73. Production and Decay of b-flavored Hadrons

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The b quark belongs to the third generation of quarks and is the weak–doublet partner of the t quark. The existence of the third–generation quark doublet was proposed in 1973 by Kobayashi and Maskawa [1] in their model of the quark mixing matrix ("CKM" matrix), and confirmed four years later by the first observation of a $b\bar{b}$ meson [2]. In the KM model, CP violation is explained within the Standard Model (SM) by an irreducible phase of the 3×3 unitary matrix. The regular pattern of the three lepton and quark families is one of the most intriguing puzzles in particle physics. The existence of families gives rise to many of the free parameters in the SM, including the fermion masses, and the elements of the CKM matrix.

Since the b quark is the lighter element of the third–generation quark doublet, the decays of b-flavored hadrons occur via generation-changing processes through CKM matrix. Because of this, and the fact that the CKM matrix is close to a 3×3 unit matrix, many interesting features such as loop and box diagrams, flavor oscillations, as well as large CP asymmetries, can be observed in the weak decays of b-flavored hadrons.

The CKM matrix is parameterized by three real parameters and one complex phase. This complex phase is the source of CP violation in B meson decays in the Standard Model. A crucial milestone was the first observation of CP violation in the B meson system in 2001, by the BaBar [3] and Belle [4] collaborations. They measured a large value for the parameter $\sin 2\beta$ $(= \sin 2\phi_1)$ [5], almost four decades after the discovery of a small CP asymmetry in neutral kaons. A more detailed discussion of the CKM matrix and CP violation can be found elsewhere in this *Review* [6,7].

The structure of this mini-review is organized as follows. After a discussion of b-quark production and current results on spectroscopy, we discuss lifetimes of b-flavored hadrons. We then discuss some basic properties of B-meson decays, followed by summaries of dominant hadronic, rare hadronic, and electroweak penguin decays of B-mesons. There are separate mini-reviews for B^0–$\overline{B}^0$ mixing [8] and the extraction of the CKM matrix elements V_{cb} and V_{ub} from B-meson decays [9] in this *Review.*

73.1 Production and spectroscopy

The bound states of a $\bar{b}$ antiquark and a u, d, s, or c quark are referred to as the B_u (B^+), B_d (B^0), B_s (B_s^0), and B_c (B_c^+) mesons, respectively. The B_c^+ is the heaviest of the ground–state b-flavored mesons, and the most difficult to produce: it was observed for the first time in the semileptonic mode by CDF in 1998 [10], but its mass was accurately determined only in 2006, from the fully reconstructed mode $B_c^+ \to J/\psi\pi^+$ [11]. Many exclusive decay channels can now be used for the accurate mass measurements, given the large statistics available at the LHC. Currently the most precise measurement is made by LHCb and yields $m(B_c^+) = 6274.47 \pm 0.27 \pm 0.17\ \text{MeV}/c^2$ [12], combining $B_c^+ \to J/\psi\pi^+$, $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$, $B_c^+ \to J/\psi p\bar{p}\pi^+$, $B_c^+ \to J/\psi D_s^+$, $B_c^+ \to J/\psi D^0 K^+$ and $B_c^+ \to B_s^0\pi^+$ decay modes.

The first excited meson is called the B^* meson, while B^{**} is the generic name for the four orbitally excited $(L = 1)$ B-meson states that correspond to the P-wave mesons in the charm system, D^{**}. Excited states of the B_s^0 meson are similarly named B_s^* and B_s^{**}.

Of the possible bound $\bar{b}b$ states, the $\Upsilon(nS)$ and $\chi_{bJ}(nP)$ states are well studied. The pseudoscalar ground state η_b has been observed for the first time by BaBar [13] indirectly through the decay $\Upsilon(3S) \to \gamma\eta_b$, and then confirmed by Babar in $\Upsilon(2S)$ decays [14] and CLEO in $\Upsilon(3S)$ decays [15]. The most accurate mass and width measurements come now from Belle, using decays $\Upsilon(5S) \to h_b(1P)\pi^+\pi^-$, $h_b(1P) \to \gamma\eta_b(1S)$ [16], $\Upsilon(4S) \to \eta h_b(1P)$, $h_b(1P) \to \gamma\eta_b(1S)$ [17], and $\Upsilon(2S) \to \gamma\eta_b(1S)$ [18]. Belle has also reported first evidence for the $\eta_b(2S)$ in the $h_b(2P) \to \eta_b(2S)\gamma$ transition [16]. In addition, Belle has observed $T_{b\bar{b}1}(10610)$ (was $Z_b(10610)$) and $T_{b\bar{b}1}(10650)$ (was $Z_b(10650)$) states in the processes $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ $(n = 1, 2, 3)$ and $\Upsilon(5S) \to h_b(mP)\pi^+\pi^-$ $(m = 1, 2)$ [19]. These $T_{b\bar{b}1}$ states are observed to decay to $\Upsilon(nS)\pi^\pm$ and $h_b(mP)\pi^\pm$, hence electrically charged and do not belong to ordinary $q\bar{q}$ mesons. For classification and naming of these and other states, see Ref. [20].

