Rare B decays: Theory

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1. **Introduction**
2. $B^0 \to l^+ l^-$ **and** $B_s \to l^+ l^-$
3. $B \to K^* \gamma$ **and** $B_s \to \phi\gamma$
4. $B \to K^* \mu^+ \mu^-$ **and** $B_s \to \phi\mu^+\mu^-$
5. **Summary**

The effective theory:

$$\mathcal{L}_{\rm (B)SM} \longrightarrow \mathcal{L}_{\rm eff} \equiv \mathcal{L}_{\rm QCD \times QED}(u,d,s,c,b;e,\mu,\tau) + \frac{4G_F}{\sqrt{2}} \sum_i f_i^{\rm CKM} C_i\, O_i$$
$$+ \text{ (dim} \geq 6 \text{ operators).}$$

Decoupling W, Z, t, H^0, and all the BSM particles with $m_i \gg m_b$.

Let's assume that all the relevant BSM particles can be decoupled.

O_i **– operators of dimension 5 or 6**

C_i **– their Wilson coefficients**

In the SM or any weakly-coupled BSM theory, C_i are perturbatively calculable functions of masses, couplings and renormalization scales.

The operators O_i that matter for $\bar{B}_s \to \mu^+\mu^-$ read:

$$O_{10} = \tfrac{\alpha_{\rm em}}{4\pi} \left(\bar{s}_L \gamma^\nu b_L\right) \left(\bar{\mu}\gamma_\nu\gamma_5\mu\right),$$

$$O_S = \tfrac{\alpha_{\rm em}}{4\pi} \left(\bar{s}_L b_R\right) \left(\bar{\mu}\mu\right) \qquad \Leftrightarrow \quad \tfrac{\alpha_{\rm em}}{4\pi m_b} \left(\bar{s}_L \gamma^\nu b_L\right) \partial_\nu \left(\bar{\mu}\mu\right), \qquad \textbf{(EOM,}\ m_s = 0\textbf{)}$$

$$O_P = \tfrac{\alpha_{\rm em}}{4\pi} \left(\bar{s}_L b_R\right) \left(\bar{\mu}\gamma_5\mu\right) \quad \Leftrightarrow \quad \tfrac{\alpha_{\rm em}}{4\pi m_b} \left(\bar{s}_L \gamma^\nu b_L\right) \partial_\nu \left(\bar{\mu}\gamma_5\mu\right)$$

The only necessary non-perturbative input:

$$\langle 0|\bar{s}_L \gamma^\nu b_L|\bar{B}_s(p)\rangle = \langle 0|\bar{s}\gamma^\nu\gamma_5 b|\bar{B}_s(p)\rangle \sim p^\nu f_{B_s}.$$

The branching ratio:

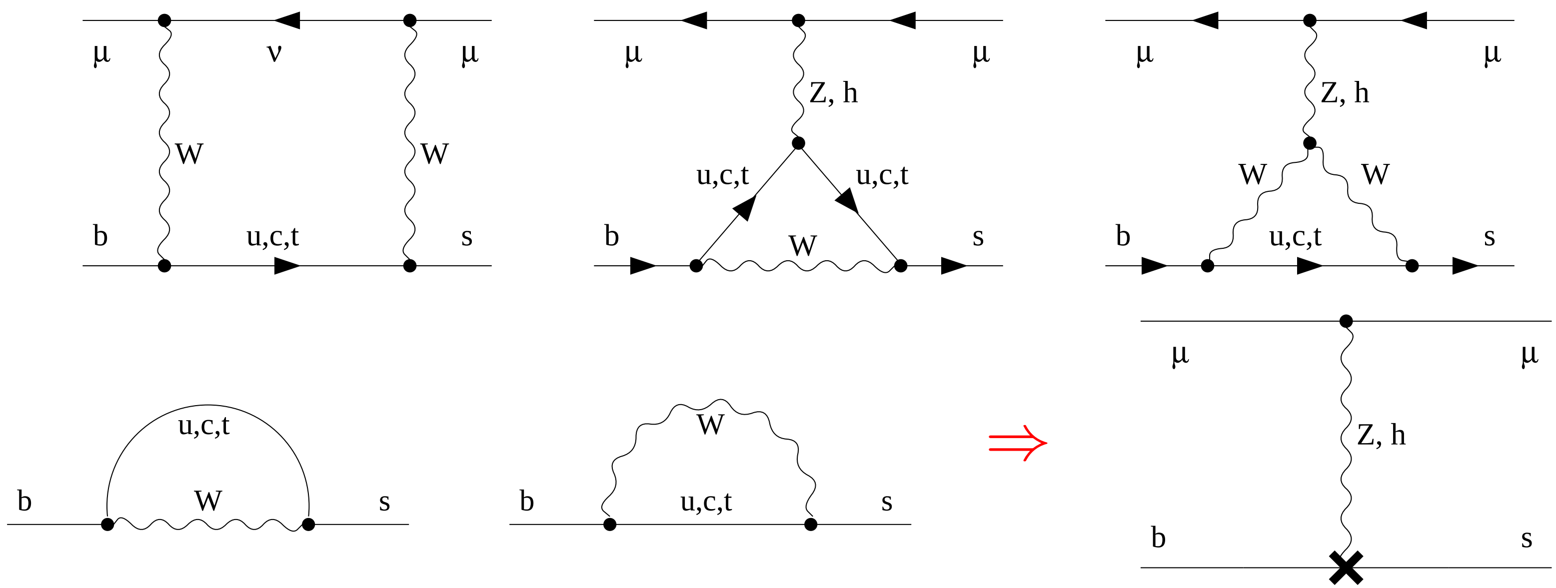
$$\mathcal{B}(\bar{B}_s \to \mu^+\mu^-) = \frac{G_F^2 \alpha_{\rm em}^2}{64\pi^3} \left|V_{ts}^* V_{tb}\right|^2 \tau_{B_s} M_{B_s}^3 f_{B_s}^2 \sqrt{1 - \frac{4m_\mu^2}{M_{B_s}^2}}$$

$$\times \left[\left(1 - \frac{4m_\mu^2}{M_{B_s}^2}\right) \left(\frac{M_{B_s}}{m_b}\, C_S\right)^2 + \left(\frac{M_{B_s}}{m_b}\, C_P - 2\frac{m_\mu}{M_{B_s}}\, C_{10}\right)^2 \right].$$

$$\mathcal{B}(\bar{B}_s \to \mu^+\mu^-) = \frac{G_F^2 \alpha_{\rm em}^2}{64\pi^3} \, |V_{ts}^* V_{tb}|^2 \, \tau_{B_s} \, M_{B_s}^3 \, f_{B_s}^2 \sqrt{1 - \frac{4m_\mu^2}{M_{B_s}^2}}$$

$$\times \left[\left(1 - \frac{4m_\mu^2}{M_{B_s}^2}\right) \left(\frac{M_{B_s}}{m_b} \, C_S\right)^2 + \left(\frac{M_{B_s}}{m_b} \, C_P - 2\frac{m_\mu}{M_{B_s}} \, C_{10}\right)^2 \right].$$

