Constraints on Wilson Coefficients from radiative B decays in a frequentist approach

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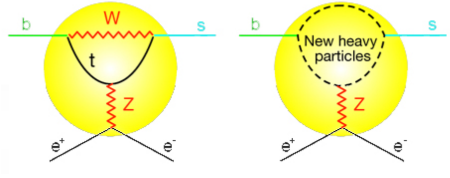
Radiative B decays as probe of SM and NP

$b \to D\gamma^{(*)}$ with $D = d, s$

- within SM: $|V_{t(d,s)}|$
- cross-check of neutral B mixing (box/penguin)
- FCNC/loop processes very sensitive to NP



Model-independent analysis in terms of effective Hamiltonian

- integrating d.o.f above b quark: t, W, Z, highly virtual γ
- separate short and long distances, separated by scale μ_b
- short distances: Wilson coefficients $C(m_t, M_W, M_Z \ldots)$
- long distances: 4-fermion operator Q_i

$$\mathcal{H}_{SM}^{b\to s} = -\frac{4G_F}{\sqrt{2}}\left(\sum_{i=1}^{10} V_{ts}^* V_{tb} C_i Q_i + V_{ub}^* V_{us}(C_1(Q_1^u - Q_1) + C_2(Q_2^u - Q_2)\right)$$

Relevant operators

Leading SM contributions to radiative decays from (normalisation vary)

- $Q_7 = \frac{e}{g^2} m_b \bar{D}\sigma^{\mu\nu}(1+\gamma_5)F_{\mu\nu}\, b$ [electromagnetic dipole]
- $Q_9 = \frac{e^2}{g^2} \bar{D}\gamma_\mu(1-\gamma_5)b\, \bar{\ell}\gamma_\mu\ell$ [dileptonic operators]
- $Q_{10} = \frac{e^2}{g^2} \bar{D}\gamma_\mu(1-\gamma_5)b\, \bar{\ell}\gamma_\mu\gamma_5\ell$

NP changes Wilson coeffs C_i, but may also add new operators Q_i'

- Chirally flipped operators (W_R, Z')

$$Q_7 \propto \bar{D}\sigma^{\mu\nu}(1+\gamma_5)F_{\mu\nu}\, b \to Q_{7'} \propto \bar{D}\sigma^{\mu\nu}(1-\gamma_5)F_{\mu\nu}\, b$$

- Scalar/pseudoscalar operators (Higgses)

$$Q_9 \propto \bar{D}\gamma_\mu(1-\gamma_5)b\, \bar{\ell}\gamma_\mu\ell \to Q_S \propto \bar{D}b(1+\gamma_5)\bar{\ell}\ell,\, Q_P \propto \bar{D}b(1+\gamma_5)\bar{\ell}\gamma_5\ell$$

- Tensor operators

$$Q_9 \propto \bar{D}\gamma_\mu(1-\gamma_5)b\, \bar{\ell}\gamma_\mu\ell \to Q_T \propto \bar{D}\sigma_{\mu\nu}(1-\gamma_5)b\, \bar{\ell}\sigma_{\mu\nu}\ell$$

Scenarios and Observables

Several nested scenarios

- SM : $\delta C_i = 0$ for all $i = 7, 9, 10, 7', 9', 10', S, P, S', P'$
- NPL : $\delta C_{7,9,10}$ free, others $\delta C_i = 0$
- NPLR : $\delta C_{7,9,10,7',9',10'}$ free, others $\delta C_i = 0$
- NPLRS : $\delta C_{7,9,10,7',9',10',S,P,S',P'}$ free [not considered today]

	Exclusive	Inclusive
Real Photon	$B \to V\gamma$ $[Br, C, S]$	$B \to X_s\gamma$ $[Br]$
Virtual Photon	$B_s \to \mu\mu$ [Br] $B \to K(^*)\ell\ell$ [many obs]	$B \to X_s\ell^+\ell^-$ [Br]

- Take δC_i real (no need for new sources of CP-violation)
- Many more observables for exclusive decays, but form factors ?

