Overview of constraints on new physics in rare $B$ decays

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Electroweak Session
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$\Delta B = \Delta S = 1$ decays as probes of new physics

**FCNC** transitions: loop- and CKM-**suppressed** in the SM, thus sensitive to NP

(Incomplete) list of promising observables in $b \to s$ decays:

<table>
<thead>
<tr>
<th>mode</th>
<th>interesting observables</th>
<th>future improvements</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \to X_s \gamma$</td>
<td>BR, $A_{CP}$</td>
<td>SuperB, Belle II</td>
</tr>
<tr>
<td>$B \to K^* \gamma$</td>
<td>BR, $S$</td>
<td>LHCb</td>
</tr>
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<td>$B_s \to \phi \gamma$</td>
<td>BR, $S$</td>
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<tr>
<td>$B \to X_s \ell^+ \ell^-$</td>
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<tr>
<td>$B \to K^* \mu^+ \mu^-$</td>
<td>BR, $F_L$, $A_{FB}$, $A_9$, $S_3$, $A_7$, $A_8$, $S_5$</td>
<td>LHCb*</td>
</tr>
<tr>
<td>$B \to K \mu^+ \mu^-$</td>
<td>BR, $F_H$</td>
<td>LHCb</td>
</tr>
<tr>
<td>$B_s \to \mu^+ \mu^-$</td>
<td>BR</td>
<td>LHCb*, CMS*, ATLAS</td>
</tr>
</tbody>
</table>

Many opportunities to probe new physics!
\[ \mathcal{H}_{\text{eff}}^{\Delta F=1} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum (C_i \phi_i + C'_i \phi'_i) \]

Wilson coefficient \hspace{1cm} Dimension-6 operator

\[ b \rightarrow s \text{ effective Hamiltonian} \]

- **Mag. dipole operator**: 
  \[ B \rightarrow (X_s, K^*)\gamma \quad \times \]

- **Semileptonic operators**: 
  \[ B \rightarrow (X_s, K^{(*)})\ell^+\ell^- \quad \times \quad \times \]

- **Scalar operators** (neglecting tensor op.s):
  \[ B_s \rightarrow \mu^+\mu^- \quad \times \quad \times \]
\[
\mathcal{H}_{\text{eff}}^{\Delta F = 1} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum (C_i \theta_i + C'_i \theta'_i)
\]

Wilson coefficient \quad Dimension-6 operator

\begin{align*}
\begin{array}{c}
\text{mag. dipole} \\
\text{operator}
\end{array} & \quad & \begin{array}{c}
\text{semileptonic} \\
\text{operators}
\end{array} & \quad & \begin{array}{c}
\text{scalar} \\
\text{operators}
\end{array} & \quad & (\text{neglecting: tensor op.s})
\end{align*}

\begin{align*}
B & \to (X_s, K^*)\gamma \quad & \times \\
B & \to (X_s, K^{(*)})\ell^+\ell^- \quad & \times & \times \\
B_s & \to \mu^+\mu^- \quad & \times & \times
\end{align*}
$B_s \to \mu^+ \mu^-$

$$\text{BR}_{SM} = (3.2 \pm 0.2) \times 10^{-9} \quad \text{BR}_{\text{exp}} < 7.7 \times 10^{-9} \hspace{1em} \text{@95\% C.L.}$$

$$\text{BR}(B_s \to \mu^+ \mu^-) \propto \left| C_S - C'_S \right|^2 \left(1 - \frac{4m_{\mu}^2}{m_{B_s}^2}\right) + \left| C_P - C'_P \right| + \frac{2m_{\mu}}{m_{B_s}^2} \left( C_{10} - C'_{10} \right)$$

Scalar operators:
Virtually unconstrained by other processes
Can easily saturate the exp. bound
$B_s \rightarrow \mu^+ \mu^-$

$$\text{BR}_{\text{SM}} = (3.2 \pm 0.2) \times 10^{-9} \quad \text{BR}_{\text{exp}} < 7.7 \times 10^{-9} \text{ @95\% C.L.}$$ [CMS 2012]

$$\text{BR}(B_s \rightarrow \mu^+ \mu^-) \propto |C_S - C'_S|^2 \left(1 - \frac{4m^2_\mu}{m^2_{B_s}}\right) + |(C_P - C'_P) + \frac{2m_\mu}{m^2_{B_s}}(C_{10} - C'_{10})|^2$$