Evaluation of the Wilson coefficients in the SM:

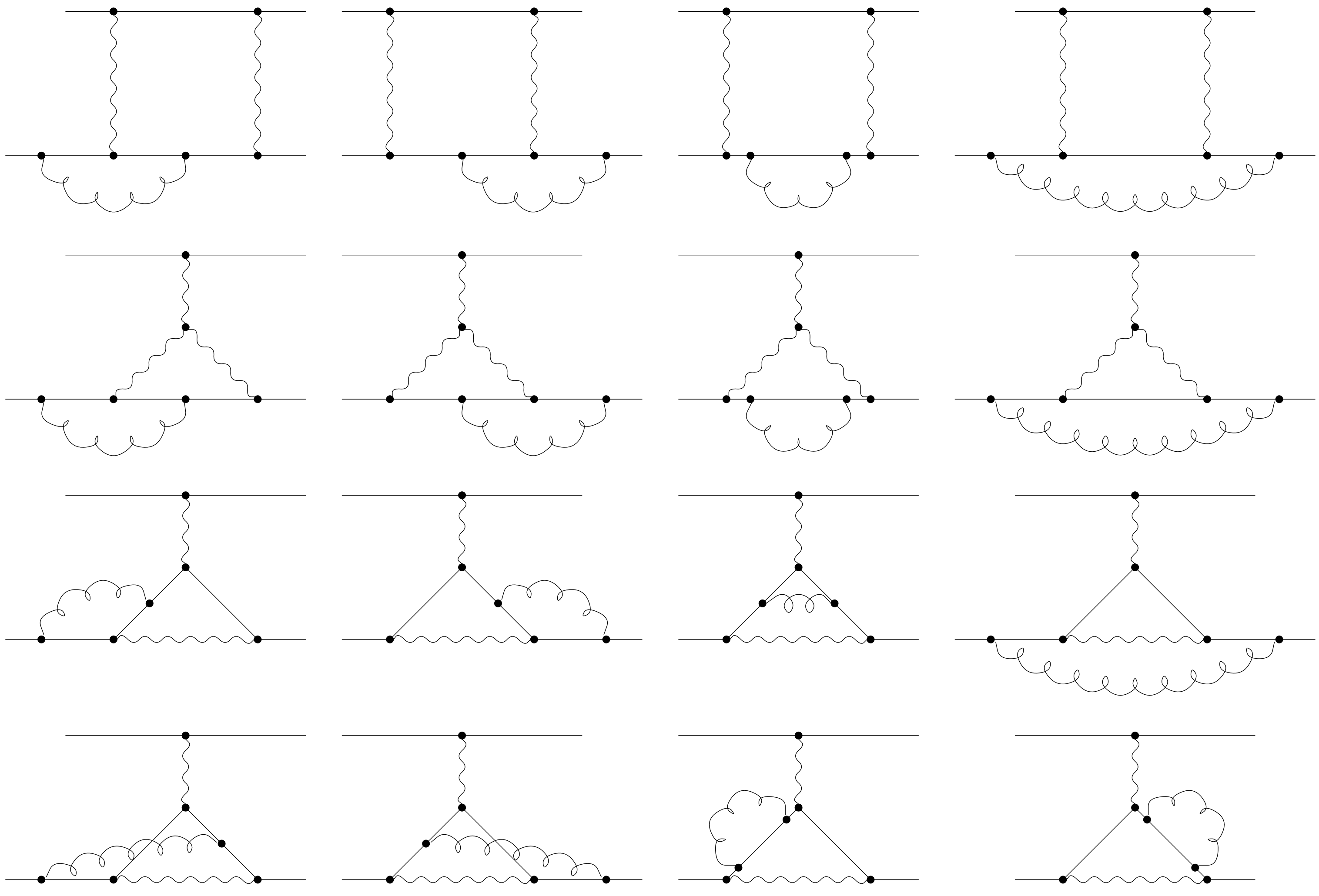


$$C_{10} = -\frac{Y_0(m_t^2/M_W^2)}{\sin^2\theta_W}, \quad Y_0(x) = \frac{3x^2}{8(x-1)^2} \ln x + \frac{x^2-4x}{8(x-1)}, \quad C_{S,P} = \mathcal{O}\left(\frac{m_\mu m_b}{M_W^2}\right).$$

Effects of $C_{S,P}$ suppressed by m_b^2/M_W^2 ⇒ negligible.

The NLO QCD corrections to C_{10} are known in the SM.

G. Buchalla and A.J. Buras, Nucl. Phys. B 400 (1993) 225,
MM and J. Urban, Phys. Lett. B 451 (1999) 161 [hep-ph/9901278],
G. Buchalla and A.J. Buras, Nucl. Phys. B 548 (1999) 309 [hep-ph/9901288]



They are small ($\sim 3\%$) when $\overline{m}_t(\overline{m}_t)$ is used at the LO.

