$B \rightarrow K^{(*)}\nu\bar{\nu}$ decays in the Standard Model and beyond

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in collaboration with A. Buras, J. Girrbach-Noe and D. Straub

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Why should one look for $B \rightarrow K^{(*)}\nu\bar{\nu}$ transitions?

- Powerful tools to test NP scenarios
  - In particular: new right-handed interactions absent in the SM
  - Theoretically very clean: No uncertainties from non-factorizable long-range photon exchange
  - Recent theory progress allows to get much better SM predictions

- New measurements on $B \rightarrow K^{(*)}\nu\bar{\nu}$ allow to put strong constraints

- Hopefully, these decays will be accessible within the next few years
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1 SM predictions

2 Model independent constraints
   - General remarks
   - Correlations with $B \rightarrow K^{(*)}\ell^+\ell^-$ decays

3 Conclusion
SM predictions

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Conclusion
In the SM only one eff. operator contributes to $b \to s\nu\bar{\nu}$ transitions.
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We have to control:

- Wilson coefficient $C_L^{SM}$
  - $\to$ two-loop electroweak contributions (Brod,Gorbahn,Stamou 1009.0947)

- hadronic form factors $\rho(q^2)$
  - $\to$ combined fit to LCSR and lattice results (Bharucha,Straub,Zwicky 1503.05534)
updated SM predictions

\[ 10^6 \, \frac{d}{dq^2} \text{BR}(B^+ \to K^+ \nu \bar{\nu}) \]

\[ 10^6 \, \frac{d}{dq^2} \text{BR}(B^0 \to K^{*0} \nu \bar{\nu}) \]

\[
\text{BR}(B^+ \to K^+ \nu \bar{\nu})_{\text{SM}} = (3.98 \pm 0.43 \pm 0.19) \times 10^{-6} \\
< 1.7 \times 10^{-5} \text{ (BaBar)}
\]

\[
\text{BR}(B^0 \to K^{*0} \nu \bar{\nu})_{\text{SM}} = (9.19 \pm 0.86 \pm 0.50) \times 10^{-6} \\
< 5.5 \times 10^{-5} \text{ (Belle)}
\]

\[ F^\text{SM}_L = 0.47 \pm 0.03 \]
SM predictions

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Conclusion
General remarks

Beyond the SM, a second eff. operator can contribute (right-handed currents!):

\[ \mathcal{H}_{\text{eff}} \propto C_L \mathcal{O}_L + C_R \mathcal{O}_R + \text{h.c.}, \]

\[ \mathcal{O}_L \propto (\bar{s}\gamma_\mu P_L b)(\bar{\nu}\gamma^\mu P_L \nu) \]

\[ \mathcal{O}_R \propto (\bar{s}\gamma_\mu P_R b)(\bar{\nu}\gamma^\mu P_L \nu) \]
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Reparametrize Wilson coefficients:

\[ \epsilon = \frac{\sqrt{|C_L|^2 + |C_R|^2}}{|C_L^{\text{SM}}|} \]
\[ \eta = \frac{-\text{Re}(C_L C_R^*)}{|C_L|^2 + |C_R|^2} \]
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\[ R_K \equiv \frac{\text{BR}(\to K)}{\text{BR}(\to K)^{\text{SM}}} = (1 - 2 \eta) \epsilon^2 \]

\[ R_{K^*} \equiv \frac{\text{BR}(\to K^*)}{\text{BR}(\to K^*)^{\text{SM}}} = (1 + 1.34 \eta) \epsilon^2 \]

\[ R_{F_L} \equiv \frac{F_L}{F_L^{\text{SM}}} = \frac{1 + 2 \eta}{1 + 1.34 \eta} \]
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\[ \mathcal{R}_K \equiv \frac{\text{BR}(\rightarrow K)}{\text{BR}(\rightarrow K)^{\text{SM}}} = (1 - 2\eta)\epsilon^2 \]
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\[ \mathcal{R}_{F_L} \equiv \frac{F_L}{F_L^{\text{SM}}} = \frac{1 + 2\eta}{1 + 1.34\eta} \]

if \( \mathcal{R}_K \neq \mathcal{R}_{K^*} \)

\[ \Rightarrow \text{right-handed currents!} \]
General remarks

Beyond the SM, a second eff. operator can contribute (right-handed currents!): 

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If \( R_K \neq R_{K^*} \)

\[ \Rightarrow \text{right-handed currents!} \]

Correlations in \( R_K, R_{K^*}, R_{F_L} \)

\[ \Rightarrow \text{new invisible particles in final state?} \]
Correlations with $B \rightarrow K^{(*)} \ell^+ \ell^-$ decays

Idea: Use SU(2)$_L$ symmetry to connect $b \rightarrow s \nu \bar{\nu}$ decays to $b \rightarrow s \ell^+ \ell^-$ decays, on which a lot of exp. data exists.
Correlations with $B \to K^{(*)}\ell^+\ell^-$ decays

**Idea:** Use SU(2)$_L$ symmetry to connect $b \to s\nu\bar{\nu}$ decays to $b \to s\ell^+\ell^-$ decays, on which a lot of exp. data exists.