Approaches

Two possibilities:

- Design new observables with good experimental prospects and limited hadronic uncertainties (exploiting low- and large-q^2 relationships among form factors from eff theories)

[Matias, Kruger, Virto, Mescia, Hiller, Bobeth, Van Dyk,...]

- Combine available experimental information (but cross-check with several approaches to form factors)

[Altmannshofer, Paradisi, Straub, Matias, Virto, Hiller, Bobeth, Van Dyk,...]

CKM fitter

- Versatile and powerful tool for frequentist for flavour metrology
- Rfit model for theoretical uncertainties

  systematics = a bias within a range, not a random variable
- Keep correlations between different sectors of fit (e.g., m_t, m_c)
- Here: combine information of different theoretical cleanliness:

  global CKM fit + all available radiative $b \to s$ observables

Inputs and main parameters

$B \to V\gamma$ [HFAG 2012]	$Br(\bar{B} \to K^{*0}\gamma)$ $Br(B_s \to \phi\gamma)$ $B(B^- \to K^{*-}\gamma)$ $Br(B^0 \to \rho^0\gamma)$ $Br(B^0 \to \omega\gamma)$ $B(B^- \to \rho^-\gamma)$	[Ball and Zwicky, Khodjamirian et al.] $T_1^{B\to K^*}(0)$ $T_1^{B_q\to V}(0)/T_1^{B\to K^*}(0)$
$B \to K^*\ell\ell$ [LHCb-CONF-2012-008]	$\langle\Gamma\rangle_{[0.05,2],[2,4.30],[4.30,8.68]}$ $\langle F_L\rangle_{[0.05,2],[2,4.30],[4.30,8.68]}$ $\langle A_{FB}\rangle_{[0.05,2],[2,4.30],[4.30,8.68]}$ $\langle S_9\rangle_{[0.05,2],[2,4.30],[4.30,8.68]}$ $\langle S_3\rangle_{[0.05,2],[2,4.30],[4.30,8.68]}$	[Ball and Zwicky, Khodjamirian et al.] $A_i^{B\to K^*}(q^2),\ V^{B\to K^*}(q^2)$ $T_i^{B\to K^*}(q^2)$
$B \to K\ell\ell$ [LHCb-PAPER-2012-024]	$\langle\Gamma\rangle_{[0.05,2],[2,4.30],[4.30,8.68]}$ $\langle F_H\rangle_{[0.05,2],[2,4.30],[4.30,8.68]}$ $\langle A_{FB}\rangle_{[0.05,2],[2,4.30],[4.30,8.68]}$	[Ball and Zwicky, Khodjamirian et al.] $f_{+,0,T}^{B\to K}(q^2)$
$B_s \to \mu\mu$ [LHCb]	Br	f_{B_s}, m_t
$B \to X_s\ell\ell$ [Babar 2004/Belle 2005]	$\langle\Gamma\rangle_{[1,6]}$	$m_c, \Gamma(B \to X_u\ell\nu)$
$B \to X_s\gamma$ [HFAG 2012]	$\langle\Gamma\rangle_{E_\gamma>1.6}$	$m_c, \Gamma(B \to X_u\ell\nu)$
C_i^{SM}		$m_t, \mu_0 \in [80, 320],\ \mu_b = 4.2 \pm 1.0$ GeV
V_{CKM}	CKMfitter Global Fit	$m_t, m_c, f_{B_s} \ldots$

Theoretical treatment

For this talk, no effective theory approach: full $B \to M\gamma^{(*)}$ form factors from LCSR, but only at low $q^2 < m^2_{J/\psi}$ due to their range of validity

[Ball and Zwicky; Khodjamirian, Mannel, Pivovarov, Wang]

- $B \to V\gamma$: $Br \propto |V_{tx} V^*_{tb}|^2 (C_7^2 + C_{7'}^2)[T_1^{B\to V}(0)]^2$
- $B \to X_s\gamma$: Br at NNLO with m_c interpolation [Misiak and Steinhauser]
- $B_s \to \mu\mu$: Br at NLO, letting μ_0 vary as estimate of higher orders
- $B \to K^*\ell\ell$: Binned observables [Matias, Mescia, Virto...]