The SM predictions:

[arXiv:0801.1833, WG2 report, "Flavor in the Era of the LHC"]

$$\mathcal{B}\left(B_s \to \tau^+\tau^-\right) = (8.20 \pm 0.31) \cdot 10^{-7} \times \frac{\tau_{B_s}}{1.527\,\mathbf{ps}} \left[\frac{|V_{ts}|}{0.0408}\right]^2 \left[\frac{f_{B_s}}{240\ \mathrm{MeV}}\right]^2$$

$$\mathcal{B}\left(B_s \to \mu^+\mu^-\right) = (3.86 \pm 0.15) \cdot 10^{-9} \times \frac{\tau_{B_s}}{1.527\,\mathbf{ps}} \left[\frac{|V_{ts}|}{0.0408}\right]^2 \left[\frac{f_{B_s}}{240\ \mathrm{MeV}}\right]^2$$

$$\mathcal{B}\left(B_s \to e^+e^-\right) = (9.05 \pm 0.34) \cdot 10^{-14} \times \frac{\tau_{B_s}}{1.527\,\mathbf{ps}} \left[\frac{|V_{ts}|}{0.0408}\right]^2 \left[\frac{f_{B_s}}{240\ \mathrm{MeV}}\right]^2$$

$$\mathcal{B}\left(B_d \to \tau^+\tau^-\right) = (2.23 \pm 0.08) \cdot 10^{-8} \times \frac{\tau_{B_d}}{1.527\,\mathbf{ps}} \left[\frac{|V_{td}|}{0.0082}\right]^2 \left[\frac{f_{B_d}}{200\ \mathrm{MeV}}\right]^2$$

$$\mathcal{B}\left(B_d \to \mu^+\mu^-\right) = (1.06 \pm 0.04) \cdot 10^{-10} \times \frac{\tau_{B_d}}{1.527\,\mathbf{ps}} \left[\frac{|V_{td}|}{0.0082}\right]^2 \left[\frac{f_{B_d}}{200\ \mathrm{MeV}}\right]^2$$

$$\mathcal{B}\left(B_d \to e^+e^-\right) = (2.49 \pm 0.09) \cdot 10^{-15} \times \frac{\tau_{B_d}}{1.527\,\mathbf{ps}} \left[\frac{|V_{td}|}{0.0082}\right]^2 \left[\frac{f_{B_d}}{200\ \mathrm{MeV}}\right]^2$$

The exp. 90%CL bounds exceed the SM predictions by factors of
12, **150**, $\mathcal{O}(10^9)$, $\mathcal{O}(10^7)$ **and** $\mathcal{O}(10^5)$ **for**
$B_s \to \mu^+\mu^-$, $B_d \to \mu^+\mu^-$, $B_s \to e^+e^-$, $B_d \to e^+e^-$ **and** $B_{s,d} \to \tau^+\tau^-$,
respectively.

The SM predictions:

[arXiv:0801.1833, WG2 report, "Flavor in the Era of the LHC"]

$$\mathcal{B}\left(B_s \to \tau^+\tau^-\right) = (8.20 \pm 0.31)\cdot 10^{-7} \times \frac{\tau_{B_s}}{1.527\,\mathbf{ps}}\left[\frac{|V_{ts}|}{0.0408}\right]^2\left[\frac{f_{B_s}}{240\ \mathrm{MeV}}\right]^2$$

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Uncertainties in the lattice determinations of f_{B_q} are $\sim 10-20\%$.

From the Belle measurement of $B^\pm \to \tau^\pm\nu$, isospin symmetry and CKM fits (assuming SM): $f_{B_d} = \left(229^{+36}_{-31}(\mathrm{stat})^{+34}_{-37}(\mathrm{syst})\right)$ **MeV**

One can get rid of f_B by normalizing to the well-measured $B_q\bar{B}_q$ mixing ($q = s$ or d):

$$R \equiv \frac{\mathcal{B}(B_q \to l^+ l^-)}{\Delta M_{B_q} \tau_{B_q}} = \left(\hat{B}_q\right)^{-1} \times \left(\begin{array}{c} \textbf{perturbatively calculable quantity} \\ \textbf{in the SM or any weakly-coupled BSM} \end{array} \right),$$

where the bag parameter $\hat{B}_q$ is given by

$$\hat{B}_q = \frac{\langle \bar{B}_q | (\bar{b}_L \gamma^\nu q_L)(\bar{b}_L \gamma_\nu q_L) | B_q \rangle}{\langle \bar{B}_q | (\bar{b}_L \gamma^\nu q_L) | 0 \rangle \langle | 0 (\bar{b}_L \gamma_\nu q_L) | B_q \rangle}.$$

Errors in the lattice determinations of $\hat{B}_q$ are $\mathcal{O}(10\%)$.

For instance,

$\hat{B}_s = 0.940 \pm 0.016 \pm 0.022$, **D. Becirevic** *et al.*, **hep-lat/0509165,**

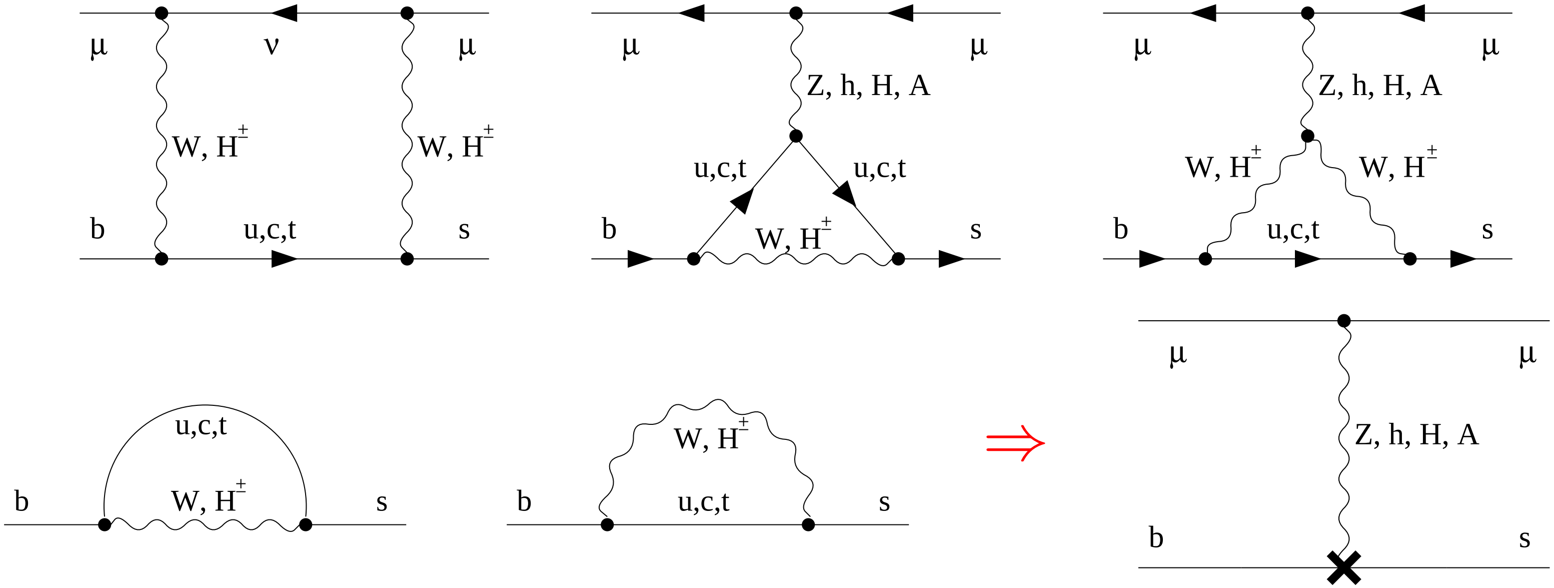
$\hat{B}_d = 0.836 \pm 0.027\,^{+0.056}_{-0.062}$, **S. Aoki** *et al.*, **hep-lat/0307039.**

In the SM (or any MFV model), also the CKM angles cancel in R.