Experimental studies of b decays have been performed in e^+e^- collisions at the $\Upsilon(4S)$ (ARGUS, CLEO, Belle, BaBar) and $\Upsilon(5S)$ (CLEO, Belle) resonances. The $e^+e^- \to b\bar{b}$ production cross-section at the $\Upsilon(4S)$ ($\Upsilon(5S)$) resonance is about 1.1 nb (0.3 nb). The full data samples of BaBar and Belle are 560 fb^{-1} and 1020 fb^{-1}, respectively, of which 433 fb^{-1} and 710 fb^{-1} are at the $\Upsilon(4S)$ resonance. Since the $\Upsilon(4S)$ decays dominantly to a pair of B mesons (either B^+B^- or $B^0\overline{B}^0$), a precise knowledge of the energy-momentum of one B meson (the 'tagging B') enables deducing the properties of the other B (the 'signal B'). This property has been exploited by both BaBar and Belle, in particular, to measure inclusive decay modes as well as final states with missing neutrinos. The Belle II experiment at SuperKEKB has started recording data in 2019, and the experiment has so far collected about 428 fb^{-1} of data by summer 2022, when their long shutdown 1 started. Of collected data, 363 fb^{-1} is at the $\Upsilon(4S)$ resonance. At the Z resonance (SLC, LEP) all species of b-flavored hadrons could be studied for the first time. The $e^+e^- \to b\bar{b}$ production cross-section at the Z resonance is about 6.6 nb.

High-energy $p\bar{p}$ (Tevatron) and pp collisions (LHC) produce b-flavored hadrons of all species with large cross-sections. At the Tevatron ($\sqrt{s} = 1.96$ TeV) the visible cross section $\sigma(p\overline{p} \to bX, |\eta| < 1)$ is about 30 μb. CDF and D0 experiments at the Tevatron have accumulated by the end of their running about 10 fb^{-1} each.

At the LHC pp collider at $\sqrt{s} = 7 - 13$ TeV, the visible b-hadron cross section at the LHCb experiment with pseudorapidity acceptance $2 < \eta < 5$ has been measured to be ~ 72 μb at 7 TeV and ~ 144 μb at 13 TeV [21] (cross section at 13 TeV corrected in Erratum). LHCb has collected about 1 fb^{-1} at 7 TeV, 2 fb^{-1} at 8 TeV, and close to 5.9 fb^{-1} at 13 TeV during LHC Runs 1 and 2. CMS and ATLAS have collected each about 5 fb^{-1} of data at $\sqrt{s} = 7$, 20 fb^{-1} at 8 TeV and about 150 fb^{-1} at 13 TeV during LHC Runs 1 and 2. The latest LHC Run 3 at 13.6 TeV started in summer 2022, with upgraded detectors. By the time of the writing (March 2024), LHC has delivered about 70 fb^{-1} to ATLAS and CMS experiments, and about 300 pb^{-1} to the LHCb experiment with major detector upgrades.

In hadron collisions, production happens as $b\bar{b}$ pairs via leading order flavor creation or higher order processes such as gluon–splitting. Single b-quarks can be produced by flavor excitation. The total b-production cross section is an interesting test of our understanding of leading and higher order QCD processes. With a wealth of measurements at LHC and at Tevatron (see Ref. [21] and references therein), and improved calculations [22], there is a reasonable agreement between measurements and predictions.

