\[ b \rightarrow s \ell \ell \text{ 2015 and New Physics} \]

*much ado about...something?*

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Radiative decays

- $b \rightarrow s \gamma$ and $b \rightarrow s \ell^+ \ell^-$ Flavour-Changing Neutral Currents
- enhanced sensitivity to New Physics effects
- analysed in model-independent approach effective Hamiltonian

$$b \rightarrow s \gamma(*) : \mathcal{H}_{\Delta F=1}^{SM} \propto \sum_{i=1}^{10} V_{ts}^* V_{tb} C_i Q_i + \ldots$$

- $Q_7 = \frac{e}{g^2} m_b \bar{s} \sigma^{\mu\nu}(1 + \gamma_5) F_{\mu\nu} b$ [real or soft photon]
- $Q_9 = \frac{e^2}{g^2} \bar{s} \gamma_{\mu}(1 - \gamma_5) b \bar{\ell} \gamma_{\mu} \ell$ [b → sμμ via Z/hard γ]
- $Q_{10} = \frac{e^2}{g^2} \bar{s} \gamma_{\mu}(1 - \gamma_5) b \bar{\ell} \gamma_{\mu} \gamma_5 \ell$ [b → sμμ via Z]

NP changes short-distance $C_i$ and/or add new operators $Q'_i$

- Chirally flipped ($W \rightarrow W_R$) $Q_7 \rightarrow Q'_7 \propto \bar{s} \sigma^{\mu\nu}(1 - \gamma_5) F_{\mu\nu} b$
- (Pseudo)scalar ($W \rightarrow H^+$) $Q_9, Q_{10} \rightarrow Q_S \propto \bar{s}(1 + \gamma_5) b \bar{\ell} \ell, Q_P$
- Tensor operators ($\gamma \rightarrow T$) $Q_9 \rightarrow Q_T \propto \bar{s} \sigma_{\mu\nu}(1 - \gamma_5) b \bar{\ell} \sigma_{\mu\nu} \ell$

Aim: disentangle hadronic effects from electroweak and NP effects
Wilson Coefficients and processes

Matching SM at high-energy scale $\mu_0 = m_t$ and evolving down at $\mu_{\text{ref}} = 4.8$ GeV

$$C_7^{SM} = -0.29, \quad C_9^{SM} = 4.1, \quad C_{10}^{SM} = -4.3,$$

(formulae known up to NNLO + e.m. corrections)

- $b \to s\gamma$ versus $b \to s\ell\ell$: $C_7, C_7'$ versus other Wilson coefficients
- Inclusive versus exclusive: OPE versus form factor uncertainties

- $B \to X_s\gamma$: strong constraints on $C_7, C_7'$
- $B \to X_s\ell\ell$: only loose constraints
- $B_s \to \mu\mu$: recent th. and exp. progress
- $B \to K(\ast)\ell\ell$: New LHCb analysis in Moriond 2015 for $B \to K\ast$
$B \rightarrow K(*)\mu\mu$: amplitudes with $\mathcal{H}_{\text{eff}}$

- $2q, 2\ell \ [C_{9(\prime)}, 10(\prime), S(\prime), P(\prime)]$  
  \[ A_9 = C_9 \langle M_\lambda | \bar{s}\gamma_\mu P_L b | B \rangle L^\mu \rightarrow C_9 F_\lambda (q^2) \]

- Electromag $[C_{7(\prime)}]$  
  \[ A_7 = C_7 \langle M_\lambda | \bar{s}\sigma_{\mu\nu} P_L b | B \rangle \frac{eq_\mu}{q^2} L^\nu \rightarrow C_7 T_\lambda (q^2) \]

- 4-quark ops $[C_{1, 2\ldots}]$: nonlocal contribution, related to $c\bar{c}$ loops  
  \[ A_2 = C_2 \int d^4 x e^{iqx} \langle M_\lambda | T[(\bar{s}\gamma_\mu P_L c \bar{c}\gamma_\mu P_L b)(0)] J_{\nu, \text{em}, c\bar{c}}^\text{em} (x) | B \rangle \frac{e^2}{q^2} L^\nu \]

  $[L^\mu$ lepton current$]$  

Two main tasks for the theorists

- Determine the form factors $F_\lambda, T_\lambda$ using nonperturbative methods
- Assess the contribution from 4-quark operators, i.e., $c\bar{c}$ loops in $A_2$
\[ B \to K^* \mu\mu: \text{angular analysis} \]

