$B \to D^{(*)}\tau\nu$ Decays in the 2HDM

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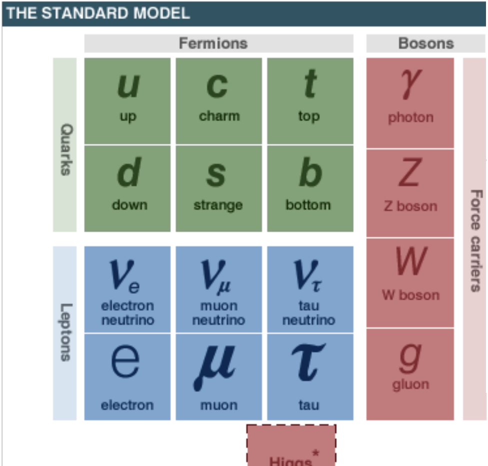
In collaboration with: Martin Jung, Xin-Qiang Li and Antonio Pich.

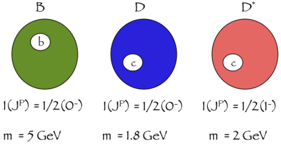
DISCRETE 2012, December 6 (2012)

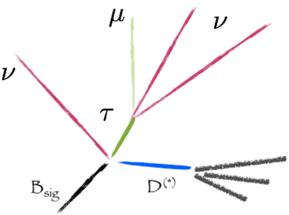
What can we learn from $B \to D^{(*)}\tau\nu$ Decays?

$$\mathcal{L}_Y = \bar{Q}_L(Y_d\, H)d_R \to \frac{M_d}{v}\bar{Q}_L\, H d_R$$

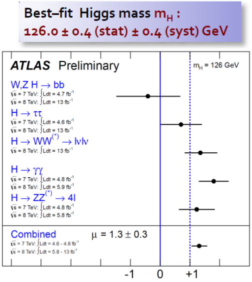
$$\mathcal{L}_W \to \frac{g}{\sqrt{2}}\left[W^+_\mu\, \bar{u}_L\, V_{CKM}\, \gamma^\mu\, d_L\right]$$



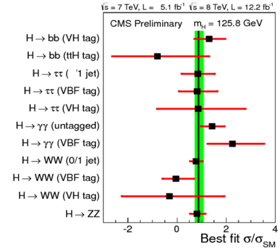




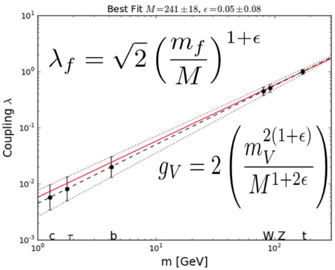
What can we learn from $B \to D^{(*)}\tau\nu$ Decays?

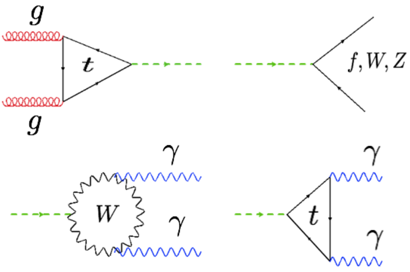


- M=125.8 ±0.4 (stat) ± 0.4 (syst) GeV



- σ/σ_{SM}=0.88±0.21

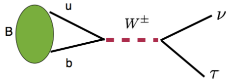


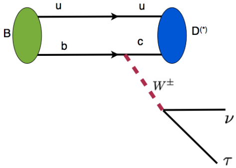


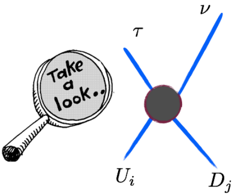
$$M = 241 \pm 18 \qquad \epsilon = 0.05 \pm 0.08$$

J. Ellis & T. You

What can we learn from $B \to D^{(*)}\tau\nu$ Decays?







a second Higgs doublet $\rightarrow$ **8 real fields**

$$\phi_k = \begin{pmatrix} {\phi_k}^{+} \\ {\phi_k}^{0} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_k^1 + i\phi_k^2 \\ \phi_k^3 + i\phi_k^4 \end{pmatrix}.$$

3 Goldstone bosons: $\mathbf{M_{W^{\pm}}, M_Z}$

3 neutral Higgs bosons: $\mathbf{h, H, A}$

2 charged Higgs: $\mathbf{H^{\pm}}$

What can we learn from $B \to D^{(*)}\tau\nu$ Decays?

