textures

  (Cheng - Sher '87)
- Discrete $\mathcal{Z}_2$ symmetries: only one $\phi_a(x)$ couples to a given $f_R(x)$

  (Glashow - Weinberg '77)

$$\mathcal{Z}_2: \quad \phi_1 \to \phi_1 \quad , \quad \phi_2 \to -\phi_2 \quad , \quad Q_L \to Q_L \quad , \quad L_L \to L_L \quad , \quad f_R \to \pm f_R$$

➡ **CP conserved in the scalar sector**

Aligned 2HDM (Pich - Tuzón '09)

Require alignment in Flavour Space of Yukawa couplings:

$$\Gamma_2 = \xi_d \, e^{-i\theta} \, \Gamma_1 \qquad , \qquad \Delta_2 = \xi_u^* \, e^{i\theta} \, \Delta_1 \qquad , \qquad \Pi_2 = \xi_l \, e^{-i\theta} \, \Pi_1$$

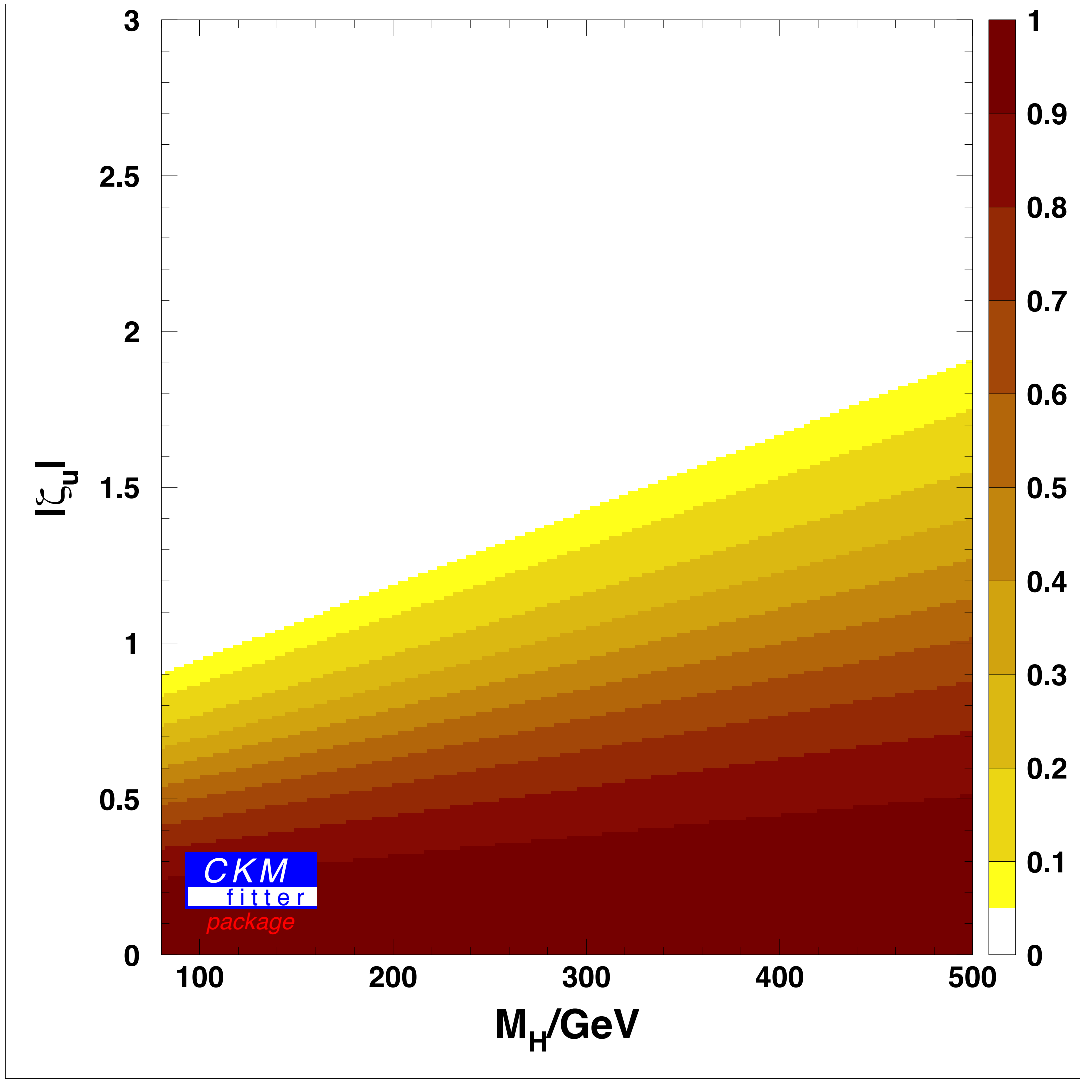
$$\Downarrow$$

$$Y_{d,l} = \varsigma_{d,l} \, M_{d,l} \, , \qquad Y_u = \varsigma_u^* \, M_u \, , \qquad \varsigma_f \equiv \frac{\xi_f - \tan\beta}{1 + \xi_f \tan\beta}$$

