Precision Flavour Physics with $B \to K\nu\bar{\nu}$ and $B \to Kl^+l^-$

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based on arXiv:0909.1512v1

Rare b-Decays @ Low Recoil (bsll2011)
June 17, 2011

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Motivation

$b \to s\nu\bar{\nu}$ transitions

- Induced at short distances (weak scale)
- FCNC processes in the SM only beyond the tree level
- Further suppressed by the off-diagonal entries of the CKM matrix
  $\Rightarrow$ sizable effects from New Physics possible

Exclusive channels, e.g. $B \to K\nu\bar{\nu}$

☺ Experimentally easier to determine than inclusive decays such as $B \to X_s\nu\bar{\nu}$

☹ Requires form factors to describe nonperturbative hadronic physics

Combined analysis of the processes $B \to K\nu\bar{\nu}$ and $B \to Kl^+l^-$

- Both decays feature similar long distance dynamics
- Does this allow us to construct precision observables?

Outline

1. Hadronic Physics
   - QCD Factorization
   - Form factors
   - Parametrization
2. Numerical Results
   - Integrated branching fractions
   - Precision observables
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3. Summary

QCD Factorization

Factorization Formula

$$\left\langle \bar{K}\ l^+ l^- \middle| H_{eff} \middle| \bar{B} \right\rangle \;=\; C \cdot f + \Phi_B \otimes T \otimes \Phi_K \;+\; \mathcal{O}(\Lambda_{QCD}/m_B)$$

- In the heavy-quark limit short-distance contributions $\mathcal{O} \sim m_B$ and long-distance contributions $\mathcal{O} \sim \Lambda_{QCD}$ are disentangled.
- Form factors f and light-cone distribution amplitudes Φ contain soft QCD effects. They are universal quantities, i.e. they do not depend on the specific decay.
- They have to be extracted from other experiments or computed using nonperturbative methods. Unfortunately these techniques give rise to rather large uncertainties.
- Semileptonic operators $(\bar{s}b)_{V-A}(\bar{l}l)_{V,A}$: simple matrix elements, dominant contributions, contained only in $C \cdot f$
- Hadronic operators $\sim (\bar{s}b)_{V-A}(\bar{q}q)_{V\pm A}$: more complicated (e.g. charm-loops, weak annihilation), relatively small contributions
- In the kinematical region of high $q^2 \sim m_b^2$ the theoretical framework to address the non-local terms is an operator product expansion.

Hadronic Matrix Elements for $B \to K$ transitions

$$\langle K(p_K)|V^\mu|B(p)\rangle = f_+(q^2)\left[p^\mu + p_K^\mu - \frac{m_B^2 - m_K^2}{q^2}q^\mu\right] + f_0(q^2)\,\frac{m_B^2 - m_K^2}{q^2}q^\mu$$

$$q_\nu\langle K(p_K)|T^{\mu\nu}|B(p)\rangle = i\,\frac{f_T(q^2)}{m_B + m_K}\left[q^2(p+p_K)^\mu - (m_B^2 - m_K^2)q^\mu\right]$$

- To describe the hadronic physics in principle three different form factors are necessary: $f_+(q^2)$, $f_0(q^2)$, and $f_T(q^2)$.
- However, in the case of semileptonic decays the contribution associated with $f_0(q^2)$ will be proportional to the lepton masses, and is therefore negligible for present experiments.
- Furthermore, there is a nontrivial relation between $f_T(q^2)$ and $f_+(q^2)$ in the heavy-quark limit:

Relation between form factors $f_T(q^2)$ and $f_+(q^2)$

$$\frac{f_T(q^2)}{f_+(q^2)} = \frac{m_B + m_K}{m_B} + \mathcal{O}(\alpha_s, \Lambda/m_b)$$

$\Rightarrow$ The entire hadronic physics can be expressed in terms of $f_+(q^2)$.