  e.g., $\langle F_L \rangle = -\frac{\int dq^2 J_{2c} + \bar{J}_{2c}}{\int dq^2 (d\Gamma/dq^2 + d\bar{\Gamma}/dq^2)} \neq -\int dq^2 \frac{J_{2c}+\bar{J}_{2c}}{(d\Gamma/dq^2 + d\bar{\Gamma}/dq^2)}$

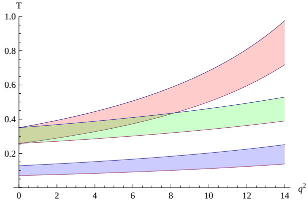
  $A^{L,R}_{||,\perp,0,s,t} = \sum_{i=7,9,10} a_{ij} C_i F_j(q^2)$ similar to LO QCDF [Barucha et al.]
- $B \to K\ell\ell$: same treatment [Hiller, Bobeth, Becirevic, Schneider...]
- $B \to X_s\ell\ell$: Br at NNLO, including e.m. corrections [Hurth, Lunghi, Huber, Misiak]

BR_{SM} : $B \to X_s\gamma_{\ (E_\gamma > 1.6)} = (3.18^{+0.22}_{-0.25}) \cdot 10^{-4}$

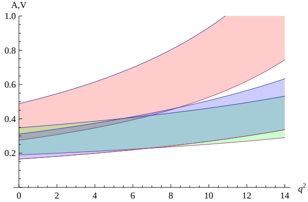
$B \to X_s\mu\mu = (1.42^{+0.07}_{-0.06}) \cdot 10^{-6}$ $\quad B_s \to \mu\mu_{\ (t=0)} = (3.47^{+0.14}_{-0.18}) \cdot 10^{-9}$

Form factors from LCSR

BZ [Ball and Zwicky]



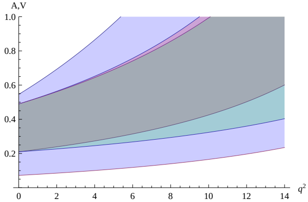
T_1 [red], T_2 [green], T_3 [blue]



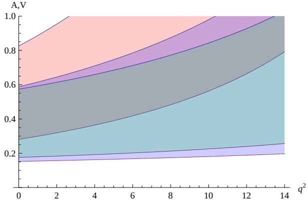
V [red], A_1 [green], A_2 [blue]

Parametrised by sum of poles

KMPW [Khodjamirian, Mannel, Pivovarov, Wang]



T_1 [red], T_2 [green], T_3 [blue]

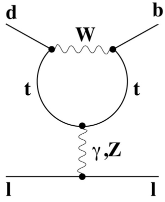


V [red], A_1 [green], A_2 [blue]

Parametrised with z-expansion

Rfit scheme: linear addition of systematic errors in the error budget

Wilson Coefficients



- SM Wilson Coeffs. C_i^{SM} at NLO, $\mu_{\rm ref} = 5$ GeV

  $$C_7^{SM} = -0.30^{+0.02}_{-0.01},\ C_9^{SM} = 4.29^{+0.18}_{-0.19},\ C_{10}^{SM} = -4.21^{+0.14}_{-0.15},$$

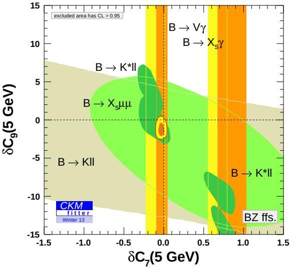
  (formulae up to NNLO + e.m. corrections)
- $C_i(\mu_b) = C_i^{SM}(\mu_b) + \delta C_i(\mu_b)$, shift at $\mu_b = 4.2 \pm 0.1$ GeV reexpressed at reference scale 5 GeV using LO RGE