Each quark of a $b\bar{b}$ pair produced in hadron collisions hadronizes separately and incoherently from the other, but it is still possible to obtain a statistical indication of the charge of a produced $b/\overline{b}$ quark ("flavor tag" or "charge tag") from the accompanying particles produced in the hadronization process, or from the decay products of the other quark. The momentum spectrum of produced b-quarks typically peaks near the b-quark mass, and extends to much higher momenta, dropping by about a decade for every ten GeV. Typical decay lengths are of the order of a centimeter at 13 TeV pp collisions; the resolution for the decay vertex must be more precise than this to resolve the fast oscillations of B_s^0 mesons.

In e^+e^- colliders, since the B mesons are very slow in the $\Upsilon(4S)$ rest frame, asymmetric beam energies are used to boost the decay products to allow time-dependent measurements that are crucial for the study of CP violation. At KEKB, the boost was $\beta\gamma = 0.43$, while PEP-II used a slightly larger boost, $\beta\gamma = 0.55$. The typical B-meson decay length is dilated from $\approx 20\ \mu m$ to $\approx 200\ \mu m$. At SuperKEKB the boost is lower, $\beta\gamma = 0.28$, which puts more demanding requirements on the track reconstruction precision at Belle II to reach a resolution in decay time measurements similar to Belle. The two B mesons produced in $\Upsilon(4S)$ decay are in a coherent quantum state, which makes it easier than in hadron collisions to infer the charge state of one B meson from observation of the other; however, the coherence also requires determination of the decay time of both mesons, rather than just one, in order to perform time–dependent CP–violation measurements. For B^0_s, which can be produced at $\Upsilon(5S)$ the situation is less favourable, as boost is not high enough to provide sufficient time resolution to resolve the fast B^0_s oscillations.

For the measurement of branching fractions, the initial composition of the data sample must be known. The $\Upsilon(4S)$ resonance decays predominantly to $B^0\overline{B}^0$ and B^+B^-; the current experimental upper limit for non-$B\overline{B}$ decays of the $\Upsilon(4S)$ is less than 4% at the 95% confidence level (CL) [23]. The observed modes of this category are decays to lower Υ states and a pion pair, η, or η', measured branching fractions being of order $10^{-4} - 10^{-5}$ [24], and decays to $h_b(1P)\eta$ with branching fraction of order 10^{-3} [17].

The ratio f_+/f_0 of the fractions of charged to neutral B productions from $\Upsilon(4S)$ decays has been measured by CLEO, BaBar, and Belle in various ways. They typically use pairs of isospin-related decays of B^+ and B^0, such that it can be assumed that $\Gamma(B^+ \to x^+) = \Gamma(B^0 \to x^0)$. In this way, the ratio of the number of events observed in these modes is proportional to $(f_+\tau_+)/(f_0\tau_0)$ [25]. BaBar has also performed an independent measurement of f_0 with a different method that does not require isospin symmetry or the value of the lifetime ratio, based on the number of events with one or two reconstructed $B^0 \to D^{*-}\ell^+\nu$ decays [26]. The combined result, from the current average of τ_+/τ_0, is $f_+/f_0 = 1.058 \pm 0.024$ [27]. The result is consistent within 2.4σ with equal production of B^+B^- and $B^0\overline{B}^0$ pairs, and we assume $f_+/f_0 = 1$ in this mini-review except where explicitly stated otherwise. This assumption is also supported by the near equality of the B^+ and B^0 masses: our fit yields $m(B^0) = 5279.72 \pm 0.08\ \text{MeV}/c^2$, $m(B^+) = 5279.41 \pm 0.07\ \text{MeV}/c^2$, and $m(B^0) - m(B^+) = 0.31 \pm 0.05\ \text{MeV}/c^2$.

Data collected at the $\Upsilon(5S)$ resonance gave CLEO, Belle and BaBar access to B^0_s decays. In $\Upsilon(5S)$ decays there are seven possible final states including a pair of non-strange B mesons and 0, 1 or 2 pions, and three final states with a pair of strange B mesons ($B_s^{*0}\overline{B}_s^{*0}$, $B_s^{*0}\overline{B}_s^0$, and $B_s^0\overline{B}_s^0$). The fraction of events with a pair of B^0_s mesons over the total number of events with a pair of b-flavored hadrons has been measured to be $f_s[\Upsilon(5S)] = 0.199^{+0.030}_{-0.029}$ [28], of which 88% is $B_s^{*0}\bar{B}_s^{*0}$ events. However, the small boost of B^0_s mesons produced in this way prevents resolution of their fast oscillations for time-dependent measurements; these are only accessible in hadron collisions (or at the Z peak).