**Scalar operators:**
Virtually unconstrained by other processes
Can easily saturate the exp. bound

**Semileptonic operators:**
Only $C_{10}$ non-zero in the SM
Constrained by $b \rightarrow s\ell^+\ell^-$
Cannot saturate exp. bound
$B_s \rightarrow \mu^+ \mu^-$

$$\text{BR}_{SM} = (3.2 \pm 0.2) \times 10^{-9} \quad \text{BR}_{exp} < 4.5 \times 10^{-9} \text{ @95\% C.L.}$$

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 Can

[LHCb 2012]
$B_s \rightarrow \mu^+ \mu^-$

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$$

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$$

**Scalar operators:**
- Virtually unconstrained by other processes
- Can easily saturate the exp. bound

**Semileptonic operators:**
- Only $C_{10}$ non-zero in the SM
- Constrained by $b \rightarrow s\ell^+\ell^-$
- Cannot saturate exp. bound

In the following:

- Assume $C_{S,P}^{(i)} = 0$
- Use $b \rightarrow s\gamma$, $b \rightarrow s\ell^+\ell^-$ to put model-independent constraints on $\text{BR}(B_s \rightarrow \mu^-\mu^+)$ in the *absence* of scalar operators
$b \rightarrow s$ effective Hamiltonian

$$\mathcal{H}_\text{eff}^{\Delta F=1} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum (C_i \bar{\phi}_i + C_i' \bar{\phi}_i')$$

Wilson coefficient
Dimension-6 operator

$C_7^{(i)}$  
$C_9^{(i)}$  
$C_{S,P}^{(i)}$

mag. dipole operator  
semileptonic operators  
scalar operators  

(neglecting: tensor op.s)

<table>
<thead>
<tr>
<th>Process</th>
<th>$C_7^{(i)}$</th>
<th>$C_9^{(i)}$</th>
<th>$C_{S,P}^{(i)}$</th>
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<tr>
<td>$B \rightarrow (X_s, K^*) \gamma$</td>
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<td></td>
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What are the allowed ranges for the Wilson coefficients?

- Measurements of experimental observables
  - Model-independent constraints on Wilson coefficients
  - Constraints on parameter space of concrete models

This talk

Altmannshofer, Paradisi, DS 1111.1257

see also
Bobeth et al. 1111.2558, 1006.5013
Descotes-Genon et al. 1104.3342
Constraints on Wilson coefficients

What are the allowed ranges for the Wilson coefficients?

Measurements of experimental observables

Model-independent constraints on Wilson coefficients

Constraints on parameter space of concrete models

"Naive theorist's combination" of EXP results;
Estimation of TH uncertainties;
All uncertainties assumed Gaussian

$$\chi^2 = \sum \frac{(O_{\text{ex}} - O_{\text{th}})^2}{\sigma_{\text{ex}}^2 + \sigma_{\text{th}}^2}$$

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Constraints on $C_7$, $C_9$, $C_{10}$

Varying 1 Wilson coefficient at a time. $C_i = C_i^{SM} + C_i^{NP}$

$\text{BR}(B \rightarrow X_s \ell^+ \ell^-)$  $\text{BR}(B \rightarrow X_s \gamma)$
Constraints on $C_7$, $C_9$, $C_{10}$

Varying 1 Wilson coefficient at a time. $C_i = C_i^{\text{SM}} + C_i^{\text{NP}}$

\[
\begin{align*}
\text{BR}(B \to X_s \ell^+ \ell^-) & \quad \text{BR}(B \to X_s \gamma) & \quad \text{BR}(B \to K^* \mu^+ \mu^-) \\
\text{Both low and high } q^2 \text{ regions}
\end{align*}
\]
Constraints on $C_7$, $C_9$, $C_{10}$