- \( \theta_l \): angle of emission between \( K^{*0} \) and \( \mu^- \) in di-lepton rest frame
- \( \theta_{K^*} \): angle of emission between \( K^{*0} \) and \( K^- \) in di-meson rest frame.
- \( \phi \): angle between the two planes
- \( q^2 \): dilepton invariant mass square

\[
\frac{d^4\Gamma}{dq^2 \, d\cos \theta_l \, d\cos \theta_{K^*} \, d\phi} = \sum_i f_i(\theta_{K^*}, \phi, \theta_l) \times I_i
\]

with 12 angular coeffs \( I_i \), interferences between 8 transversity ampl.
- \( \perp, \parallel, 0, t \) polarisation of (real) \( K^* \) and (virtual) \( V^* = \gamma^*, Z^* \)
- \( L, R \) chirality of \( \mu^+ \mu^- \) pair

Amplitudes \( A_{\perp,L/R}, A_{\parallel,L/R}, A_0,L/R, A_t \) + scalar \( A_s \) depend on
- Wilson coefficients \( C_7, C_9, C_{10}, C_S, C_P \) (and flipped chiralities)
- \( B \to K^* \) form factors \( A_{0,1,2}, V, T_{1,2,3} \) from \( \langle K^* | Q_i | B \rangle \)
- terms describing \( c\bar{c} \) contribution
Four kinematic regions

- **Very large $K^*$-recoil** ($4m_\ell^2 < q^2 < 1$ GeV$^2$): $\gamma$ almost real ($C_7/q^2$ divergence and light resonances)
- **Large $K^*$-recoil** ($q^2 < 9$ GeV$^2$): energetic $K^*$ ($E_{K^*} \gg \Lambda_{QCD}$: form factors via light-cone sum rules LCSR)
- **Charmonium region** ($q^2 = m_{\psi, \psi'}^2$ ... between 9 and 14 GeV$^2$)
- **Low $K^*$-recoil** ($q^2 > 14$ GeV$^2$): soft $K^*$ ($E_{K^*} \approx \Lambda_{QCD}$: form factors lattice QCD)

**EFT approaches** at low and large-$K^*$ recoils: expansion in
- $\Lambda/m_b$ (separating soft and hard dynamics)
- $\alpha_s$ (for dynamics of hard gluons)
In the limits of low and large $K^*$ recoil, separation of scales $\Lambda$ and $m_B$ in the 7 form factors for

- **Large-recoil limit** ($\sqrt{q^2} \sim \Lambda_{QCD} \ll m_B$) [LEET/SCET, QCDF]
  - two soft form factors $\xi_\perp(q^2)$ and $\xi_\parallel(q^2)$
  - $O(\alpha_s)$ corr. from hard gluons [computable], $O(\Lambda/m_B)$ [nonpert] [Charles et al., Beneke and Feldmann]

- **Low-recoil limit** ($E_{K^*} \sim \Lambda_{QCD} \ll m_B$) [HQET]
  - three soft form factors $f_\perp(q^2), f_\parallel(q^2), f_0(q^2)$
  - $O(\alpha_s)$ corr. from hard gluons [computable] and $O(\Lambda/m_B)$ [nonpert] [Grinstein and Pirjol, Hiller, Bobeth, Van Dyk...]
From form factors to amplitudes

Large recoil: NLO QCD factorisation

\[ V, A_i, T_i = \xi_{||,\perp} \]
\[ + \text{factorisable } O(\alpha_s, \Lambda/m_b) \]
\[ A_{0,||,\perp} = C_i \times \xi_{||,\perp} \]
\[ + \text{factorisable } O(\alpha_s, \Lambda/m_b) \]
\[ + \text{nonfactorisable } O(\alpha_s, \Lambda/m_b) \]

Two approaches to get correlations among form factors
- Extract soft form factors + factorisable power corrections from fit to full form factors
- Replace soft form factors + factorisable power corrections by full form factors with correlations

Low recoil: OPE + HQET

\[ A_{0,||,\perp} = C_i \times f_{0,||,\perp} + O(\alpha_s) \text{ corrections} + O(\Lambda/m_b) \text{ corrections} \]
\[ f_{0,||,\perp} \propto CL(A_1, A_2), A_1, V + O(\Lambda/m_b) \text{ corrections} \]
[or use directly lattice results for the form factors]
Form-factor “independent” observables