In high-energy collisions, the produced b or $\bar{b}$ quarks can hadronize with different probabilities into the full spectrum of b-hadrons, either in their ground or excited states. The hadronization does not have to be identical in $p\overline{p}$ or pp collisions and in Z decay, because of the different momentum distributions of the b-quark in these processes; the sample used in the $p\overline{p}$ measurements has momenta close to the b mass, rather than $m_Z/2$ in Z decay. The available data from Tevatron and LHC show that the production fractions f_d, f_u, f_s, and f_{baryon} of B^0, B^+, B^0_s, and b baryons, respectively, of weakly decaying b hadrons depend on the kinematics of the produced b hadron. Recently LHCb experiment found evidence for dependence of b-quark hadronization on multiplicity in pp collisions [29]. The production fractions of b hadrons are discussed in more detail in the $B^0 - \overline{B}^0$

mixing section in this *Review* [8].

Excited B-meson states have been thoroughly studied by CLEO, LEP, CUSB, D0 and CDF (an admixture of B mesons) and LHCb (B^{*+}-meson). The current world average of the B^*–B mass difference is 45.21 ± 0.21 MeV/c^2. Excited B_s^*-meson states have observed in $\Upsilon(5S)$ decays by CUSB, CLEO and Belle.

For orbitally excited $B_{(s)}$ meson states, with relative angular momentum L=1 of the two quarks, there exist four states $(J, j_q) = (0, 1/2), (1, 1/2), (1, 3/2), (2, 3/2)$, where j_q is the total angular momentum of the light u, d or s quark and J is the total angular momentum of the B meson. These states are collectively called as $B_{(s)}^{**}$ mesons. The $j_q = 1/2$ states are named $B_{(s)0}^*$ $(J = 0)$ and $B_{(s)1}$ $(J = 1)$ mesons, while the states with $j_q = 3/2$ are named $B_{(s)1}$ $(J = 1)$ and $B_{(s)2}^*$ $(J = 2)$ mesons. The states with $j_q = 1/2$ can decay through an S-wave transition and are expected to have a large width, but the $j_q = 3/2$ states are narrow D-wave decays. Evidence for B^{**} production has been initially obtained at LEP as a broad $B\pi$ resonance [30] or a B^+K^- enhancement [31]. Detailed results have been obtained for the narrow states $B_1(5721)^{0,+}$ and $B_2(5747)^{0,+}$ at the Tevatron and by LHCb, and clear enhancements compatible with the higher mass states $B_J(5840)^{0,+}$ and $B_J(5970)^{0,+}$ have been observed [32]. Also the narrow B_s^{**} states $B_{s1}(5830)^0$ and $B_{s2}(5840)^0$ have been measured at the CDF [32], LHCb [33], and CMS [34].

Excited states of B_c^+ mesons will provide important information about the strong potential. A $B_c^+\pi^+\pi^-$ resonance has been observed for the first time by ATLAS [35]. The mass of the resonance has been measured precisely by CMS and LHCb as 6871.2 ± 1.0 MeV/c^2 [36]. The resonance may be interpreted as the second S-wave state of the B_c^+ meson, $B_c^+(2S)$, but the quantum numbers are to be confirmed.

Baryon states containing a b quark are labeled according to the same scheme used for non-b baryons, with the addition of a b subscript [20]. The first observed b baryon was the Λ_b^0 (quark composition udb). Thanks to the large samples accumulated at the Tevatron and specially at the LHC many new b baryons have been found. The masses of all these new baryons have been measured to a precision of a few MeV/c^2, and found to be in agreement with predictions from Heavy Quark Effective Theory (HQET).