Use most general $\mathcal{G}_{\text{SM}}$-invariant basis of dim6-operators. (Grzadkowski et al. 1008.4884)

$$
Q^{(1)}_{Hq} = i(\bar{q}_L\gamma_\mu q_L)H^\dagger D^\mu H, \quad Q^{(1)}_{ql} = (\bar{q}_L\gamma_\mu q_L)(\bar{I}_L\gamma^\mu l_L),
$$

$$
Q^{(3)}_{Hq} = i(\bar{q}_L\gamma_\mu \tau^a q_L)H^\dagger D^\mu \tau_a H, \quad Q^{(3)}_{ql} = (\bar{q}_L\gamma_\mu \tau^a q_L)(\bar{I}_L\gamma^\mu \tau_a l_L),
$$

$$
Q_{Hd} = i(\bar{d}_R\gamma_\mu d_R)H^\dagger D^\mu H, \quad Q_{dl} = (\bar{d}_R\gamma_\mu d_R)(\bar{I}_L\gamma^\mu l_L),
$$

$$
Q_{de} = (\bar{d}_R\gamma_\mu d_R)(\bar{e}_R\gamma^\mu e_R), \quad Q_{qe} = (\bar{q}_L\gamma_\mu q_L)(\bar{e}_R\gamma^\mu e_R)
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$$O_9 \propto (\bar{s} \gamma_\mu P_L b)(\bar{\ell} \gamma^\mu \ell)$$

$$O_R \propto (\bar{s} \gamma_\mu P_R b)(\bar{\nu} \gamma^\mu P_L \nu)$$

$$O_9' \propto (\bar{s} \gamma_\mu P_R b)(\bar{\ell} \gamma^\mu \ell)$$

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

$$O_{10}' \propto (\bar{s} \gamma_\mu P_R b)(\bar{\ell} \gamma^\mu \gamma_5 \ell)$$
Idea: Use SU(2)_L symmetry to connect $b \to s\nu\bar{\nu}$ decays to $b \to s\ell^+\ell^-$ decays, on which a lot of exp. data exits.

Use most general $G_{SM}$-invariant basis of dim6-operators. (Grzadkowski et al. 1008.4884)
So, one finds a dictionary:

\[
C_L = C_{L}^{SM} + \tilde{c}_{q_l}^{(1)} - \tilde{c}_{q_l}^{(3)} + \tilde{c}_Z, \\
C_9 = C_{9}^{SM} + \tilde{c}_{q_e} + \tilde{c}_{q_l}^{(1)} + \tilde{c}_{q_l}^{(3)} - 0.08 \tilde{c}_Z, \\
C_{10} = C_{10}^{SM} + \tilde{c}_{q_e} - \tilde{c}_{q_l}^{(1)} - \tilde{c}_{q_l}^{(3)} + \tilde{c}_Z
\]

\[
C_R = \tilde{c}_{d_l} + \tilde{c}_{l'}_Z, \\
C'_9 = \tilde{c}_{d_e} + \tilde{c}_{d_l} - 0.08 \tilde{c}_Z, \\
C'_{10} = \tilde{c}_{d_e} - \tilde{c}_{d_l} + \tilde{c}_{l'}_Z
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with \( \tilde{c}_Z = \frac{1}{2}(\tilde{c}_{Hq}^{(1)} + \tilde{c}_{Hq}^{(3)}) \), \( \tilde{c}'_Z = \frac{1}{2} \tilde{c}_{Hd} \).
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\]
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C_{10} = C_{10}^{SM} + \tilde{c}_{qe} - \tilde{c}_{ql}^{(1)} - \tilde{c}_{ql}^{(3)} + \tilde{c}_Z , \quad C_{10}' = \tilde{c}_{de} - \tilde{c}_{dl} + \tilde{c}_Z ,
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with \( \tilde{c}_Z = \frac{1}{2}(\tilde{c}_{Hq}^{(1)} + \tilde{c}_{Hq}^{(3)}) , \quad \tilde{c}_Z' = \frac{1}{2} \tilde{c}_{Hd} . \)