= Observable where (soft) form factors cancel at LO in EFT

- Zero of forward-back. asym. \( A_{FB}(s_0) = 0: C_{9}^{\text{eff}}(s_0) + 2 \frac{m_b M_B}{s_0} C_{7}^{\text{eff}} = 0 \)

- Transversity asymmetries

\[
P_1 = A_{T}^{(2)} = \frac{l_3}{2 l_{2s}} = \frac{|A_\perp|^2 - |A_\parallel|^2}{|A_\perp|^2 + |A_\parallel|^2}, \quad P_2 = \frac{A_T^{re}}{2} = \frac{l_{6s}}{8 l_{2s}} = \frac{\text{Re}[A_L^* A_L - A_R A_{R*}]}{|A_\perp|^2 + |A_\parallel|^2}
\]

- 6 form-factor indep. observ. at large recoil \( P_1, P_2, P_3, P_4', P_5', P_6' \)

+ 2 form-factor dependent obs. (\( \Gamma, A_{FB}, F_L \ldots \))

exhausting information in (partially redundant) angular coeffs \( l_i \)
Sensitivity to form factors

- $P_i$ designed to have limited sensitivity to form factors
- $S_i$ CP-averaged version of angular coefficient $I_i$

\[ P_1 = \frac{2S_3}{1 - F_L} \quad F_L = \frac{I_{1c} + \bar{I}_{1c}}{\Gamma + \bar{\Gamma}} \quad S_3 = \frac{I_3 + \bar{I}_3}{\Gamma + \bar{\Gamma}} \]

Different sensitivity to form factors inputs for given NP scenario
(form factors from LCSR: green [Ball, Zwicky] vs gray [Khodjamirian et al.])

- $P_1$ apt to discriminate NP (green/gray) vs SM case (yellow)
Power corrections

in $A_{\perp,||,0}$ (non-factor.)
in FFs (factor)

Observables with limited sensitivity to soft form factors

$\implies$ important role played by $O(\Lambda/m_b)$ power corrections!

Power corrections to form factors

$$F(q^2) = F^{\text{soft}}(\xi_{\perp,||}(q^2)) + \Delta F^{\alpha_s}(q^2) + a_F + b_F(q^2/m_B^2) + \ldots$$

- Set $\xi_{||,\perp}$ identifying them with two form factors
- Central value $a_F, b_F, \ldots$: fit to the full form factor $F$
- Error on $a_F, b_F, \ldots$: 10% of the full form factor $F$

Remaining power corrections to amplitudes

- multiply part not associated to form factors $\mathcal{T}_i^{\text{had}}$ with a complex $q^2$-dependent factor (10% magnitude) $\mathcal{T}_i^{\text{had}} \rightarrow (1 + r_i(q^2))\mathcal{T}_i^{\text{had}}$
- since contributions from rescattering may yield arbitrary phases
Charm-loop effects

- **Charmonium resonances**
  - Large recoil: $q^2 \leq 7-8 \text{ GeV}^2$ to avoid $J/\psi$ tail
  - Low recoil: quark-hadron duality OK at a few percent if wide bin

- **Short-distance non-resonant (hard gluons)**
  - LO included $C_9 \rightarrow C_9 + Y(q^2)$, dependence on $m_c$
  - higher-order short-distance QCD via QCDF/HQET

[Beylich, Buchalla, Feldmann]

- **Long-dist. non-resonant (soft gluons)**
  - At large recoil (partly included already in power corrections)
  - Global $\Delta C_9^{BK(*)}$ using LCSR: for $B \rightarrow K^*$, partial computation yields $\Delta C_9^{BK^*} > 0$ [Khodjamirian, Mannel, Pivovarov Wang]
  - Perform the separation
    $$\Delta C_9^{BK^*} = \delta C_{9,\text{pert}}^{BK(*)} + \delta C_{9,\text{non pert}}^{BK(*)}$$
    and compute uncertainty by varying nonperturbative part $\pm \delta C_{9,\text{non pert}}^{BK(*)}$
Resulting uncertainties for SM predictions: $P'_5$ vs $S_5$