Observable $= \sum_i A_i B_i^*$ with A_i=linear combinations of C_i

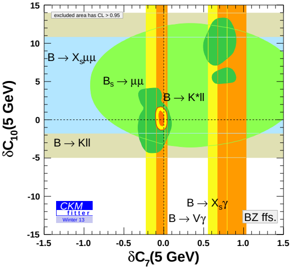
- Almost exact degeneracy $(\delta C_i = 0, \delta C_i = -2C_i^{SM})$
- Broken by 4-quark operators, in particular due to $c\bar{c}$ loops

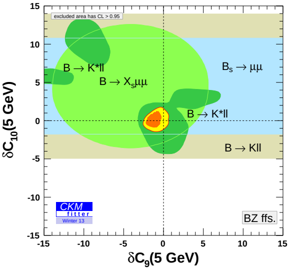
$Br(B \to V\gamma)$	$C_7^2 + C_{7'}^2$	[Khodjamirian et al.]
$Br(B \to K^*\gamma)$ low-q^2	$C_7^2 + C_{7'}^2$	
$A_{FB}(B \to K^*\gamma)$ low-q^2	0	
$F_L(B \to K^*\gamma)$ low-q^2	$C_7 - C_{7'}$	
$B_s \to \mu\mu$	$C_S - C'_S,\ C_P - C_{P'} + (2m_\ell/m_b)(C_{10} - C_{10'})$	
$Br(B \to K\ell\ell)$	$C_9 + C_{9'} + (2f_T/f_+)(C_7 + C_{7'}),\ C_{10} + C_{10'}$	

NPL / BZ

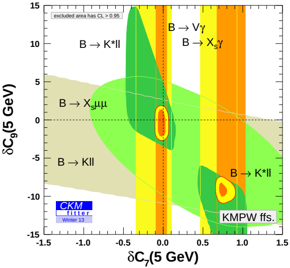


- NPL: NP only in $C_{7,9,10}$
- Form factors: [Ball and Zwicky]
- $B_s \to \mu\mu$ (blue), $B \to K\ell\ell$ (gray), $B \to K^*\ell\ell$ (dark green), $B \to X_s\mu\mu$ (light green), $B \to V\gamma$ (yellow), $B \to X_s\gamma$ (orange)
- First 3 bins only for $B \to K(^*)\ell\ell$





NPL / KMPW



- NPL: NP only in $C_{7,9,10}$
- Form factors: [Khodjamirian, Mannel, Pivovarov, Wang]
- $B_s \to \mu\mu$ (blue), $B \to K\ell\ell$ (gray), $B \to K^*\ell\ell$ (dark green), $B \to X_s\mu\mu$ (light green), $B \to V\gamma$ (yellow), $B \to X_s\gamma$ (orange)
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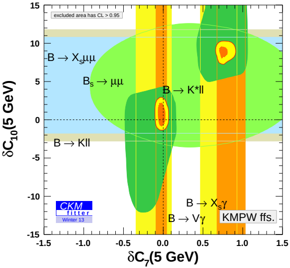
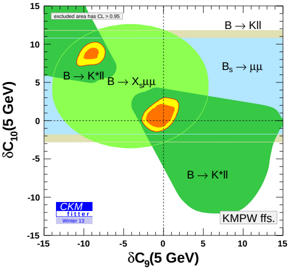
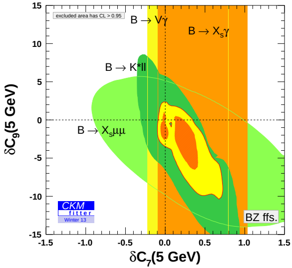
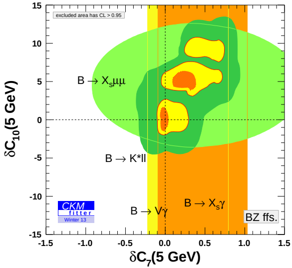