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v}\bar{Q}_L(M_d\,\phi_1 + Y_d\,\phi_2)d_R$$

FCNC at tree level! ‣ see G. C. Branco, et. al. (2011) for a review

$Y_f = \varsigma_f\, M_f$ **Yukawa Alignment** [Pich, Tuzon (2009)]

$\varsigma_u = \cot\beta\,, \qquad \varsigma_d = \varsigma_l = -\tan\beta$ Type II 2HDM

$$H^+(x)\left\{\bar{u}(x)\left[\varsigma_d\, V M_d \mathcal{P}_R - \varsigma_u\, M_u^\dagger V \mathcal{P}_L\right] d(x) \,+\, \varsigma_l\, \bar{\nu}(x) M_l \mathcal{P}_R l(x)\right\}$$

Charged scalar couplings proportional to fermion masses

$B \to D^{(*)}\tau\nu$ decays are an excellent laboratory to look for NP effects related to EWSB

What can we learn from $B \to D^{(*)}\tau\nu$ Decays?

[Y. Sakaki, H. Tanaka, R. Watanabe, U. Nierste, S. Trine, S. Westhoff, S. Faller, T. Mannel, S. Turczyk , S. Fajfer, J. F. Kamenik, I. Nisandzic, F. Mescia, A. Crivellin, C. Greub, A. Kokulu, A. Datta, M. Duraisamy, D. Ghosh]

Normalization by light leptons possible

$\Rightarrow$ get rid of many sources of uncertainty

$$R\left(D^{(*)}\right) = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\nu)}{\Gamma(\bar{B} \to D^{(*)}l\nu)} \qquad l = e \text{ or } \mu$$

theoretical errors at the level of $6\ \%$ and $1.6\ \%$ for D and D^*

$R(D)_{SM} = (0.296 \pm 0.017)$ $\qquad$ $R(D^*)_{SM} = (0.252 \pm 0.004)$

$R(D)_{exp} = (0.438 \pm 0.056)$ $\qquad$ $R(D^*)_{exp} = (0.354 \pm 0.026)$

Belle and BaBar Averages.

Enhancement could be due to charged scalar contributions

excess cannot be explained in the Type II 2HDM

Phys. Rev. Lett. **109** (2012) 101802 see talk by E. Manoni

What can we learn from $B \to D^{(*)}\tau\nu$ Decays?

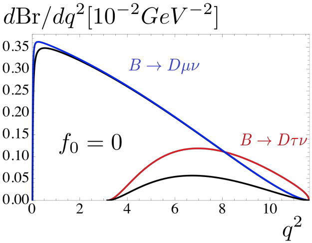
$$q^2 = (p_B - p_{D^{(*)}})^2$$

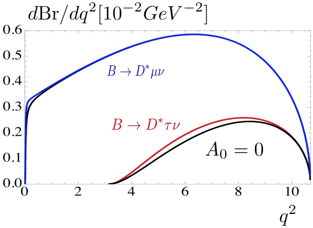
[Caprini, Lellouch, Neubert, Isgur, Wise]

$B \to D$	$B \to D^*$
$f_0(q^2)\,,\, f_+(q^2)$	$A_0(q^2), V(q^2), A_1(q^2), A_2(q^2)$

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

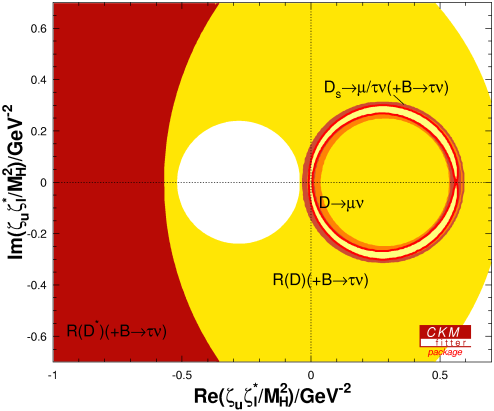
$$\tilde{A}_0(q^2) = A_0(q^2)\left[1 - \frac{q^2}{m_{H^\pm}^2}\left(\frac{m_c\,\varsigma_u\varsigma_l^* + m_b\,\varsigma_d\varsigma_l^*}{m_b + m_c}\right)\right]$$





$R(D)$ and $R(D^*)$ in the 2HDM

$B \to \tau\nu$, $D_{(s)} \to \mu\nu$, $D_s \to \tau\nu$



At 95% C.L.