The current uncertainty in the SM prediction for R is $\mathcal{O}(15\%)$.

Evaluation of the Wilson coefficients beyond the SM.

Example 1: the Two-Higgs-Doublet Model II



$$\tan\beta = v_2/v_1, \qquad r = M_{H^\pm}^2/m_t^2,$$

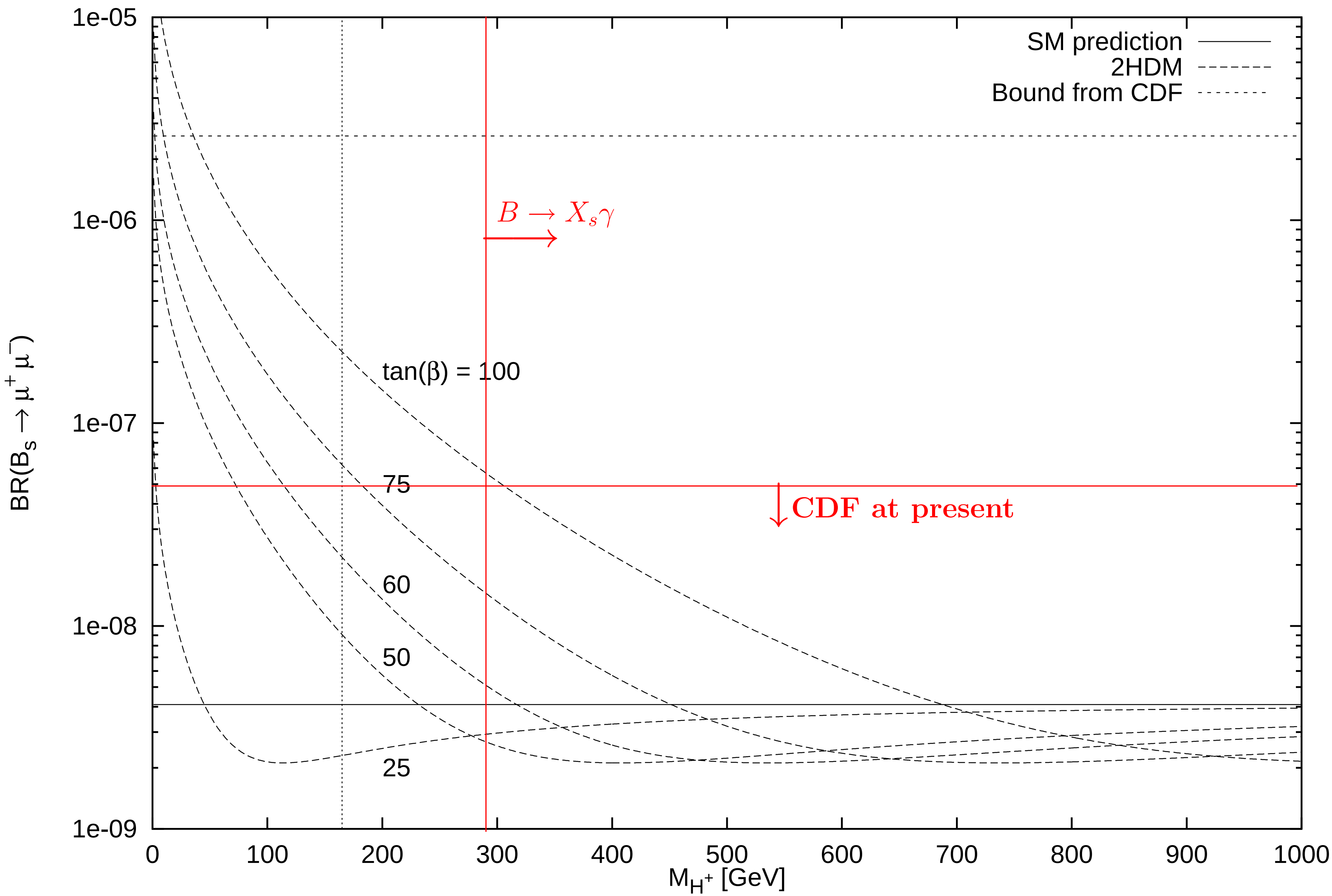
$$C_S \simeq C_P \simeq -\frac{m_\mu m_b}{2M_W^2}\,\frac{\tan^2\beta}{\sin^2\theta_W}\,\frac{\ln r}{r-1} < 0,$$

H.E. Logan and U. Nierste, NPB 586 (2000) 39
($\mathcal{O}(\tan\beta)$ neglected)

$$\mathcal{B}(\bar{B}_s \to \mu^+\mu^-) \sim \left[\left(1-\frac{4m_\mu^2}{M_{B_s}^2}\right)\left(\frac{M_{B_s}}{m_b}\,C_S\right)^2 + \left(\frac{M_{B_s}}{m_b}\,C_P - 2\frac{m_\mu}{M_{B_s}}\,C_{10}\right)^2\right]$$

$$C_{10} = \underbrace{C_{10}^{\rm SM}}_{\textbf{negative}} + \underbrace{\Delta C_{10}}_{\textbf{small}} \qquad \Rightarrow \begin{cases} \textbf{suppression for moderate } C_{S,P} \\ \textbf{enhancement for huge } \tan\beta \textbf{ only} \end{cases}$$