Clear signals of four strongly–decaying baryon states, Σ_b^+, Σ_b^{*+} (uub), Σ_b^-, Σ_b^{*-} (ddb) have been obtained by CDF [37] and LHCb [38]. LHCb has also observed two new mass peaks in the $\Lambda_b^0\pi^\pm$ systems, consistent with single resonances and named as $\Sigma_b^\pm(6097)$ [38]. The nature of these resonances is, however, not yet clear. The isodublet of strange b baryons Ξ_b^0 (usb) and $\Xi_b^\pm$ (dsb) has been observed by CDF and D0 [39]. Masses, lifetimes, and branching ratios have been accurately measured by LHCb [40–42] and CDF [43]. LHCb has also measured several parameters sensitive to P and CP violation [42,44]. Other observed Ξ_b baryons are spin-3/2 states $\Xi_b(5945)^0$ (Ξ_b^{*0}) [45,46], $\Xi_b^*(5955)^-$ [46,47] and $\Xi_b(6100)^-$ [46,48], a spin-1/2 state $\Xi_b'(5935)^-$ [46,47], and resonance states $\Xi_b^-(6227)$ [41,49], $\Xi_b^0(6327)$ [50] and $\Xi_b^0(6333)$ [50]. The doubly–strange bottom baryon Ω_b^- has been observed first by D0 and CDF [51]. Mass and mean life have been measured precisely by LHCb [52] and CDF [43]. LHCb has also observed four excited Ω_b^- states $\Omega_b^-(6316)$, $\Omega_b^-(6330)$, $\Omega_b^-(6340)$ and $\Omega_b^-(6350)$ [53].

The so-called exotic states have raised a lot of interest recently. While many exotic states were seen in the charm sector, in bottom sector there are fewer seen. The D0 Collaboration claimed a narrow state $X(5568)$ decaying into a $B_s^0\pi^\pm$ final state [54]. While this would be an interesting addition to the observed states as the first exotic state with constituent quarks with four different flavours (b, s, u, d), analysis by LHCb yields negative result [55]. Also CMS finds no such a state [56].

73.2 Lifetimes

Precise lifetimes are key in extracting the weak parameters that are important for understanding the role of the CKM matrix in CP violation, such as the determination of V_{cb} and B_s^0–$\overline{B}_s^0$ mixing parameters. In the naive spectator model, the heavy-flavored hadrons can decay only via the external spectator mechanism, and thus, the lifetimes of all mesons and baryons containing b quarks would be equal. Non–spectator effects, such as the interference between contributing amplitudes, modify this simple picture and give rise to a lifetime hierarchy for b-flavored hadrons similar to the one in the charm sector. However, since the lifetime differences are expected to scale as $1/m_Q^2$, where m_Q is the mass of the heavy quark, the variations in the b system are expected to be only 10% or less [57, 58]. We expect:

$$\tau(B^+) \geq \tau(B^0) \approx \tau(B_s^0) > \tau(\Lambda_b^0) \gg \tau(B_c^+) . \tag{73.1}$$

For the B_c^+, both quarks decay weakly, so the lifetime is much shorter.

Measurements of the lifetimes of the different b-flavored hadrons thus provide a means to determine the importance of non-spectator mechanisms in the b sector. Availability of large samples of fully–reconstructed decays of different b-hadron species has resulted in precise measurements with small statistical and systematic uncertainties ($\sim$1%). The world averages given in Table 73.1 have been determined by the Heavy Flavor Averaging Group (HFLAV) [59].

Table 73.1: Summary of the world-average b-hadron lifetime measurements. For the B_s^0 lifetimes, see text below.

Particle	Lifetime [ps]
B^+	1.638 ± 0.004
B^0	1.517 ± 0.004
B_s^0	1.520 ± 0.005
B_{sL}^0	1.429 ± 0.006
B_{sH}^0	1.623 ± 0.008
B_c^+	0.510 ± 0.009
Λ_b^0	1.471 ± 0.009
Ξ_b^-	1.572 ± 0.040
Ξ_b^0	1.480 ± 0.030
Ω_b^-	$1.64^{+0.18}_{-0.17}$

The B_s^0 lifetime in Table 73.1 is defined as $1/\Gamma_s$, where Γ_s is the average width of the light (L) and heavy (H) mass eigenstates, $(\Gamma_L + \Gamma_H)/2$. In the absence of CP violation, the light (heavy) B_s^0 mass eigenstate is the CP-even (CP-odd) eigenstate. Thus, the lifetime of the light (heavy) mass eigenstate can be measured from CP-even (odd) final states. The lifetimes can also be obtained from time-dependent angular analysis of $B_s^0 \to J/\psi\phi$ decays.

The short B_c^+ lifetime is in good agreement with predictions [60]. With large samples of B_c^+ mesons at the LHC precision on the lifetimes can still improve. The measurement using semileptonic decays gives $\tau_{B_c^+} = 0.509 \pm 0.008 \pm 0.012$ ps [61] while using decays $B_c^+ \to J/\psi\pi^+$ yields $\tau_{B_c^+} = 0.5134 \pm 0.0110 \pm 0.0057$ ps [62]. Each of these is more precise than the combination of all previous experiments.