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v} H^+ \left\{ \bar{u} \left[\varsigma_d \, V_{\mathrm{CKM}} M_d \mathcal{P}_R - \varsigma_u \, M_u^\dagger V_{\mathrm{CKM}} \mathcal{P}_L \right] d \; + \; \varsigma_l \; \left(\bar{\nu} \, M_l \, \mathcal{P}_R \, l \right) \right\}$$
$$- \frac{1}{v} \sum_{\varphi_i^0, f} y_f^{\varphi_i^0} \, \varphi_i^0 \; \left(\bar{f} \, M_f \, \mathcal{P}_R \, f \right) \quad + \quad \mathrm{h.c.}$$

$R_b = \Gamma(Z \to \bar{b}b)/\Gamma(Z \to \text{hadrons})$

Jung, Pich, Tuzon [JHEP 1011 (2010) 003]

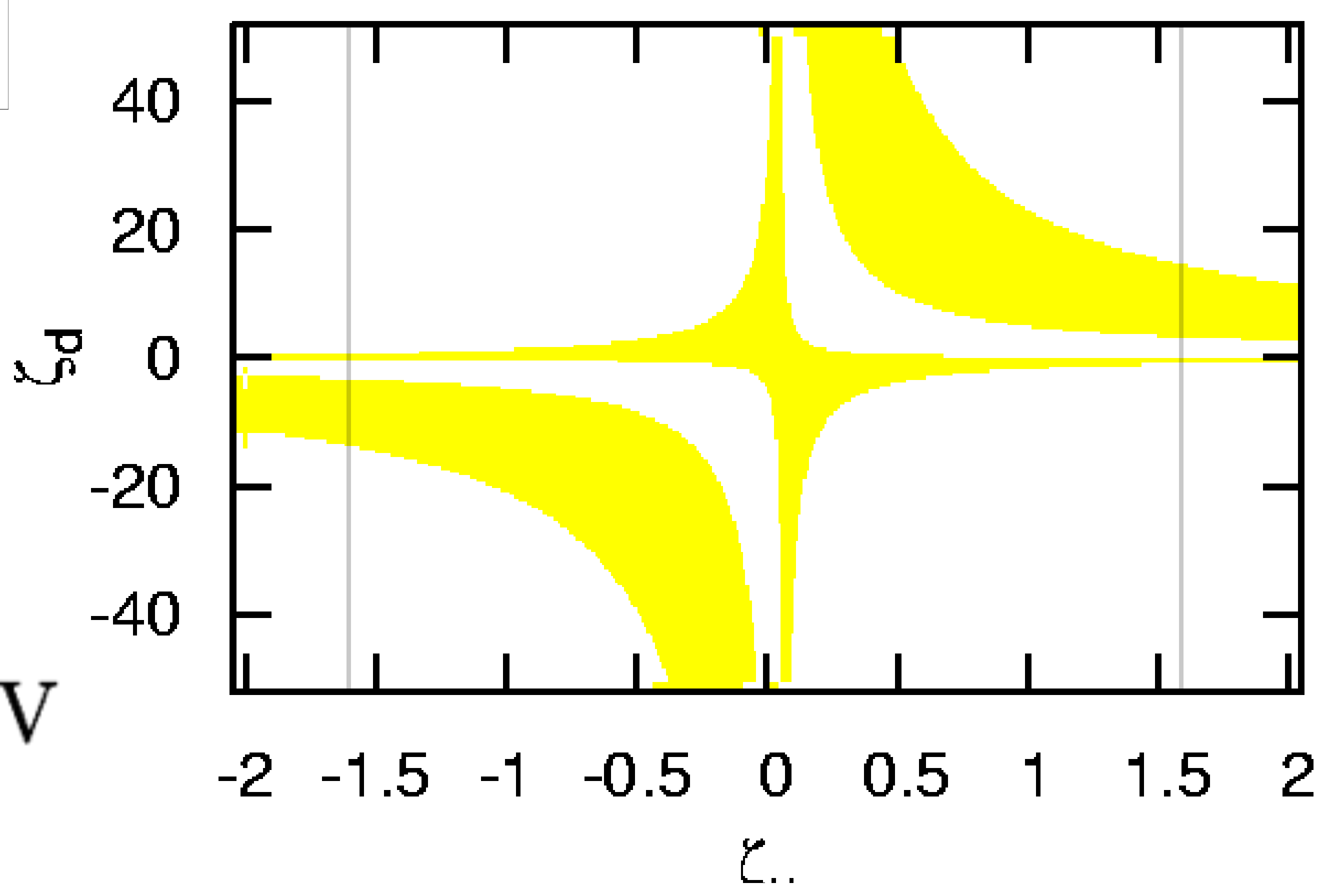


adding τ decays constraints

$$|\varsigma_u \varsigma_l^*|/M_{H^\pm}^2 < 0.005\ \text{GeV}^{-2}$$