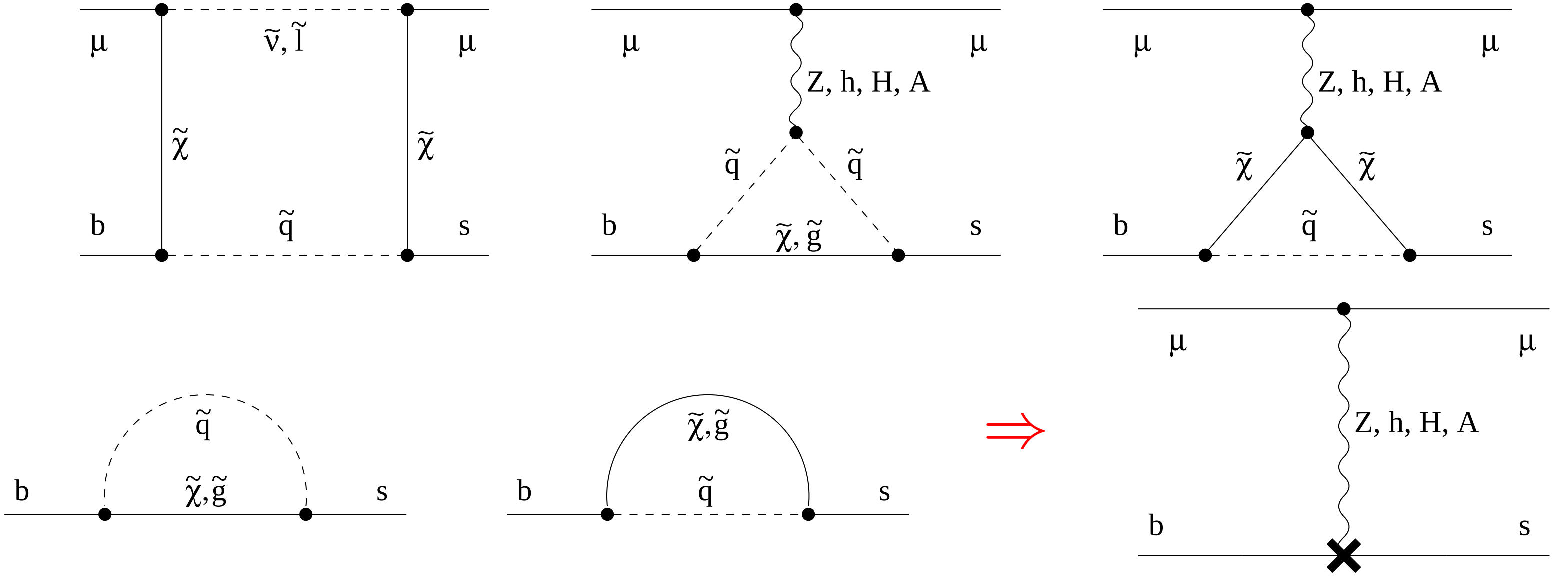
Fig. 3 of Logan & Nierste, hep-ph/0004139:



For $M_{H^\pm} = 500 GeV$ and $\tan\beta = 50$: suppression by $\mathcal{O}(50\%)$.
Enhancement possible only for $\tan\beta > 60$.

Evaluation of the Wilson coefficients beyond the SM.

Example 2: the MSSM.



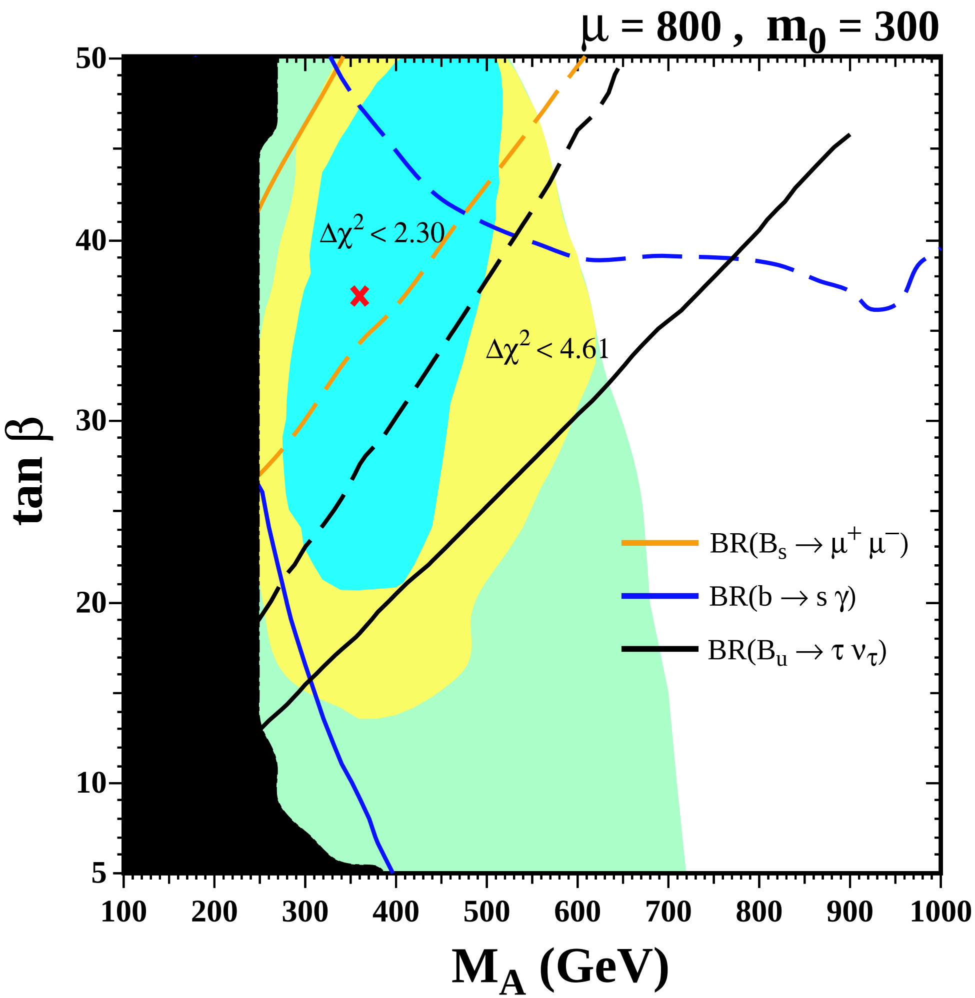
For large $\tan\beta$**:** $$\mathcal{B}\left(B_s \to \mu^+\mu^-\right) \sim \frac{m_b^2 m_\mu^2}{M_A^4} \tan^6\beta$$

K. S. Babu and C. F. Kolda, Phys. Rev. Lett. 84 (2000) 228.

Example of constraints on the MSSM parameter space from

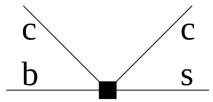
J. Ellis, T. Hahn, S. Heinemeyer, K. A. Olive and G. Weiglein, JHEP 0710 (2007) 092