The recent Λ_b^0 lifetime measurements from LHC experiments and CDF are precise and favour lifetime close to the lifetime of B^0 meson, in agreement with theory.

For precision comparisons with theory, lifetime ratios are more sensitive. Experimentally it is found [59]:

$$\frac{\tau_{B^+}}{\tau_{B^0}} = 1.076 \pm 0.004\,, \ \frac{\tau_{B^0_s}}{\tau_{B^0}} = 1.002 \pm 0.004\,,$$
$$\frac{\tau_{\Lambda^0_b}}{\tau_{B^0}} = 0.969 \pm 0.006\,,$$

while recent Heavy Quark Expansion (HQE) predictions give [58]:

$$\frac{\tau_{B^+}}{\tau_{B^0}} = 1.04^{+0.05}_{-0.01} \pm 0.02 \pm 0.01\ , \ \frac{\tau_{B^0_s}}{\tau_{B^0}} = 1.001 \pm 0.002\ ,$$
$$\frac{\tau_{\Lambda^0_b}}{\tau_{B^0}} = 0.935 \pm 0.054.$$

The ratio of B^+ to B^0 lifetimes has a precision of better than 1%, and is significantly different from 1.0, in agreement with predictions [57]. The ratio of B^0_s to B^0 lifetimes is expected to be very close to 1.0.

For a detailed discussion on neutral B^0 and B^0_s oscillation and relevant CP violation measurements see Ref. [8].

73.3 Features of decays

The ground states of b-flavored hadrons decay via weak interactions. In most decays of the b-flavored hadrons, where the b-quark is accompanied by lighter partner quarks (d, u, s, or c), the decay modes are well described by the decay of the b quark (spectator model) [63]. The dominant decay mode of a b quark is $b \to cW^{*-}$ (referred to as a "tree" or "spectator" decay), where the virtual W materializes either into a pair of leptons $\ell\bar{\nu}$ ("semileptonic decay"), or into a pair of quarks which then hadronizes. The transition $b \to u$ is suppressed by $|V_{ub}/V_{cb}|^2 \sim (0.1)^2$ relative to $b \to c$ transitions. The decays in which the spectator quark combines with one of the quarks from W^* to form one of the final state hadrons are suppressed by a factor $\sim (1/3)^2$, because the colors of the two quarks from different sources must match ("color–suppression").

Semileptonic B decays $B \to X_c\ell\nu$ and $B \to X_u\ell\nu$ provide an excellent way to measure the magnitude of the CKM elements $|V_{cb}|$ and $|V_{ub}|$ respectively, because the strong interaction effects are much simplified due to the two leptons in the final state. Both exclusive and inclusive decays can be used with dominant uncertainties being complementary. For exclusive decay analysis, knowledge of the form factors for the exclusive hadronic system $X_{c(u)}$ is required. For inclusive analysis, it is usually necessary to restrict the available phase-space of the decay products to suppress backgrounds; subsequently uncertainties are introduced in the extrapolation to the full phase-space. Moreover, restriction to a small corner of the phase-space may result in breakdown of the operator-product expansion scheme, thus making theoretical calculations unreliable. A more detailed discussion of B semileptonic decays and the extraction of $|V_{cb}|$ and $|V_{ub}|$ is given elsewhere in this *Review* [9]. While traditionally B^0 and B^+ decays were used, over time also other B hadron studies became available. Most notably, determination of of $|V_{ub}|$ using $\Lambda^0_b \to p\mu^-\bar{\nu}_\mu$ decays by LHCb [64] was more precise than expected. Besides, there have been measurements of inclusive semileptonic decay rates of B^0_s [65] and B^+_c [66] mesons. One of the latest additions in this area is the observation of the $B^0_s \to K^-\mu^+\nu_\mu$ decays by LHCb using only a fraction of their available data [67].

On the other hand, hadronic B decays are complicated because of strong interaction effects caused by the surrounding cloud of light quarks and gluons. While this complicates the extraction of CKM matrix elements, it also provides a great opportunity to study perturbative and non-perturbative QCD, hadronization, and Final State Interaction (FSI) effects.