Varying 1 Wilson coefficient at a time. $C_i = C_i^{SM} + C_i^{NP}$

$$
\text{BR}(B \rightarrow X_s \ell^+ \ell^-) \quad \text{BR}(B \rightarrow X_s \gamma) \quad \text{BR}(B \rightarrow K^* \mu^+ \mu^-) \quad A_{FB}(B \rightarrow K^* \mu^+ \mu^-)
$$

Both low and high $q^2$ regions
Constraints on $C_7, C_9, C_{10}$

Varying 1 Wilson coefficient at a time. $C_i = C_i^{\text{SM}} + C_i^{\text{NP}}$

- Good agreement with SM expectations
- Complementarity between observables crucial to break degeneracies

\[ \text{BR}(B \rightarrow X_s \ell^+ \ell^-) \quad \text{BR}(B \rightarrow X_s \gamma) \quad \text{BR}(B \rightarrow K^* \mu^+ \mu^-) \quad A_{FB}(B \rightarrow K^* \mu^+ \mu^-) \]
Constraints on the NP scale

Results can be interpreted as bounds on the scale of new physics:

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_{j=7,9,10} \frac{e^{i\phi_j}}{\Lambda_j^2} \theta_j \]

~tree level generic flavour violation
Constraints on the NP scale

Results can be interpreted as bounds on the scale of new physics:

\[ \mathcal{L} = \mathcal{L}_{SM} - \sum_{j=7,9,10} \frac{V_{tb} V_{ts}^* e^{i\phi_j}}{16\pi^2} \frac{1}{\Lambda_j^2} \mathcal{O}_j \]

~loop level CKM-like flavour violation
Constraints on the NP scale

Results can be interpreted as bounds on the scale of new physics:

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} - \sum_{j=7,9,10} \frac{V_{tb} V_{ts}^*}{16\pi^2} \frac{e^{i\phi_j}}{\Lambda_j^2} \mathcal{O}_j \]

\( \sim \) loop level CKM-like flavour violation

- Bounds are weaker in the presence of CP violation beyond the CKM
- Reason: only CP-averaged observables
- Measurement of CP asymmetries would be welcome
Impact of CP asymmetries

**Example 1:** direct CP asymmetry in $B \rightarrow X_s \gamma$

Dominated by poorly known long-distance contribution in the SM

Very limited usefulness to constrain NP  [Benzke, Lee, Neubert, Paz (2010)]

**Example 2:** angular CP asymmetry $A_7$ in $B \rightarrow K^*\mu^+\mu^-$ at low $q^2$

(0 in the SM, not suppressed by small strong phases)

95% C.L. from hypothetical measurement $\langle A_7 \rangle = 0 \pm 0.1$
Impact of CP asymmetries

Example 1: direct CP asymmetry in $B \rightarrow X_s\gamma$
Dominated by poorly known long-distance contribution in the SM
Very limited usefulness to constrain NP \cite{Benzke, Lee, Neubert, Paz (2010)}

Example 2: angular CP asymmetry $A_7$ in $B \rightarrow K^*\mu^+\mu^-$ at low $q^2$
(0 in the SM, not suppressed by small strong phases)

$\langle A_7 \rangle = 0 \pm 0.05$

- Measurement of $A_7$ with precision $< 0.1$ would give a valuable constraint
- Is it doable?
Constraints on $C_7$ vs. $C_9$ vs. $C_{10}$

Now: correlations between 2 real Wilson coefficients

$BR(B \rightarrow X_s \ell^+\ell^-)$  $BR(B \rightarrow X_s \gamma)$
Constraints on $C_7$ vs. $C_9$ vs. $C_{10}$

Now: correlations between 2 real Wilson coefficients

\[ \text{BR} (B \to X_s \ell^+ \ell^-) \quad \text{BR} (B \to X_s \gamma) \quad \text{BR} (B \to K^* \mu^+ \mu^-) \]
Constraints on $C_7$ vs. $C_9$ vs. $C_{10}$

Now: correlations between 2 real Wilson coefficients

$$\text{BR}(B \to X_s \ell^+\ell^-) \quad \text{BR}(B \to X_s \gamma) \quad \text{BR}(B \to K^* \mu^+\mu^-) \quad A_{FB}(B \to K^* \mu^+\mu^-)$$
Constraints on $C_7$ vs. $C_9$ vs. $C_{10}$