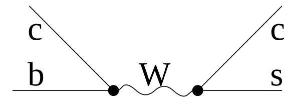
Fig. 9b



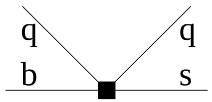
$$\mathcal{B}\left(B_s \to \mu^+\mu^-\right) = \begin{cases} 2 \times 10^{-8}, & \text{dashed orange line,} \\ 4.7 \times 10^{-8}, & \text{current CDF 90\%CL bound,} \\ 1 \times 10^{-7}, & \text{solid orange line.} \end{cases}$$

The operators O_i that matter for $\bar{B} \to \bar{K}^*\gamma$ and $\bar{B}_s \to \phi\gamma$ read:

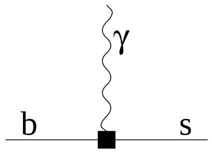
$O_{1,2} =$ 

$= (\bar{s}\Gamma_i c)(\bar{c}\Gamma'_i b),$ **from** 

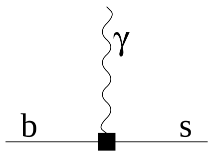
$, \qquad |C_i(m_b)| \sim 1$

$O_{3,4,5,6} =$ 

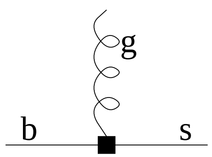
$= (\bar{s}\Gamma_i b)\sum_q(\bar{q}\Gamma'_i q), \qquad |C_i(m_b)| < 0.07$

$O_7 =$ 

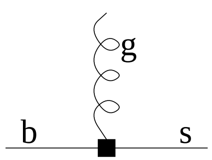
$= \frac{e m_b}{16\pi^2}\, \bar{s}_L \sigma^{\mu\nu} b_R F_{\mu\nu}, \qquad C_7^{\rm SM}(m_b) \simeq -0.3$

$O'_7 =$ 

$= \frac{e m_b}{16\pi^2}\, \bar{s}_R \sigma^{\mu\nu} b_L F_{\mu\nu}, \qquad C_7^{\prime\rm SM} = \frac{m_s}{m_b} C_7^{\rm SM}$

$O_8 =$ 

$= \frac{g m_b}{16\pi^2}\, \bar{s}_L \sigma^{\mu\nu} T^a b_R G^a_{\mu\nu}, \qquad C_8^{\rm SM}(m_b) \simeq -0.15$

$O'_8 =$ 

$= \frac{g m_b}{16\pi^2}\, \bar{s}_R \sigma^{\mu\nu} T^a b_L G^a_{\mu\nu}, \qquad C_8^{\prime\rm SM} = \frac{m_s}{m_b} C_8^{\rm SM}$

Their SM Wilson coefficients are known up to $\mathcal{O}(\alpha_s^2)$ (NNLO).

Assumption: no relevant NP effects in the 4-quark operators.

$$\Gamma(\bar{B}^0 \to K^{*0}\gamma)_{\rm exp} = (4.01 \pm 0.20) \times 10^{-5}$$ **[HFAG],**

$$\Gamma(\bar{B}_s \to \phi\gamma)_{\rm exp} = \left(5.7^{+1.8}_{-1.5}(\text{stat})^{+1.2}_{-1.1}(\text{syst})\right) \times 10^{-5}$$ **[BELLE, PRL 100 (2008) 121801].**

The decay rates $\Gamma(\bar{B} \to \bar{K}^*\gamma)$ and $\Gamma(\bar{B}_s \to \phi\gamma)$ are proportional to (practically) the same combinations of the Wilson coefficients as the inclusive rate $\Gamma(\bar{B} \to X_s\gamma)$.

Errors in the inclusive rate are $\mathcal{O}(7\%)$, both EXP and TH.

Theory uncertainties in the exclusive rates are $\mathcal{O}(30\%)$ due to non-perturbative form-factors.

A promising exclusive observable for constraining the Wilson coefficients:

The mixing-induced CP asymmetry

$$A_{\rm CP}(t) = \frac{\Gamma\left[\bar{B}^0(t)\to\bar{K}^{*0}\gamma\right] - \Gamma\left[B^0(t)\to K^{*0}\gamma\right]}{\Gamma\left[\bar{B}^0(t)\to\bar{K}^{*0}\gamma\right] + \Gamma\left[B^0(t)\to K^{*0}\gamma\right]} = C_{K^*\gamma}\cos(\Delta m_B t) + S_{K^*\gamma}\sin(\Delta m_B t).$$

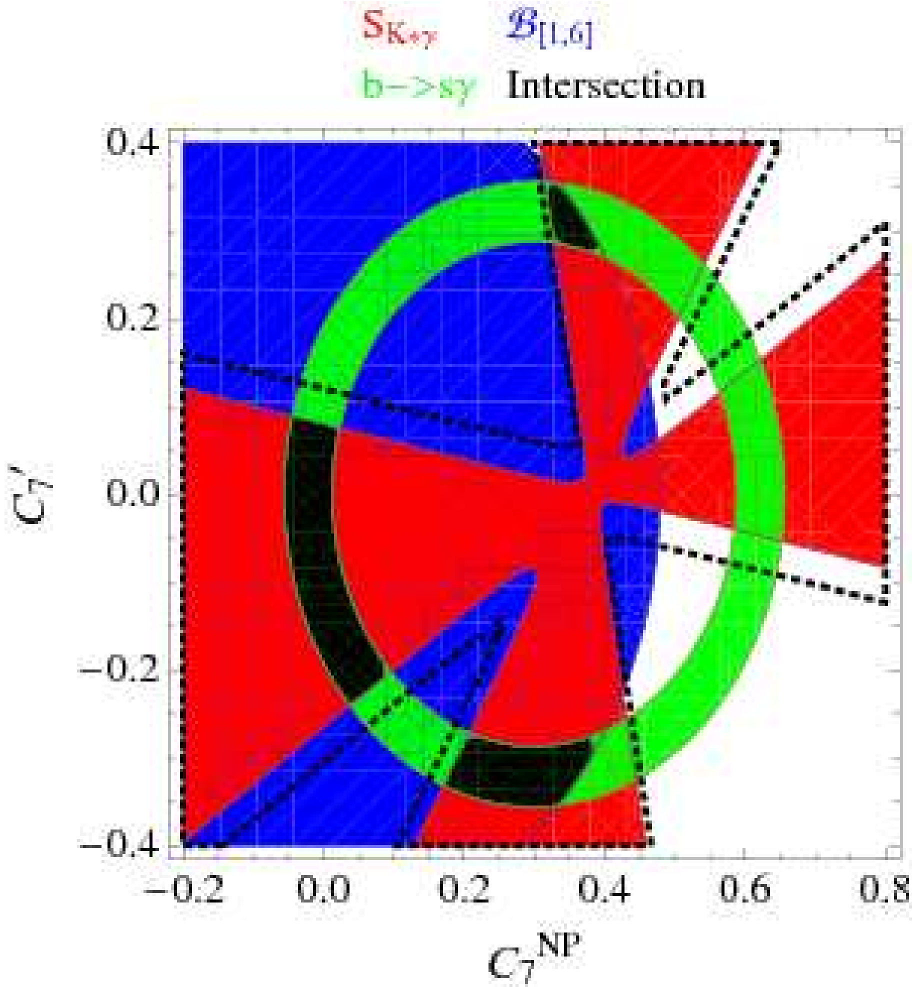
$$S^{\rm th}_{K^*\gamma} = -\frac{2|z|}{1+|z|^2}\sin\left[2\beta - \arg\left(C_7 C_7'\right)\right] + \ldots \stackrel{\rm SM}{\simeq} -0.03, \qquad z = \frac{C_7'}{C_7} \stackrel{\rm SM}{\simeq} \frac{m_s}{m_b}.$$