$P'_5$ and $S_5$ computed with
- [Khodjamirian et al.] form factors (green)
- [Ball and Zwicky] ffs (red)
- [Jäger and Camalich] approach (yellow)

- $P'_5$: Agreement and same errors for [Khodjamirian et al.] and [Ball and Zwicky]
- $S_5$: Different uncertainties for [Khodjamirian et al.] and [Ball and Zwicky] inputs, due to increased sensitivity of $S_5$ to form factor inputs
- Agreement within errors between our results for [Ball and Zwicky] and the updated analysis of [Bharucha, Straub, Zwicky]

Non optimal scheme to determine soft form factors
- No use of information from form factors to set power corrections
  \(\Rightarrow\) range in the absence of info on form factors (enhancing errors)
$P'_5$ in 2013 and 2015

- **Definition:**
  \[
  P'_5 = \sqrt{2} \frac{\text{Re}(A^L_0 A^{L*}_0 - A^R_0 A^{R*}_0)}{\sqrt{|A_0|^2 (|A_\perp|^2 + |A_\parallel|^2)}}
  \]

- **Improved consistency of the 2015 data**

- **In SM,** $C_9 \sim -C_{10}$ leading to $A^R_{\perp,\parallel,0} \ll A^L_{\perp,\parallel,0}$, $P'_5$ saturates at -1
  when $C_{9,10}$ dominates (i.e. $q^2 > 5 \text{ GeV}^2$)
$B \rightarrow K\mu\mu$

- Simpler kinematics: only one angle and 3 observables: $Br$, $F_H$, $A_{FB}$ [Hiller, Bobeth, Piranishvili]
- Only $Br$ brings information (other observables are small, both exp. and th.)
- 3 form factors, down to 1 soft form factor at large recoil
- Contribution from soft gluons negligible compared to hadronic uncertainties
- Discrepancy with SM at low $q^2$ ($Br$ involves $C_9 + C_9'$)
$B_{s} \to \mu\mu$

- Sensitive to $C_{10} - C_{10}'$, $C_{S} - C_{S}'$, $C_{P} - C_{P}'$
- $\langle Br(B_{s} \to \mu\mu) \rangle = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$
- LHCb+CMS: $\langle Br(B_{s} \to \mu\mu) \rangle = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$
- Theoretical progress
  - Inclusion of $B_{s}$ mixing in time-integrated rate from LHCb and CMS:
    $\langle Br(B_{s} \to \mu\mu) \rangle \simeq 1.1 Br_{t=0}$
  - NLO QCD + LO EW $\rightarrow$ NNLO QCD + NLO EW

- $Br(B_{s} \to \mu\mu)$ in very good agreement with SM
- Correlation in SM (and in MFV)

$$Br(B_{d} \to \mu\mu)_{t=0} / Br(B_{s} \to \mu\mu)_{t=0} = 0.0298^{+0.0008}_{-0.0010}$$
Global fits: 1D hypotheses

- $\chi^2$ frequentist analysis to determine $C_i(\mu_{\text{ref}}) = C_i^{SM} + C_i^{NP}$
- $B \rightarrow K^*\mu\mu$ ($P_{1,2}, P_{4,5,6,8}, F_L$: 5 large-recoil + 1 low-recoil bins),
  $B^+ \rightarrow K^+\mu\mu$, $B^0 \rightarrow K^0\mu\mu$, $B \rightarrow X_s\gamma$, $B \rightarrow X_s\mu\mu$, $B_s \rightarrow \mu\mu$ (Br),
  $B \rightarrow K^*\gamma$ ($A_I$ and $S_{K^*\gamma}$)

[Moriond 15, no correlations]

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Best fit</th>
<th>Pull</th>
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<tbody>
<tr>
<td>$C_9^{NP}$</td>
<td>-1.1</td>
<td>4.6</td>
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<tr>
<td>$C_{10}^{NP}$</td>
<td>0.62</td>
<td>2.4</td>
</tr>
<tr>
<td>$C'_9$</td>
<td>-1.0</td>
<td>3.4</td>
</tr>
<tr>
<td>$C'_{10}$</td>
<td>0.61</td>
<td>3.3</td>
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</tbody>
</table>

$C_9^{NP} = -C_{10}^{NP}$
$C_9^{NP} = C_{10}^{NP}$
$C'_9 = C_{10}'$
$C'_9 = -C_{10}'$

$C_9^{NP} < 0$ preferred, but alternatives with $C_9^{NP} = -C_{10}^{NP}$ and $C_9^{NP} = C'_9$
Global fits: 2D hypotheses