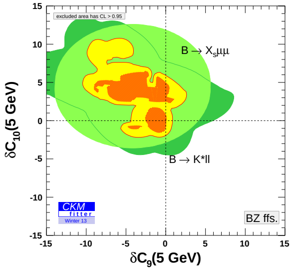


NPLR / BZ

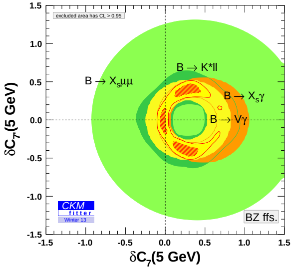


- NPLR: NP in $C_{7,9,10,7',9',10'}$
- Form factors: [Ball and Zwicky]
- $B_s \to \mu\mu$ (blue), $B \to K\ell\ell$ (gray), $B \to K^*\ell\ell$ (dark green), $B \to X_s\mu\mu$ (light green), $B \to V\gamma$ (yellow), $B \to X_s\gamma$ (orange)
- First 3 bins only for $B \to K(^*)\ell\ell$





NPLR / BZ



- NPLR: NP in $C_{7,9,10,7',9',10'}$
- Form factors: [Ball and Zwicky]
- $B_s \to \mu\mu$ (blue), $B \to K\ell\ell$ (gray), $B \to K^*\ell\ell$ (dark green), $B \to X_s\mu\mu$ (light green), $B \to V\gamma$ (yellow), $B \to X_s\gamma$ (orange)
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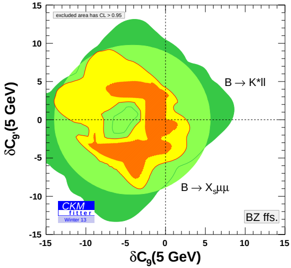
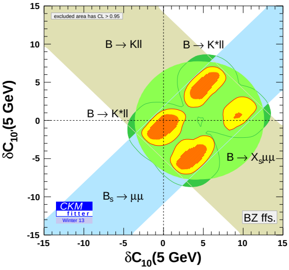
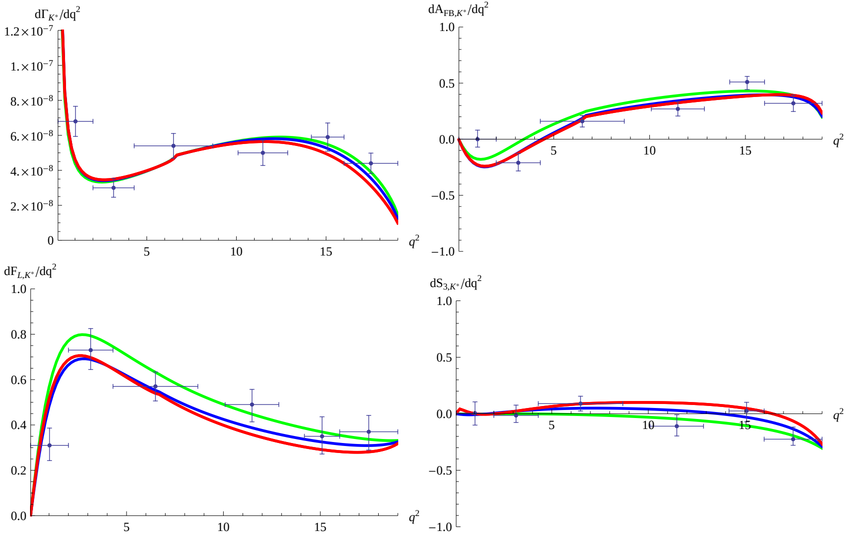