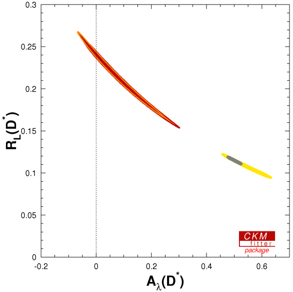
Departure from family Universality of Yukawa couplings

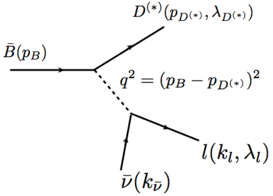
$$Y_q = \varsigma_q \, M_q$$

[A.C., M. Jung, X. Li, A. Pich. (2012)]

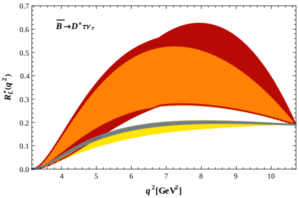
$B \to D^{(*)}\tau\nu$ at future Super-Flavor Factories

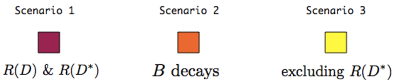
[Korner, Schuler, Hagiwara, Martin, Wade, Nierste, Trine, Westhoff, Tanaka, Watanabe, Sakaki, Chen, Geng, Fajfer, Kamenik, Nisandzic, Datta, Duraisamy, Ghosh]





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





[A.C., M. Jung, X. Li, A. Pich. (2012)]

Conclusions

- $B \to D^{(*)}\tau\nu$ **decays are an excellent laboratory to test the mechanism of electroweak symmetry breaking** (c, b, τ, ν_τ)**. NP at tree level. Rich three-body kinematics. All the ingredients to look for new physics "and determine its nature".**
- **What are the prospects for future Super Flavor Factories?,** $B_c \to \tau\nu$ **?**
- **Experimentally very challenging process... I hope to have convinced you that it worths the effort.**
- Expected update from Belle. Will LHCb surprise us?

Conclusions

Not covered in this talk: Recent progress on the theoretical determination of the form-factors

Bailey *et al.* [1206.4992]

Becirevic, Kosnik, Tayduganov [1206.4977]

Other NP models proposed to explain the observed excess in $B \to D^{(*)}\tau\nu$ decays:

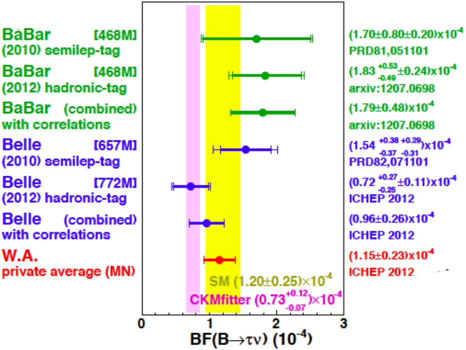
Fajfer, Kamenik, Nisandzic, Zupan [1206.1872]
Crivellin, Greub, Kokulu [1206.2634]
Xiao-Gang He, Valencia [1211.0348]
Deshpande, Menon [1208.4134]

Apologies to authors whose contributions might have not been mentioned in this talk.

Back-Up Slides

$B \to \tau\nu$ Decays

large theoretical uncertainties from f_B and $|V_{cb}|$



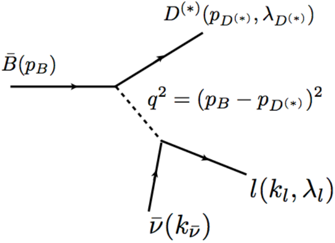
From Nakao talk, ICHEP 2012.

BR_{SM} : $(0.79^{+0.06}_{-0.04}\pm0.08)\times10^{-4}$ $\quad$ BR_{exp} : $(1.15\pm0.23)\times10^{-4}$

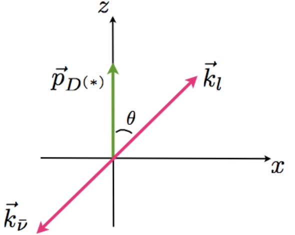
$|V_{ub}|$ *from exclusive and inclusive semileptonic $b \to ul\bar{\nu}$ transitions*

$$\mathrm{Br}(B^- \to \tau\bar{\nu}) \overset{m_u=0}{\simeq} \mathrm{Br}(B^- \to \tau\bar{\nu})_{SM} \left|1 - \varsigma_d \varsigma_l^* \frac{m_B^2}{m_{H^\pm}^2}\right|^2$$

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

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

[Falk, Neubert (1992)]