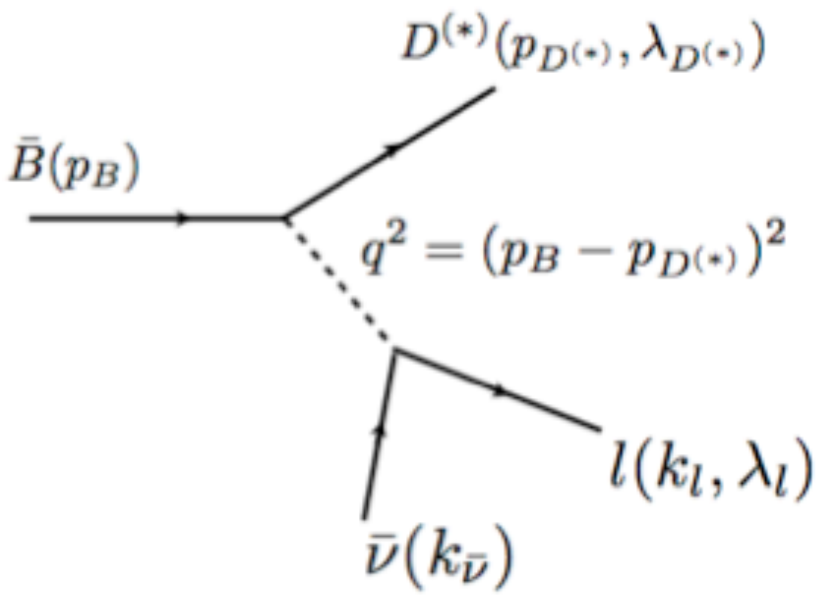
with $|\varsigma_d| < 50$

$\text{Br}(\bar{B} \to X_s \gamma)$

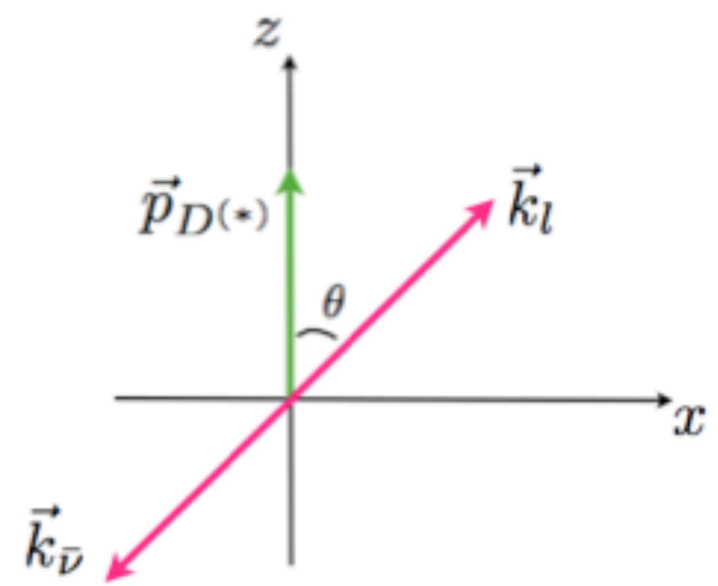


$M_{H^\pm} \in [80, 500]$ GeV

$\bar{B} \to D^{(*)} l \bar{\nu}$ Decays



$$m_l^2 \le q^2 \le (m_B - m_{D^{(*)}})^2$$



In the $l - \bar{\nu}$ rest frame

$$\left|\mathcal{M}(\bar{B} \to D^{(*)} l \bar{\nu})\right|^2 = \left|\langle D^{(*)} l \bar{\nu} | \mathcal{L}_{eff} | \bar{B} \rangle\right|^2 = L_{\mu\nu} H^{\mu\nu}$$

$$\frac{d^2\Gamma_l}{dq^2 d\cos\theta} = \frac{G_F^2 |V_{cb}|^2}{(2\pi)^3} \frac{|\vec{p}_B|}{2m_B^2} \left(1 - \frac{m_l^2}{q^2}\right) L_{\mu\nu} H^{\mu\nu}$$