Now: correlations between 2 real Wilson coefficients

\[ \text{BR}(B \to X_s \ell^+\ell^-) \quad \text{BR}(B \to X_s \gamma) \quad \text{BR}(B \to K^*\mu^+\mu^-) \quad A_{FB}(B \to K^*\mu^+\mu^-) \]

\[ \bullet \quad B \to K^*\mu^+\mu^- \text{ data exclude various “mirror solutions”} \]
Constraints on $C_7$ vs. $C_9$ vs. $C_{10}$

Now: allow all 3 real coefficients to vary and marginalize over the third one

Flipped-sign solutions:

- $C_{7,9,10} = -C_{SM}^{7,9,10}$ cannot be excluded, but . . .
- $C_7 = -C_{SM}^7$ disfavoured by $BR(B \to X_s\ell^+\ell^-)$ [Gambino, Haisch, Misiak (2004)]
- $C_{9,10} = -C_{SM}^{9,10}$ NEW: disfavoured by $B \to K^*\mu^+\mu^-$ data
Constraints on $C_7$ vs. $C_9$ vs. $C_{10}$

Now: allow all 3 real coefficients to vary and marginalize over the third one

Flipped-sign solutions:

- $C_{7,9,10} = -C_{7,9,10}^{SM}$ cannot be excluded, but . . .
- $C_7 = -C_7^{SM}$ disfavoured by BR($B \to X_s \ell^+\ell^-$) [Gambino, Haisch, Misiak (2004)]
- $C_{9,10} = -C_{9,10}^{SM}$ NEW: disfavoured by $B \to K^* \mu^+\mu^-$ data
Constraints in the presence of phases

More general case with phases and/or right-handed currents: constraints weakened
e.g. $\text{Re}(C_9)$ vs. $\text{Re}(C_{10})$

![Graphs showing constraints]

SM operator basis
only CKM CP violation

SM operator basis
generic CP violation

SM op. + chirality-flipped
generic CP violation

More data needed to break degeneracies
Observables directly sensitive to chirality and/or CPV
## Fit predictions

| Scenario          | $10^9 \text{BR}(B_s \to \mu\mu)$ | $|\langle A_7 \rangle|$ | $|\langle A_8 \rangle|$ | $|\langle A_9 \rangle|$ | $\langle S_3 \rangle$ |
|-------------------|----------------------------------|--------------------------|--------------------------|--------------------------|------------------------|
| Real LH           | [1.0, 5.6]                       | 0                        | 0                        | 0                        | 0                      |
| Complex LH        | [1.0, 5.4]                       | $< 0.31$                 | $< 0.15$                 | 0                        | 0                      |
| Complex RH        | $< 5.6$                          | $< 0.22$                 | $< 0.17$                 | $< 0.12$                 | $[-0.06, 0.15]$        |
| Generic NP        | $< 5.5$                          | $< 0.34$                 | $< 0.20$                 | $< 0.15$                 | $[-0.11, 0.18]$        |
| LH Z peng.        | [1.4, 5.5]                       | $< 0.27$                 | $< 0.14$                 | 0                        | 0                      |
| RH Z peng.        | $< 3.8$                          | $< 0.22$                 | $< 0.18$                 | $< 0.12$                 | $[-0.03, 0.18]$        |
| Generic Z p.      | $< 4.1$                          | $< 0.28$                 | $< 0.21$                 | $< 0.13$                 | $[-0.07, 0.19]$        |

$$B \to K^* \mu^+\mu^-$$
## Fit predictions

| Scenario       | $10^9 \text{BR}(B_s \rightarrow \mu\mu)$ | $|\langle A_7 \rangle|$ | $|\langle A_8 \rangle|$ | $|\langle A_9 \rangle|$ | $\langle S_3 \rangle$ |
|----------------|----------------------------------------|------------------|------------------|------------------|------------------|
| Real LH        | $[1.0, 5.6]$                           | $0$              | $0$              | $0$              | $0$              |
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| Generic Z p.   | $< 4.1$                                | $< 0.28$         | $< 0.21$         | $< 0.13$         | $[−0.07, 0.19]$  |