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

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

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

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

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

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

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

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

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

- $$\langle D^*(p_{D^*}, \epsilon^*) | \bar{c}\gamma_\mu \gamma_5 b | \bar{B}(p_B) \rangle \; = \; 2m_{D^*} \, A_0(q^2) \, \frac{\epsilon^* \cdot q}{q^2} \, q_\mu$$

$$+ \, (m_B + m_{D^*}) \, A_1(q^2) \, \left(\epsilon^*_\mu - \frac{\epsilon^* \cdot q}{q^2} \, q_\mu \right)$$

$$- \, A_2(q^2) \, \frac{\epsilon^* \cdot q}{m_B + m_{D^*}} \, \left[(p_B + p_{D^*})_\mu - \frac{m_B^2 - m_{D^*}^2}{q^2} \, q_\mu \right] \, .$$

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)]

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

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

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

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

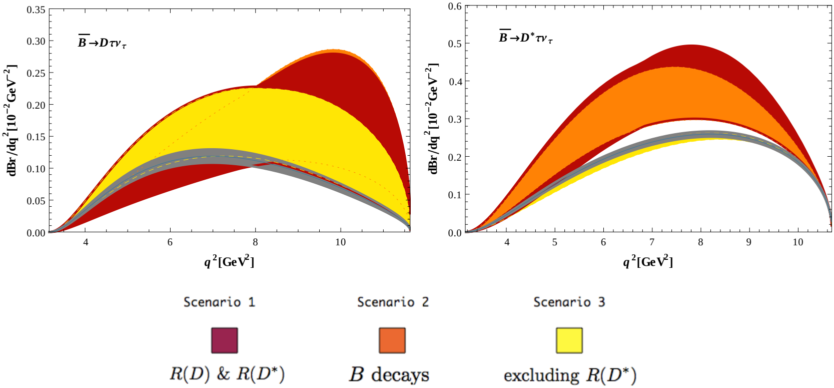
Hagiwara, Martin, Wade [Phys. Lett. B **228** (1989) 144, Nucl. Phys. B **327** (1989) 569]

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

Fajfer, Kamenik,Nisandzic [1203.2654]

q^2 distributions

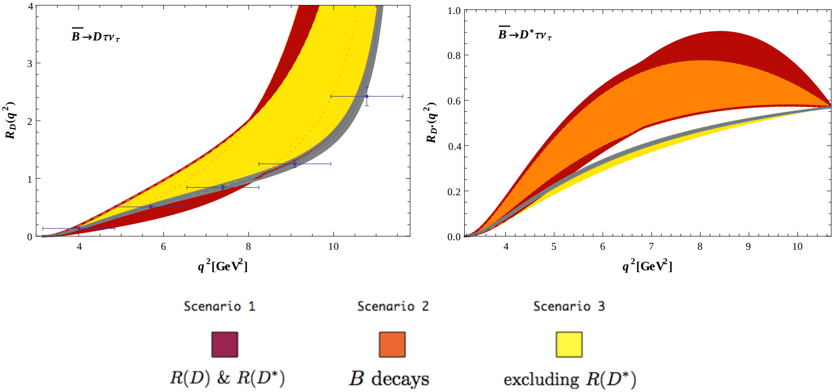
$$\frac{d\mathrm{Br}(B \to D^{(*)}\tau\nu)}{dq^2}$$



[A.C., M. Jung, X. Li, A. Pich. (2012)]

q^2 distributions

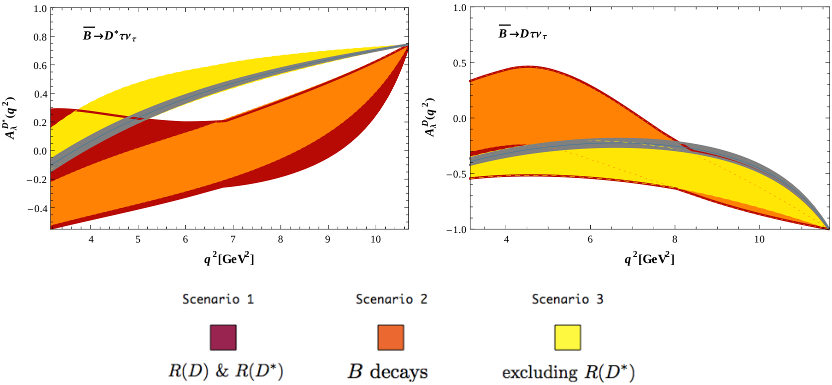
$$R_{D^{(*)}}(q^2) = \frac{d\Gamma(B \to D^{(*)}\tau\nu)/dq^2}{d\Gamma(B \to D^{(*)}l\nu)/dq^2}$$