- Now, use \( b \rightarrow s \ell^+ \ell^- \) data to constraint the Wilson coefficients and see how large effects in \( b \rightarrow s \nu \bar{\nu} \) can still get. (Altmannshofer, Straub 1411.3161)
So, one finds a dictionary:

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- Now, use \( b \to s\ell^{+}\ell^{-} \) data to constraint the Wilson coefficients and see how large effects in \( b \to s\nu\bar{\nu} \) can still get. (Altmannshofer, Straub 1411.3161)
- Consider only certain scenarios of NP where only a subset of operators is active.
Two different scenarios
Two different scenarios

NP dominated by:

- Modified (flavour changing) $Z$-couplings [e.g. MSSM, partial compositeness]

\[
\begin{align*}
C_L &= C_{L}^{\text{SM}} + \tilde{c}(1) q_{1} - \tilde{c}(3) q_{3} + \tilde{c} Z, \\
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C_R &= \tilde{c} + \tilde{c}' Z, \\
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C_R &= \tilde{c}_d + \tilde{c}'_d, \\
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\end{align*}
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- 4-Fermion-Operators [e.g. exchange of heavy $Z'$ boson]

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Model independent constraints Correlations with $B \to K^{(*)} \ell^+ \ell^-$ decays

Current $b \to s \ell^+ \ell^-$ data favour:

- Suppression of $\mathcal{R}_{K^{(*)}}$ if NP mainly in modified Z couplings
- Enhancement of $\mathcal{R}_{K^{(*)}}$ if NP mainly in 4-Fermion operators

**blue**: modified Z couplings
**red**: 4-Fermion operators

**solid**: real
**dashed**: complex
Model independent constraints

Correlations with $B \to K(*)\ell^+\ell^-$ decays

Current $b \to s\ell^+\ell^-$ data favour:

- Suppression of $\mathcal{R}_{K(*)}$ if NP mainly in modified $Z$ couplings
- Enhancement of $\mathcal{R}_{K(*)}$ if NP mainly in 4-Fermion operators

Correlations between $\mathcal{R}_K$ and $\mathcal{R}_{K*}$ allow to disentangle both scenarios.

Due to tensions in $b \to s\ell^+\ell^-$.  

\textbf{blue:} modified $Z$ couplings  
\textbf{red:} 4-Fermion operators  
\textbf{solid:} real  
\textbf{dashed:} complex
1. SM predictions

2. Model independent constraints
   - General remarks
   - Correlations with $B \to K(\ast) \ell^+ \ell^-$ decays

3. Conclusion
Conclusion

RH $\nu_\tau$, LH: $c_{ql}(1) = -c_{ql}(3)$ or $\nu_\tau$
RH or LH: LFV
RH LFU: disfavoured

RH $\nu_\tau$, RH: $\nu_e$ $Z$, LFU
MSSM

$R_K$: theoretically inaccessible

LH: $c_{ql}(1) = -c_{ql}(3)$ for certain PC scenarios
MSSM $SU(2)_L$ singlet or triplet LQ

$R_K \neq R_{K}^*$ enhancement:
hints to $Z'$ dominated NP

$R_K \neq R_{K}^*$ suppression:
hints to NP in $Z$ couplings

large effects only for $c_{ql}(1) = -c_{ql}(3)$ (e.g. certain LQ)
only couplings to $\tau$ and $\nu_\tau$
otherwise effects max.

$\pm 60\%$ LFU
$\pm 20\%$ only $\mu$

Christoph Niehoff (EXC Universe, TUM)

Vienna, July 24, 2015
\[ \mathcal{R}_K \neq \mathcal{R}_{K^*} \] problematic for

- MFV
- LH Z' couplings
- certain PC scenarios
- MSSM
- SU(2)\textsubscript{L} singlet or triplet LQ
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otherwise effects max. \( \left\{ \begin{array}{ll} \pm 60\% \text{ LFU} \\ \pm 20\% \text{ only } \mu \end{array} \right. \)
Things to take home

Updated values for SM predictions for these decays

We still need a factor of $\sim 5$ in experimental precision

Belle2 can do this!

Moderate NP effects are still possible!

For some special cases even very large effects are still viable

Correlations between $B \to K \nu \bar{\nu}$ and $B \to K^* \nu \bar{\nu}$ (and also $B \to K^*(\ell\ell)$ and $B_s \to \ell\ell$) can help to identify possible NP scenarios
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- Correlations between $B \to K\nu\bar{\nu}$ and $B \to K^*\nu\bar{\nu}$ (and also $B \to K^{(*)}\ell\ell$ and $B_s \to \ell\ell$) can help to identify possible NP scenarios