$\bar{B} \to D l \bar{\nu}$ hadronic matrix elements

- $$\langle D(p_D)|\bar{c}\gamma^\mu b|\bar{B}(p_B)\rangle = f_+(q^2)\left[(p_B+p_D)^\mu - \frac{m_B^2-m_D^2}{q^2}q^\mu\right] + f_0(q^2)\,\frac{m_B^2-m_D^2}{q^2}q^\mu$$

- $$\langle D(p_D)|\bar{c}\,\gamma^\mu\gamma_5 b|\bar{B}(p_B)\rangle = 0$$

$B \to D$ form factors

$$f_+(q^2) = \frac{G_1(w)}{R_D}, \qquad f_0(q^2) = R_D \frac{(1+w)}{2} G_1(w) \frac{1+r}{1-r} \Delta(w),$$

[Falk, Neubert (1992)]

$$R_{D^{(*)}} = 2\sqrt{m_B m_{D^{(*)}}}/(m_B + m_{D^{(*)}}), \qquad r = m_{D^{(*)}}/m_B$$

$$w = v_B \cdot v_{D^{(*)}} = \frac{m_B^2 + m_{D^{(*)}}^2 - q^2}{2 m_B m_{D^{(*)}}}$$

$$\Delta(w) = 0.46 \pm 0.02$$

de Divitiis, Petronzio, Tantalo [0707.0587]
Bailey *et al.* [1206.4992]
Becirevic, Kosnik, Tayduganov [1206.4977]

$$G_1(w) = G_1(1) \left[1 - 8\rho_1^2 z(w) + (51\rho_1^2 - 10) z(w)^2 - (252\rho_1^2 - 84) z(w)^3\right]$$

$z(w) = (\sqrt{w+1} - \sqrt{2})/(\sqrt{w+1} + \sqrt{2})$ Caprini, Lellouch, Neubert [9712417]

$G_1(1)$ and ρ values from $\bar{B} \to D\ell\bar{\nu}$ ($\ell = e, \mu$) ‣ Heavy Flavor Averaging Group (HFAG)

$\bar{B} \to D l \bar{\nu}$ differential decay width

$$H_0(q^2) = \frac{2m_B|\vec{\mathbf{p}}|}{\sqrt{q^2}}\, f_+(q^2)\,, \qquad H_t(q^2) = \frac{m_B^2 - m_D^2}{\sqrt{q^2}}\, f_0(q^2)\,,$$

- $$\frac{d^2\Gamma^D[\lambda_l = -1/2]}{dq^2 d\cos\theta} = \frac{G_F^2 |V_{cb}|^2 q^2}{128\pi^3 m_B^2} \times \left(1 - \frac{m_l^2}{q^2}\right)^2 |\vec{\mathbf{p}}|\, |H_0(q^2)|^2 \sin^2\theta$$

- $$\frac{d^2\Gamma^D[\lambda_l = +1/2]}{dq^2 d\cos\theta} = \frac{G_F^2 |V_{cb}|^2 q^2}{128\pi^3 m_B^2} \times \left(1 - \frac{m_l^2}{q^2}\right)^2 |\vec{\mathbf{p}}|\, \frac{m_l^2}{q^2}\, |H_0(q^2)\cos\theta - H_t(q^2)|^2$$

Hagiwara, Martin, Wade [Phys. Lett. B **228** (1989) 144, Nucl. Phys. B **327** (1989) 569]
Korner, Schuler [Z. Phys. C **46** (1990) 93]
Kamenik, Mescia [0802.3790]

$\bar{B} \to D^* l \bar{\nu}$ hadronic matrix elements

- $\langle D^*(p_{D^*}, \epsilon^*) | \bar{c}\gamma_\mu b | \bar{B}(p_B) \rangle \;=\; \dfrac{2iV(q^2)}{m_B + m_{D^*}} \, \epsilon_{\mu\nu\alpha\beta} \, \epsilon^{*\nu} p_B^\alpha p_{D^*}^\beta \,,$

- $$\langle D^*(p_{D^*}, \epsilon^*) | \bar{c}\gamma_\mu \gamma_5 b | \bar{B}(p_B) \rangle \;=\; 2m_{D^*} \, A_0(q^2) \, \frac{\epsilon^* \cdot q}{q^2} \, q_\mu$$
$$+ (m_B + m_{D^*}) \, A_1(q^2) \left(\epsilon^*_\mu - \frac{\epsilon^* \cdot q}{q^2} \, q_\mu \right)$$
$$- A_2(q^2) \, \frac{\epsilon^* \cdot q}{m_B + m_{D^*}} \left[(p_B + p_{D^*})_\mu - \frac{m_B^2 - m_{D^*}^2}{q^2} \, q_\mu \right] .$$