$$S^{\rm exp}_{K^*\gamma} = -0.19 \pm 0.23$$ **[BaBar,Belle $\to$ HFAG].**

Constraints in the $(C_7^{\rm NP} \equiv C_7 - C_7^{\rm SM}, C_7')$ plane from

C. Bobeth, G. Hiller and G. Piranishvili, **arXiv:0805.2525**

Fig. 2a



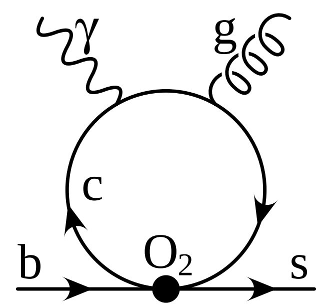
Green: $\bar{B} \to X_s \gamma$,

Blue: $\bar{B} \to X_s l^+ l^-$

$q^2_{\rm dilept} \in [1, 6]\ {\rm GeV}^2$,

Red: $S_{K^*\gamma}$

Black dotted lines: Effect of enlarging the uncertainty in the SM prediction for $S_{K^*\gamma}$ due to the $\mathcal{O}(\Lambda/m_b)$ fraction of right-handed photons originating from:



B. Grinstein, Y. Grossman, Z. Ligeti and D. Pirjol, Phys. Rev. D 71 (2005) 011504.

Assumptions for the above plot:

(i) $C_7^{\rm NP}$ and C_7' are real.

(ii) All the other Wilson coefficients are fixed at their SM values.

The operators O_i that matter for $\bar{B} \to \bar{K}^* \mu^+ \mu^-$ and $\bar{B}_s \to \phi \mu^+ \mu^-$ are the same as those for $\bar{B} \to \bar{K}^* \gamma$ and $\bar{B}_s \to \phi\gamma$, plus:

$$O_9 = \frac{\alpha_{\rm em}}{4\pi} \left(\bar{s}_L \gamma^\nu b_L\right) \left(\bar{\mu}\gamma_\nu \mu\right), \qquad O_9' = \frac{\alpha_{\rm em}}{4\pi} \left(\bar{s}_R \gamma^\nu b_R\right) \left(\bar{\mu}\gamma_\nu \mu\right),$$

$$O_{10} = \frac{\alpha_{\rm em}}{4\pi} \left(\bar{s}_L \gamma^\nu b_L\right) \left(\bar{\mu}\gamma_\nu \gamma_5 \mu\right), \qquad O_{10}' = \frac{\alpha_{\rm em}}{4\pi} \left(\bar{s}_R \gamma^\nu b_R\right) \left(\bar{\mu}\gamma_\nu \gamma_5 \mu\right),$$

and, in principle, also the four chirality-violating operators that do not contribute to $\bar{B}_s \to \mu^+ \mu^-$:

$$O_S' = \frac{\alpha_{\rm em}}{4\pi} \left(\bar{s} b\right) \left(\bar{\mu} \mu\right), \qquad O_P' = \frac{\alpha_{\rm em}}{4\pi} \left(\bar{s} b\right) \left(\bar{\mu} \gamma_5 \mu\right),$$

$$O_T = \frac{\alpha_{\rm em}}{4\pi} \left(\bar{s} \sigma^{\nu\lambda} b\right) \left(\bar{\mu} \sigma_{\nu\lambda} \mu\right), \qquad O_T' = \frac{\alpha_{\rm em}}{4\pi} \left(\bar{s} \sigma^{\nu\lambda} b\right) \left(\bar{\mu} \sigma_{\nu\lambda} \gamma_5 \mu\right).$$

The full angular distribution of $\bar{B} \to \bar{K}^*(\to \bar{K}\pi)\mu^+\mu^-$:

[C. Bobeth, G. Hiller and G. Piranishvili, arXiv:0805.2525]

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_{K^*}\, d\phi} = \frac{3}{8\pi} J(q^2, \theta_l, \theta_{K^*}, \phi),$$

$$\begin{aligned} J(q^2, \theta_l, \theta_{K^*}, \phi) \;=\; & J_1^s \sin^2\theta_{K^*} + J_1^c \cos^2\theta_{K^*} + (J_2^s \sin^2\theta_{K^*} + J_2^c \cos^2\theta_{K^*}) \cos 2\theta_l \\ +\; & J_3 \sin^2\theta_{K^*} \sin^2\theta_l \cos 2\phi + J_4 \sin 2\theta_{K^*} \sin 2\theta_l \cos\phi \\ +\; & J_5 \sin 2\theta_{K^*} \sin\theta_l \cos\phi + J_6 \sin^2\theta_{K^*} \cos\theta_l + J_7 \sin 2\theta_{K^*} \sin\theta_l \sin\phi \\ +\; & J_8 \sin 2\theta_{K^*} \sin 2\theta_l \sin\phi + J_9 \sin^2\theta_{K^*} \sin^2\theta_l \sin 2\phi. \end{aligned}$$

