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Phenomenology of $B \to X_s \ell^+ \ell^-$

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We present a brief review of the status and phenomenology of $B \to X_s \ell^+ \ell^-$ decays. The $B \to X_s \ell^+ \ell^-$ rate is known at the next-to-next-to-leading order in QCD and NLO in QED. QED corrections include only log-enhanced corrections of the type $\alpha_{\rm em} \ln(M_W^2/m_b^2)$ and $\alpha_{\rm em} \ln(m_b^2/m_\ell^2)$. The latter originate from a collinear singularity, they vanish when integrated over the whole phase space but survive the integration over the low dilepton invariant mass region $1\ {\rm GeV}^2 < m_{\ell\ell}^2 < 6\ {\rm GeV}^2$. For the low-$m_{\ell\ell}^2$ integrated branching ratio in the muonic case, we find $\mathscr{B}(B \to X_s \mu^+ \mu^-) = (1.59 \pm 0.11) \times 10^{-6}$, where the error includes the parametric and perturbative uncertainties only. For $\mathscr{B}(B \to X_s e^+ e^-)$, in the current BaBar and Belle setups, the logarithm of the lepton mass gets replaced by angular cut parameters. In effect, the integrated branching ratio for the electrons is expected to be close to that for the muons.

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PoS(HEP2005)278

1. Phase space cuts: experimental and theoretical considerations

In order to suppress background from the double semileptonic decay $b \to \ell^- \nu_\ell c\, (\to s \ell^+ \overline{\nu}_\ell) = b \to s \ell^+ \ell^- +$ *missing energy*, the invariant mass of the X_s system is restricted to $m_{X_s} < 2.1$ GeV. The numerical impact of this cut has been investigated [2] and experimental results are corrected to take it into account.

The di–lepton invariant mass (s) spectrum contains peaks corresponding to intermediate $c\overline{c}$ resonances: $B \to X_s (J/\psi, \psi', \ldots) \to X_s \ell^+ \ell^-$. Due to failure of quark-hadron duality and in order to isolate the non-resonant branching ratio, these resonances have to be eliminated by suitable cuts. We identify three regions: the very-low-s region ($s \in [0.04, 1]$ GeV^2), the low-s region ($s \in [1, 6]$ GeV^2), and the high-s region ($s > 14.4$ GeV^2). In the very-low-s region the branching ratio is dominated by the quasi-real photon pole and the physics involved is the same as in $B \to X_s \gamma$. In the low-s region we are sensitive to new Wilson coefficients while non-perturbative effects are well under control. The high-s region is also interesting from the physics point of view but the calculation of the spectrum is non reliable, there are large power corrections and the branching ratio is very small. Therefore, the integrated BR in the low-s region is the best compromise between theoretical accuracy, experimental observability and probe of new physics; in the following we'll focus on this region and refer, for instance, to Ref. [3] for a discussion of the high-s scenario.

2. A short history of $\bar{B} \to X_s \ell^+ \ell^-$

Using quark-hadron duality, the decay width is given by the quark level process up to calculable power corrections: $\Gamma(\bar{B} \to X_s \ell^+ \ell^-) = \Gamma(b \to X_s \ell^+ \ell^-) +$ power corrections$(1/m_{b,c})$. Power corrections have been calculated ($1/m_b^2$ [4], $1/m_b^3$ [5], $1/m_c^2$ [6]) and found to be very small.

The low-energy effective theory approach is most convenient to disentangle short and long distance effects. The effective Hamiltonian that we use is defined in Ref. [1] and our choice of evanescent operators is the same as in Refs. [7, 8, 9].

The matching conditions required at NNLO in QCD and NLO in QED have been calculated in Refs. [10, 11, 12, 13, 14, 15, 16]. In order to resum all the *QCD* large logs associated with QED corrections (i.e. of the type $\alpha_{\rm em} \ln(M_W/\mu_b)$), we have to use mixed QCD and QED renormalization group equations. The relevant matching conditions and anomalous dimensions, as well as the explicit solution of the RGE's can be found in Ref. [1]. The missing anomalous dimensions required by QED corrections were calculated in Ref. [9] and confirmed in Ref. [1].

The matrix elements and the corresponding bremsstrahlung processes required at NNLO in QCD have been calculated in Refs. [17, 18, 3, 9]; the new matrix elements required at NLO in QED have been presented in Ref. [1]. The latter contain a mass singularity (i.e. proportional to $\ln(m_b^2/m_\ell^2)$) that survives the integration over the low-s region and are, therefore, quite sizable. This log is originated by quasi-collinear real photon emission from the final state leptons and must, therefore, vanish upon integration over the whole phase space. Due to details of the electron energy reconstruction in the analyses of both BaBar and Belle, the $\ln(m_b^2/m_e^2)$ in the correction term for the decay into electrons gets replaced by angular cuts parameters; contributions to the branching ratios into electrons and muons, turn out to be similar in size. We refer to [1] for a discussion of these issues as well as for a detailed description of the technical issues involved in the calculation.