LHCb starts to probe the region accessible to models without scalar op.s!
Summary

- Rare $b \to s$ decays probe flavour physics **beyond the SM**
- **Model-independent** constraints: bounds on Wilson coefficients
- At the moment, everything **consistent with SM**
- But: still **room for new physics**

- **Most constraining** observables at present:
  - $\text{BR}(B \to X_s \gamma)$, angular obs. in $B \to K^* \mu^+ \mu^-$, $B_s \to \mu^+ \mu^-$, $S_{K^* \gamma}$

- **Waiting for** improved measurements of observables sensitive to chirality/CP violation
  - $A_{7,8,9}(B \to K^* \mu^+ \mu^-)$, $S_3(B \to K^* \mu^+ \mu^-) (\sim A_T^{(2)})$, $S_{K^* \gamma}$, ...
...and now
extra slides
$B \to K^{(*)}\nu\bar{\nu}$

Semi-leptonic $b \to s\ell^+\ell^-$ operators as well as $b \to s\nu\bar{\nu}$ operators receive $Z$ mediated contributions.

If other contributions can be neglected: correlation between $b \to s\ell^+\ell^-$ and $b \to s\nu\bar{\nu}$ decays

Fit result, generic CP violating left- and right-handed $Z$ penguins
$\mathcal{H}_{\text{eff}}^{\Delta F=1} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum (C_i \bar{\theta}_i + C'_i \bar{\theta}'_i)$

$O_7 = \frac{m_b}{e} (\bar{s} \sigma_{\mu\nu} P_R b) F^{\mu\nu},$

$O_8 = \frac{g m_b}{e^2} (\bar{s} \sigma_{\mu\nu} T^a P_R b) G^{\mu\nu a},$

$O_9 = (\bar{s} \gamma_\mu P_L b)(\bar{\ell} \gamma^\mu \ell),$

$O_{10} = (\bar{s} \gamma_\mu P_L b)(\bar{\ell} \gamma^\mu \gamma_5 \ell),$

$O_S = m_b (\bar{s} P_R b)(\bar{\ell} \ell),$

$O_P = m_b (\bar{s} P_R b)(\bar{\ell} \gamma_5 \ell),$

$C_7^{\text{eff}}(\mu_b) = -0.304,$

$C_9(\mu_b) = 4.211,$

$C_{10}(\mu_b) = -4.103,$

$C_7^{\text{eff}}(\mu_b) = C_7^{\text{eff,SM}}(\mu_b) + C_7^{\text{NP}}(\mu_b),$  

$C_9(\mu_b) = C_9^{\text{eff,SM}}(\mu_b) + C_9^{\text{NP}},$

$C_{10} = C_{10}^{\text{SM}} + C_{10}^{\text{NP}},$

$C_7(\mu_b) = C_7^{\text{NP}}(\mu_b),$  

$C_9,10(\mu_b) = C_{9,10}^{\text{NP}}.$

$(\mu_h = 160 \ \text{GeV})$  

$C_7^{(')}^{\text{NP}}(\mu_b) = 0.623 \ C_7^{(')}^{\text{NP}}(\mu_h) + 0.101 \ C_8^{(')}^{\text{NP}}(\mu_h).$
$B \to K^* \ell^+ \ell^-$

$B \to K^* (\to K\pi) \ell^+ \ell^-$ offers a plethora of observables sensitive to new physics

\[ d^4\Gamma \over dq^2 d\cos\theta_\ell d\cos\theta_{K^*} d\phi = \sum_{i,a} l_i^{(a)}(q^2) f(\theta_\ell, \theta_{K^*}, \phi) \]

\[ S_i^{(a)}(q^2) = \left( l_i^{(a)}(q^2) + \bar{l}_i^{(a)}(q^2) \right) \over d(q\Gamma + \bar{\Gamma}) \]

\[ A_i^{(a)}(q^2) = \left( l_i^{(a)}(q^2) - \bar{l}_i^{(a)}(q^2) \right) \over d(q\Gamma + \bar{\Gamma}) \]

CP-averaged angular coefficients (e.g. forward-backward asymmetry)

CP asymmetries
Plots, plots, plots