Parametrization

$$f_+(s) = f_+(0)\frac{1+(a_0 b_0 - b_0 - b_1)s}{(1-b_0 s)(1-b_1 s)} \qquad s = q^2/m_B^2$$

- In this parametrization the parameter b_0 represents the position of the B_s^* pole and will be treated as fixed at $b_0 = \frac{m_B^2}{m_{B_s^*}^2} \approx 0.95$.
  [D. Becirevic and A. B. Kaidalov, Phys. Lett. B 478, 2000]
- The remaining parameters have been calculated with QCD sum rules. [P. Ball and R. Zwicky, Phys. Rev. D 71, 2005].
- Combined with recent data from Belle [J. T. Wei and P. Chang, arXiv:0904.0770v1] the following parameter space seems reasonable.

Range of parameter space

$$f_+(0) = 0.304 \pm 0.042, \qquad a_0 = 1.6 \pm 0.2, \qquad b_1/b_0 = 1.0^{+0.0}_{-0.5}$$

Differential Branching Fractions

$$\frac{dB(B\to Kl^+l^-)}{ds} = \tau_B \frac{G_F^2\alpha^2 m_B^5}{1536\pi^5}|V_{ts}V_{tb}|^2\lambda_k^{\frac{3}{2}}(s)f_+^2(s)(|\tilde{C}_{10}|^2+|C_9^{eff}(s)|^2)$$

$$\frac{dB(B\to K\nu\overline{\nu})}{ds} = \tau_B \frac{G_F^2\alpha^2 m_B^5}{256\pi^5}|V_{ts}V_{tb}|^2\lambda_k^{\frac{3}{2}}(s)f_+^2(s)|\tilde{C}_\nu|^2$$

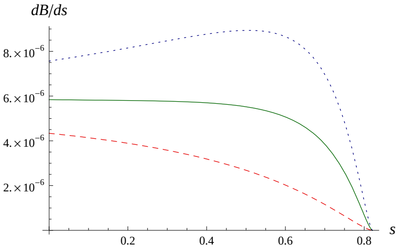

Figure: 1: $B\to K\nu\bar{\nu}$

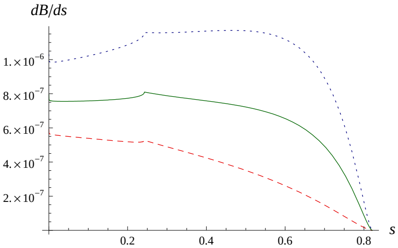

Figure: 2: $B\to Kl^+l^-$

Numerical Results

Integrated Branching Fractions

$$\mathcal{B}(B^- \to K^- \nu\bar{\nu})\left[10^{-6}\right] = 4.4 \; {}^{+1.3}_{-1.1}(f_+(0)) \; {}^{+0.8}_{-0.7}(a_0) \; {}^{+0.0}_{-0.7}(b_1)$$

$$\mathcal{B}(B^- \to K^- l^+ l^-)\left[10^{-7}\right] = 5.8 \; {}^{+1.7}_{-1.5}(f_+(0)) \; {}^{+1.0}_{-0.9}(a_0) \; {}^{+0.0}_{-0.9}(b_1) \; {}^{+0.4}_{-0.3}(\mu)$$

Uncertainties from other Sources

- Contributions of relative size $\left|\frac{V_{us}^* V_{ub}}{V_{ts}^* V_{tb}}\right| < 0.02$ have been neglected.
- Weak annihilation diagrams contribute at leading order. Nevertheless the numerical impact is less than 1% and therefore negligible.
- The reaction $B^- \to \tau^- \bar{\nu}_\tau \to K^- \nu_\tau \bar{\nu}_\tau$ produces a background for the decay $B^- \to K^- \nu_\tau \bar{\nu}_\tau$. The resulting uncertainties will diminish to roughly 1% with increasing accuracy of the $B^- \to \tau^- \bar{\nu}_\tau$ measurement. [J. F. Kamenik and C. Smith, arXiv:0908.1174v1]