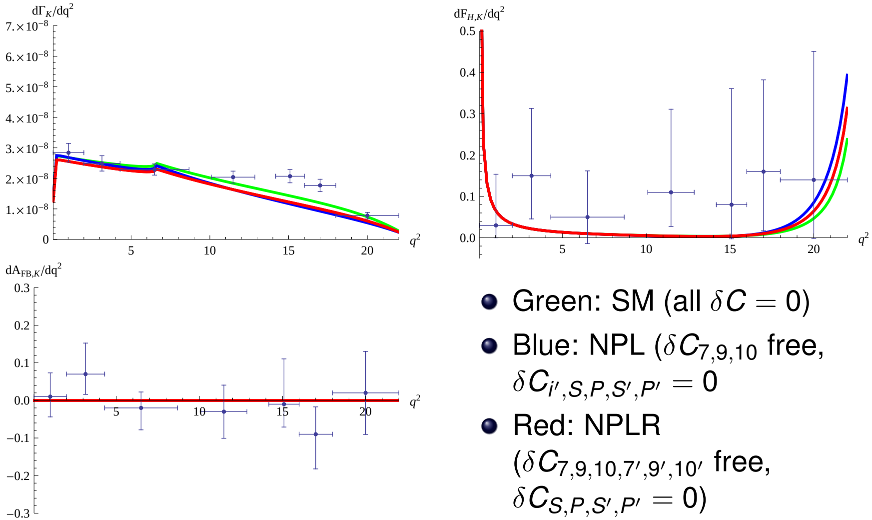
$B \to K^*\ell^+\ell^-$: central value for BZ



Green: SM, Blue: NPL, Red: NPLR,

(S_9 uniformly 0 in the absence of scalar operators)

$B \to K\ell^+\ell^-$: central values for BZ



- Green: SM (all $\delta C = 0$)
- Blue: NPL ($\delta C_{7,9,10}$ free, $\delta C_{i',S,P,S',P'} = 0$
- Red: NPLR ($\delta C_{7,9,10,7',9',10'}$ free, $\delta C_{S,P,S',P'} = 0$)

Results for the δC_i's

	NPL		NPLR	
	BZ	KMPW	BZ	KMPW
δC_7	$-0.029^{+0.027}_{-0.027}$	$-0.024^{+0.037}_{-0.035}$	$-0.028^{+0.039}_{-0.018}$	$-0.030^{+0.044}_{-0.029}$
δC_9	$-1.59^{+0.60}_{-0.46}$	$0.17^{+0.97}_{-1.65}$	$-1.13^{+0.88}_{-0.99}$	$0.0^{+1.5}_{-7.2}$
δC_{10}	$-0.05^{+1.04}_{-0.53}$	$0.61^{+0.81}_{-1.22}$	$-0.30^{+1.55}_{-0.96}$	$0.6^{+1.2}_{-1.5}$ or $4.70^{+0.82}_{-1.30}$
$\delta C_{7'}$	0	0	$-0.04^{+0.13}_{-0.09}$	$-0.01^{+0.08}_{-0.11}$ or $0.45^{+0.04}_{-0.09}$
$\delta C_{9'}$	0	0	$2.3^{+1.8}_{-4.4}$	$0.4^{+4.8}_{-4.4}$ or $-4.7^{+0.1}_{-0.5}$
$\delta C_{10'}$	0	0	$4.5^{+0.8}_{-1.2}$ or $-4.6^{+0.4}_{-0.4}$	$0.0^{+1.1}_{-1.3}$

- SM hypothesis in NPL scenario [$\delta C_{7,9,10} = 0$]:
  BZ 2.5 σ, KMPW 0.1 σ
- NPL hypothesis in NLPR scenario [$\delta C_{7',9',10'} = 0$]:
  BZ 0.2 σ, KMPW 0.0 σ

- In agreement with previous curves & KMPW larger errors than BZ
- Need for NP mostly dependent on the form factors chosen

Outlook

CKM fitter

- Powerful tool to combine flavour constraints
- Frequentist analysis of model-independent constraints from radiative B decays
- Good agreement with SM, but details depend on treatment of $B \to K(^*)\ell\ell$

Many improvements to come

- Low- and high-q^2 effective theory approaches for $B \to K(^*)\ell\ell$ and $B \to V\gamma$ to limit hadronic uncertainties and check stability

[Matias, Vitro, Hiller, Bobeth. . .]

- Extension of analysis to NPLRS (scalar case) and complex case
- Form factors including lattice results at high q^2 [Feldmann et al.]
- Inclusion of further observables: $B \to K^*\gamma$ asymmetries, $B \to K^*ee$, $B_s \to \phi\mu\mu$, additional observables (S_i, A_i, P_i, P_i')

More to come from LHCb results !