Hagiwara, Martin, Wade [Phys. Lett. B **228** (1989) 144, Nucl. Phys. B **327** (1989) 569]
Korner, Schuler [Z. Phys. C **46** (1990) 93]

Fajfer, Kamenik,Nisandzic [1203.2654]

$B \to D^*$ form factors

$$V(q^2) = \frac{R_1(w)}{R_{D^*}} h_{A_1}(w) \qquad A_0(q^2) = \frac{R_0(w)}{R_{D^*}} h_{A_1}(w)$$

$$A_1(q^2) = R_{D^*} \frac{w+1}{2} h_{A_1}(w) \qquad A_2(q^2) = \frac{R_2(w)}{R_{D^*}} h_{A_1}(w)$$

$$\begin{aligned}
h_{A_1}(w) &= h_{A_1}(1)\left[1 - 8\rho^2 z(w) + (53\rho^2 - 15)\, z(w)^2 - (231\rho^2 - 91)\, z(w)^3\right] \\
R_0(w) &= R_0(1) - 0.11(w-1) + 0.01(w-1)^2 \\
R_1(w) &= R_1(1) - 0.12(w-1) + 0.05(w-1)^2 \\
R_2(w) &= R_2(1) - 0.11(w-1) - 0.06(w-1)^2
\end{aligned}$$

Caprini, Lellouch, Neubert [9712417]

$h_{A_1}(1)$, ρ^2, $R_1(1)$ and $R_2(1)$ values from $\bar{B} \to D^* \ell \bar{\nu}$ $(\ell = e, \mu)$ ‣ HFAG

$R_0(1)$ extracted from Heavy Quark Effective Theory [Falk, Neubert (1992)]

$$R_3(1) = \frac{R_2(1)(1-r) + r\,[R_0(1)(1+r) - 2]}{(1-r)^2} = 0.97 \pm 0.10$$

includes leading-order perturbative (in α_s) and power $(1/m_{b,c})$ corrections to the heavy-quark limit, plus 10% uncertainty to account for higher-order contributions.

$\bar{B} \to D^* l \bar{\nu}$ helicity amplitudes

- $$H_{\pm\pm}(q^2) = (m_B + m_{D^*})\, A_1(q^2) \mp \frac{2m_B}{m_B + m_{D^*}} |\vec{\mathbf{p}}|\, V(q^2)$$
- $$H_{00}(q^2) = \frac{1}{2m_{D^*}\sqrt{q^2}} [(m_B^2 - m_{D^*}^2 - q^2)\,(m_B + m_{D^*})\, A_1(q^2) - \frac{4m_B^2|\vec{\mathbf{p}}|^2}{m_B + m_{D^*}} A_2(q^2)]$$
- $$H_{0t}(q^2) = \frac{2m_B|\vec{\mathbf{p}}|}{\sqrt{q^2}} A_0(q^2)$$

Hagiwara, Martin, Wade [Phys. Lett. B **228** (1989) 144, Nucl. Phys. B **327** (1989) 569]

Korner, Schuler [Z. Phys. C **46** (1990) 93]

Fajfer, Kamenik,Nisandzic [1203.2654]

$\bar{B} \to D^* l \bar{\nu}$ differential decay width

- $$\frac{d^2\Gamma^{D^*}[\lambda_l = -1/2]}{dq^2 d\cos\theta} = \frac{G_F^2 |V_{cb}|^2 |\vec{\mathbf{p}}| q^2}{256\pi^3 m_B^2} \left(1 - \frac{m_l^2}{q^2}\right)^2 \times \left[(1-\cos\theta)^2 \, |H_{++}|^2 + (1+\cos\theta)^2 \, |H_{--}|^2 + 2\sin^2\theta \, |H_{00}|^2\right]$$

- $$\frac{d^2\Gamma^{D^*}[\lambda_l = +1/2]}{dq^2 d\cos\theta} = \frac{G_F^2 |V_{cb}|^2 |\vec{\mathbf{p}}| q^2}{256\pi^3 m_B^2} \left(1 - \frac{m_l^2}{q^2}\right)^2 \frac{m_l^2}{q^2} \times \left[\sin^2\theta \, (|H_{++}|^2 + |H_{--}|^2) + 2\, |H_{0t} - H_{00}\cos\theta|^2\right]$$

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