PoS(HEP2005)278

$\alpha_s(M_z) = 0.1182 \pm 0.0027$	$m_e = 0.51099892$ MeV
$\alpha_e(M_z) = 1/127.918$	$m_\mu = 105.658369$ MeV
$s_W^2 \equiv \sin^2\theta_W = 0.2312$	$m_\tau = 1.77699$ GeV
$\lvert V_{ts}^* V_{tb}/V_{cb}\rvert^2 = 0.967 \pm 0.009$ [21]	$m_c(m_c) = (1.224 \pm 0.017 \pm 0.054)$ GeV [22]
$BR(B \to X_c e \bar{\nu})_{\rm exp} = 0.1061 \pm 0.0017$ [23]	$m_b^{1S} = (4.68 \pm 0.03)$ GeV [20]
$M_Z = 91.1876$ GeV	$m_{t,\rm pole} = (172.7 \pm 2.9)$ GeV [24]
$M_W = 80.426$ GeV	$m_B = 5.2794$ GeV
$\lambda_2 \simeq \frac{1}{4}\left(m_{B^*}^2 - m_B^2\right) \simeq 0.12\ {\rm GeV}^2$	$C = 0.58 \pm 0.01$ [20]

Table 1: Numerical inputs that we use in the phenomenological analysis.

3. Predictions in the SM and experimental results

In order to minimize uncertainties stemming from $m_{b,pole}^5$, we normalize the differential decay width to the measured semileptonic one. We follow the analysis of Ref. [19] to avoid uncertainties due to the perturbative $B \to X_c e\nu$ phase space factor. The final expression for the differential branching ratio is [1]

$$\frac{{\rm d}\mathscr{B}(\bar{B} \to X_s \ell^+ \ell^-)}{{\rm d}\hat{s}} = \mathscr{B}(B \to X_c e \bar{\nu})_{\rm exp} \left| \frac{V_{ts}^* V_{tb}}{V_{cb}} \right|^2 \frac{4}{C} \frac{\Phi_{\ell\ell}(\hat{s})}{\Phi_u} , \tag{3.1}$$

where

$$\frac{{\rm d}\Gamma(\bar{B} \to X_s \ell^+ \ell^-)}{{\rm d}\hat{s}} = \frac{G_F^2 m_{b,\rm pole}^5}{48\pi^3} |V_{ts}^* V_{tb}|^2 \, \Phi_{\ell\ell}(\hat{s}) , \tag{3.2}$$

$$\Gamma(B \to X_u e \bar{\nu}) = \frac{G_F^2 m_{b,\rm pole}^5}{192\pi^3} |V_{ub}|^2 \, \Phi_u . \tag{3.3}$$

The factor $C = |V_{ub}/V_{cb}|^2 \, \Gamma(\bar{B} \to X_c e \bar{\nu})/\Gamma(\bar{B} \to X_u e \bar{\nu}) = 0.58 \pm 0.01$ has been recently determined from a global analysis of the semileptonic data [20]. The numerical inputs that we use are summarized in Table 1. Our results for the branching ratios integrated in the low-s region read

$$\begin{pmatrix} \mathscr{B}_{\mu\mu} \\ \mathscr{B}_{ee} \end{pmatrix} = \Big[\begin{matrix} 1.59 \\ 1.64 \end{matrix} \pm 0.08_{\rm scale} \pm 0.06_{m_t} \pm 0.024_{C,m_c} \pm 0.015_{m_b} \pm 0.02_{\alpha_s(M_Z)} \pm 0.015_{\rm CKM} \pm 0.026_{{\rm BR}_{sl}} \Big] \times 10^{-6} = \Big[\begin{matrix} 1.59 \\ 1.64 \end{matrix} \pm 0.11 \Big] \times 10^{-6} . \tag{3.4}$$

We assume the errors on C and m_c to be fully correlated. The electron and muon channels receive different contributions because of the $\ln(m_b^2/m_\ell^2)$ present in the bremsstrahlung corrections. The difference gets reduced when the BaBar and Belle angular cuts are included.

These predictions are in excellent agreement with Belle [25] and BaBar [26] experimental results:

$$\mathscr{B}(B \to X_s \ell^+ \ell^-) = (1.493 \pm 0.504^{+0.411}_{-0.321}) \times 10^{-6} \quad ({\rm Belle}) , \tag{3.5}$$

$$\mathscr{B}(B \to X_s \ell^+ \ell^-) = (1.8 \pm 0.7 \pm 0.5) \times 10^{-6} \quad ({\rm BaBar}) , \tag{3.6}$$

yielding to a world average

$$\mathscr{B}(B \to X_s \ell^+ \ell^-) = (1.60 \pm 0.51) \times 10^{-6} . \tag{3.7}$$

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