<table>
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<tr>
<th>Hyp.</th>
<th>Best-fit pt</th>
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<tbody>
<tr>
<td>((C_7^{\text{NP}}, C_9^{\text{NP}}))</td>
<td>(0.0, -1.1)</td>
<td>4.2</td>
</tr>
<tr>
<td>((C_9^{\text{NP}}, C_{10}^{\text{NP}}))</td>
<td>(-1.1, 0.2)</td>
<td>4.2</td>
</tr>
<tr>
<td>((C_9^{\text{NP}}, C_9'))</td>
<td>(-1.0, -0.1)</td>
<td>4.2</td>
</tr>
<tr>
<td>((C_{10}^{\text{NP}}, C_{10}'))</td>
<td>(0.5, 0.6)</td>
<td>3.4</td>
</tr>
</tbody>
</table>

→ Main effect from \(C_9\)

Explanations?
- \(Z'\) boson
- Leptoquarks
- Composite models
- Difficult with susy (?)

[Almannshoffer, Straub, Haisch, Gauld, Peczak, Buras, De Fazio, Girrbach, Hiller, Schmaltz, Varzielas, Crivellin...]

S. Descotes-Genon (LPT-Orsay)  

\(b \rightarrow sll\) 2015 & NP
Global fits: to be continued

Work in progress to add

- Experimental and theoretical correlations  (reduce significance)
- Complex phases in soft-gluon contributions  (reduce significance)
- Electronic modes and $B_s \rightarrow \phi \mu \mu$  (increase significance)
- New form factors  [Bharucha, Straub, Zwicky]  (increase significance)

General pattern and preferred hypotheses unchanged!

Similar analysis by  [Almannshoffer and Straub]

- Full form factors with correlations  (rather than soft form factors)
- Different form factors, power corrections, $c\bar{c}$ contributions
- Similar preferred hyp: $C_9^{NP} (3.7 \sigma)$ or $C_9^{NP} = -C_{10}^{NP} (3.2 \sigma)$
- $C_9^{NP}$ can be $q^2$-independent (NP ?)
Other interesting results

- $R_K = \frac{Br(B \to K\mu\mu)}{Br(B \to Kee)} |_{[1,6]} = 0.745^{+0.090}_{-0.074} \pm 0.036$
  - cannot be mimicked by a hadronic effect
  - OK with $C_9^{\mu, NP} \approx -1$, or $C_9^{\mu, NP} = -C_{10}^{\mu, NP} \approx -0.5$ $[C_9,_{10} \approx 0]$
  - [Hiller, Schmalz]

- Lattice: $B \to K^* \ell\ell$ and $B_s \to \phi \ell\ell$ form factors $[\text{Horgan et al.}]

- SM preds for BRs higher than exp
  - (blue, pink: SM, dashed: $C_9^{NP} = -C_{10}^{NP} = -1.1$)

- Frequentist analysis with only low recoil $B_q \to V \ell\ell$ favours $C_9^{NP} < 0$
  - (and $C_9$, mildly negative)

- Maybe more: LHCb finds $\Lambda_b \to \Lambda \mu\mu$ with too low branching ratio at large recoil...
Outlook

$b \rightarrow s\ell\ell$ transitions

- Very interesting playing ground for FCNC studies
- Many observables, more or less sensitive to hadronic unc.
- Confirmation of LHCb results for $B \rightarrow K^*\mu\mu$, supporting $C_9^{NP} < 0$ with large significance, and room for NP in other Wilson coeffs
- And a lot theoretical discussions on accuracy of computations and/or interpretation in terms of NP

How to improve?

- Check the size of hadronic effects by comparing different exclusive modes: $B \rightarrow K^*\mu\mu, B \rightarrow K\mu\mu, B_s \rightarrow \phi\mu\mu, \Lambda_b \rightarrow \Lambda\mu\mu \ldots$
- Improve the measurement of $q^2$-dependence of the observables
- Confirm $R_K$ by comparing modes with $\ell = e$ and $\ell = \mu$
- Sharpen the estimate of soft-gluon contribs and power corrections
- Provide lattice form factors over whole kinematic range with corr.

A lot of (interesting) work on the way!