[A.C., M. Jung, X. Li, A. Pich. (2012)]

Tau spin asymmetry

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

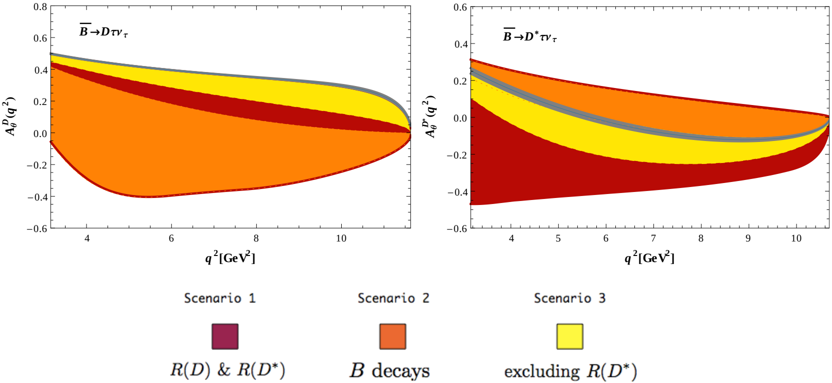


▸ [A.C., M. Jung, X. Li, A. Pich. (2012)]

Forward-backward asymmetry

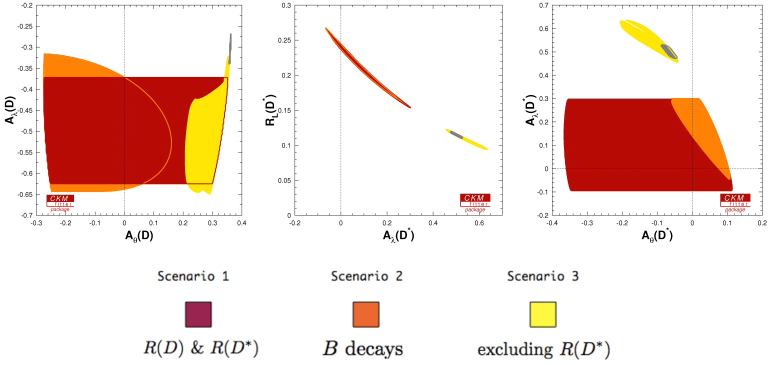
[A.C., M. Jung, X. Li, A. Pich. (2012)]

$$A_\theta^{D^{(*)}}(q^2) = \frac{\int_{-1}^{0} d\cos\theta \left(\frac{d^2\Gamma_\tau^{D^{(*)}}}{dq^2\, d\cos\theta}\right) - \int_{0}^{1} d\cos\theta \left(\frac{d^2\Gamma_\tau^{D^{(*)}}}{dq^2\, d\cos\theta}\right)}{d\Gamma_\tau^{D^{(*)}}/dq^2}$$



Integrated asymmetries and other observables

[A.C., M. Jung, X. Li, A. Pich. (2012)]



Observables independent of scalar contributions

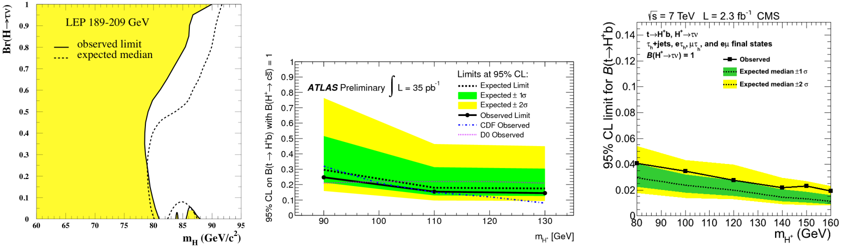
$$X_1(q^2) = R_{D^*}(q^2) - R_L^*(q^2)$$

$$X_2^{D^{(*)}}(q^2) = R_{D^{(*)}}(q^2)\left(A_\lambda^{D^{(*)}}(q^2) + 1\right)$$

if only scalar NP relevant, $X_{1,2}$ should be equal to the SM prediction

Interplay between flavor and LHC physics.

LEP upper limit on the charged Higgs mass $e^+e^- \to H^+H^-$



Charged Higgs coupling with the top quark

LHC searches for a charged Higgs $t \to W^+(H^+)b$

Loop induced processes: $Z \to b\bar{b}$, Kaon mixing, B mixing.