$q^2 =$ **dilepton invariant mass squared,**
$\theta_l =$ **angle between the μ^- and $\bar{B}$ momenta in the dilepton c.m.s.,**
$\theta_{K^*} =$ **angle between the $\bar{K}$ and $\bar{B}$ momenta in the $\bar{K}\pi$ c.m.s.,**
$\phi =$ **angle between the normals to the $\bar{K}\pi$ and $\mu^+\mu^-$ planes in the $\bar{B}$-meson rest frame.**

The forward-backward asymmetry:

$$A_{FB}(q^2) = \left(\frac{d\Gamma}{dq^2}\right)^{-1} \left[I_0^1 - I_{-1}^0 \right] d\cos\theta_l \frac{d^2\Gamma}{dq^2\, d\cos\theta_l} = \left(\frac{d\Gamma}{dq^2}\right)^{-1} J_6(q^2)$$

Quantities similar to $A_{FB}(q^2)$ can be obtained by integrating the full distribution with various angular weighting functions. Such quantities are functions of ratios of the Wilson coefficients C_i/C_j and ratios of q^2-dependent form-factors.

In general: 7 independent form-factors
[see e.g. F. Krüger, J. Matias, Phys. Rev. D71 (2005) 094009].

In the large E_{K^*} limit $(m_{K^*}/E_{K^*} \sim \Lambda/m_b \ll 1)$: only $\xi_\perp(q^2)$ and $\xi_\|(q^2)$, up to $\mathcal{O}(\alpha_s, \Lambda/m_b)$.
[see e.g. M. Beneke and T. Feldmann, Nucl. Phys. B 612 (2001) 3].

Two strategies:

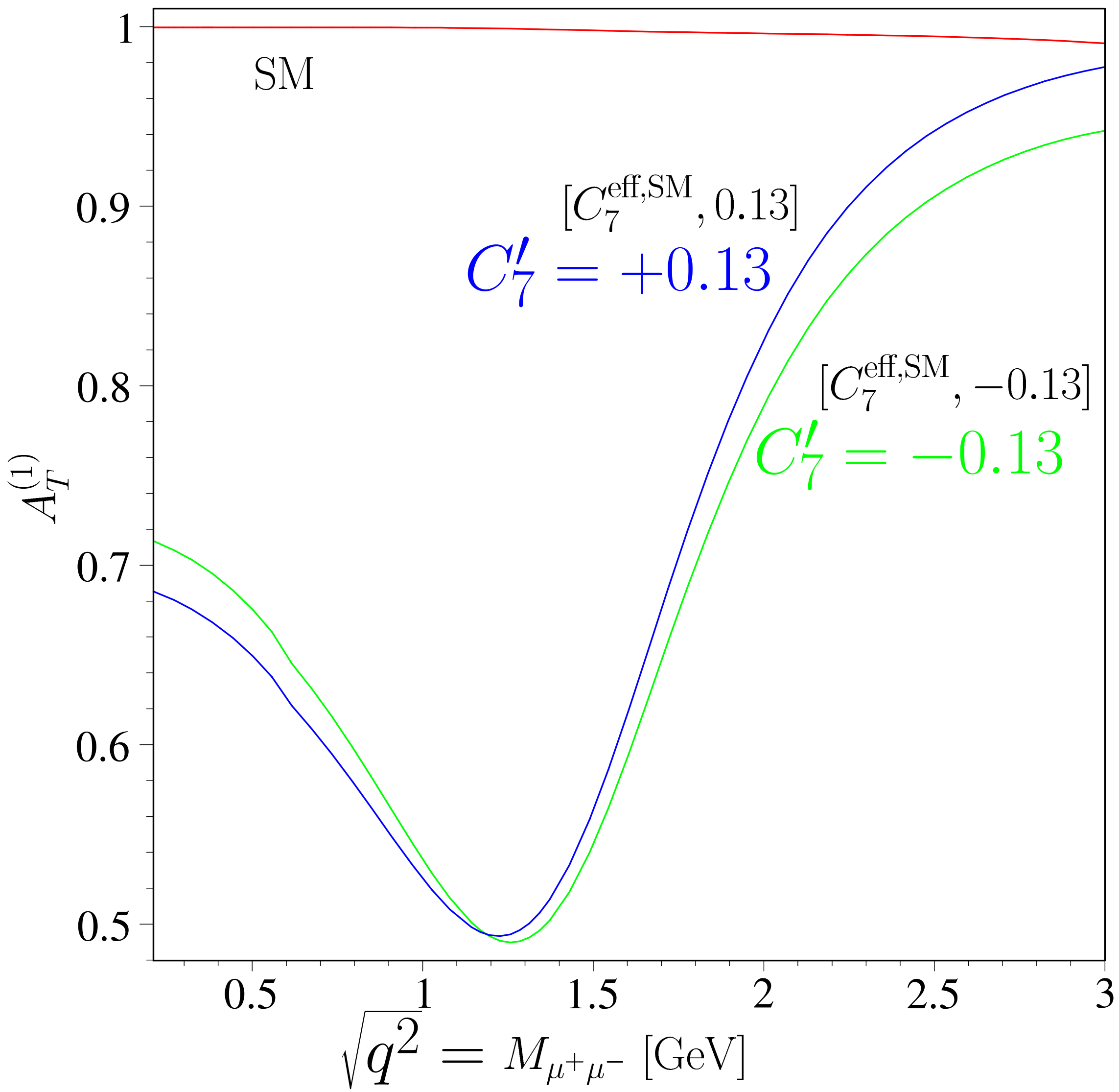
1. **Determine $\xi_\perp/\xi_\|$ together with C_i/C_j from experiment.**
2. **Search for quantities in which the form-factors cancel out.**

Example: see next slide

The transverse asymmetry $A_T^{(1)}$ as a function of $\sqrt{q^2}$ from

F. Krüger, J. Matias, Phys. Rev. D71 (2005) 094009.

Fig. 3b



Summary:

- **Large deviations of $\mathcal{B}(\bar{B}_s \to \mu^+\mu^-)$ from its SM value can likely occur.**

- **Even if they do not show up, we can still test $\mathcal{O}(15\%)$ effects.**

- **Sizeable deviations of various $B_{(s)} \to K^*(\phi)\gamma$ and $B_{(s)} \to K^*(\phi)\mu^+\mu^-$ observables from their SM values are possible.**

- **Even if they do not occur, we shall still find constraints on the Wilson coefficients.**