Numerical Results

Precision Observables

$$\mathcal{R} = 7.59 \,^{+0.01}_{-0.01}(a_0) \,^{+0.00}_{-0.02}(b_1) \,^{-0.48}_{+0.41}(\mu)$$

$$\mathcal{R}_{25} = 7.60 \,^{+0.00}_{-0.00}(a_0) \,^{+0.00}_{-0.00}(b_1) \,^{-0.43}_{+0.36}(\mu)$$

$$\mathcal{R}_{256} = 14.6 \,^{+0.28}_{-0.38}(a_0) \,^{+0.10}_{-0.02}(b_1) \,^{-0.80}_{+0.62}(\mu)$$

[M. Bartsch, M. Beylich, G. Buchalla, D.-N Gao], [Hurth, Wyler]

The charmonium resonances $\Psi(1S)$ and $\Psi(2S)$ spoil the validity of perturbation theory in the kinematical region $0.25 \leq s \leq 0.6$. To obtain theoretically clean observables and still examine most of the spectrum the ratios $\mathcal{R}_{25}$ and $\mathcal{R}_{256}$ were defined in the following way:

$$\mathcal{R} \equiv \frac{\mathcal{B}(B^- \to K^- \nu\bar{\nu})}{\mathcal{B}(B^- \to K^- l^+ l^-)}$$

$$\mathcal{R}_{25} \equiv \frac{\int_0^{0.25} ds\; d\mathcal{B}(B^- \to K^- \nu\bar{\nu})/ds}{\int_0^{0.25} ds\; d\mathcal{B}(B^- \to K^- l^+ l^-)/ds}$$

$$\mathcal{R}_{256} \equiv \frac{\int_0^{s_{max}} ds\; d\mathcal{B}(B^- \to K^- \nu\bar{\nu})/ds}{\int_0^{0.25} ds\; d\mathcal{B}(B^- \to K^- l^+ l^-)/ds + \int_{0.6}^{s_{max}} ds\; d\mathcal{B}(B^- \to K^- l^+ l^-)/ds}$$

Experimental status

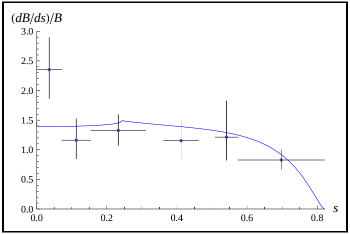

Figure: Shape of $B \to K l^+ l^-$ from Belle data (crosses) and theory with best-fit parameters (solid curve).

$$\mathcal{B}^{exp}\left(B^0 \to K^0 \nu \bar{\nu}\right) \leq 160 \cdot 10^{-6}$$
$$\mathcal{B}^{exp}\left(B^+ \to K^+ \nu \bar{\nu}\right) \leq 14 \cdot 10^{-6}$$
$$\mathcal{B}^{exp}\left(B^+ \to K^+ l^+ l^-\right) = 0.48^{+0.05}_{-0.04} \pm 0.03 \cdot 10^{-6}$$

$\Rightarrow$ Combining the experimental value for $\mathcal{B}\left(B^+ \to K^+ l^+ l^-\right)$ with the theoretical prediction of $\mathcal{R}$ one can improve the estimate for the neutrino mode: $\mathcal{B}(B^- \to K^- \nu \bar{\nu}) = (3.64 \pm 0.47) \cdot 10^{-6}$.

Summary

- The branching fractions of $B \to K\nu\bar{\nu}$ and $B \to Kl^+l^-$ are suppressed in the SM and therefore sensitive to New Physics.
- The long distance dynamics factorize from the NP in the Wilson Coefficients and can be described essentially only through f_+.
- The hadronic uncertainties contained in the form factors are eliminated almost completely by considering suitable ratios of the integrated branching fractions. At the same time the sensitivity to physics beyond the SM is preserved.
- The remaining perturbative uncertainty of suitable ratios is roughly $\pm 5\%$ at next-to-leading (NLO). A further improvement by a NNLO analysis is achievable.