Many aspects of B decays can be understood through the Heavy Quark Effective Theory (HQET) [68]. This has been particularly successful for semileptonic decays. For further discussion of HQET, see for instance Ref. [69]. For hadronic decays, one typically uses effective Hamiltonian calculations that rely on a perturbative expansion with Wilson coefficients. In addition, some form of the factorization hypothesis is commonly used, where, in analogy with semileptonic decays, two-body hadronic decays of B mesons are expressed as the product of two independent hadronic currents, one describing the formation of a charm meson (in case of the dominant $b \to cW^{*-}$ decays), and the other describing the hadronization of the remaining $\overline{u}d$ (or $\overline{c}s$) system from the virtual W^-. Qualitatively, for B decays with a large energy release, e.g. $b \to uW^{*-}$ transitions, the $\overline{u}d$ pair (produced as a color singlet) travels fast enough to leave the interaction region without influencing the meson containing the spectator quark. This is known to work well for the dominant spectator decays [70]. There are several common implementations of these ideas for hadronic B decays, the most common of which are QCD factorization (QCDF) [71], perturbative QCD (pQCD) [72], and soft collinear effective theory (SCET) [73].

The transitions $b \to s$ and $b \to d$ are flavor-changing neutral-current (FCNC) processes. Although they are not allowed in the SM as a tree-process, they can occur via loop diagrams (denoted "penguin" decays). The rates for $b \to s$ penguin decays are comparable to the CKM-suppressed $b \to u$ tree processes. Pure-penguin decays were first established by the observation of $B \to K^*(892)\gamma$ [74]. Penguin processes involving $b \to d$ transitions are further suppressed by CKM, and have been observed for $B \to (\rho/\omega)\gamma$ decays [75, 76]. LHCb has observed a $b \to d$ penguin transition in the $B^+ \to \pi^+\mu^+\mu^-$ mode and measured its branching fraction to be $(1.83 \pm 0.24 \pm 0.05) \times 10^{-8}$ [77].

Other decay processes discussed in this *Review* include W–exchange (a W is exchanged between initial–state quarks), penguin annihilation (the gluon from a penguin loop attaches to the spectator quark, similar to an exchange diagram), and pure–annihilation (the initial quarks annihilate to a virtual W, which then decays). Some observed decay modes such as $B^0 \to D_s^- K^+$, may be interpreted as evidence of a W-exchange process [78]. The evidence for the purely leptonic decay $B^+ \to \tau^+\nu$ from Belle [79] and BaBar [80] is the first sign of a pure annihilation decay. The average branching fraction is $(1.09 \pm 0.24) \times 10^{-4}$, which is somewhat larger than, though consistent with, the value expected in the SM. A substantial region of parameter space of charged Higgs mass vs. $\tan\beta$ is excluded by the measurements of this mode. A dedicated discussion of purely leptonic decays of charged pseudoscalar mesons is given elsewhere in this *Review* [81].

73.4 Dominant hadronic decays

Most of the hadronic B decays involve $b \to c$ transition at the quark level, resulting in a charmed hadron or charmonium in the final state. Other types of hadronic decays are very rare and will be discussed separately in the next section. The experimental results on hadronic B decays have steadily improved over the years, and the measurements have reached sufficient precision to challenge our understanding of the dynamics of these decays. With good particle detection and hadron identification capabilities of B-factory detectors, a substantial fraction (roughly on the order of a few per mill) of hadronic B decay events can be fully reconstructed. In particular, good performances for detecting π^0 and other neutral particles helped Belle and BaBar to make comprehensive measurements of the decays $\overline{B}^0 \to D^{(*)0}h^0$ [82], where h^0 stands for light neutral mesons such as $\pi^0, \eta^{(\prime)}, \rho^0, \omega$. The measurements are being complemented by LHCb, in decays like $\overline{B^0} \to D^0\pi^+\pi^-$ [83], where no neutral particles reconstruction is needed. These decays proceed through color-suppressed diagrams, hence they provide useful tests on the factorization models.

Because of the kinematic constraint of $\Upsilon(4S) \to B\bar{B}$, the energy sum of the final-state particles of a B meson decay is always equal to one half of the total energy in the center of mass frame. As a result, the two variables, ΔE (energy difference) and M_B (B candidate mass with a beam-energy constraint) are very effective for reducing combinatorial background both from $\Upsilon(4S)$ and

$e^+e^- \to q\bar{q}$ continuum events. In particular, the energy-constraint in M_B improves the signal resolution by almost an order of magnitude.

The kinematically clean environment of B meson decays provides an excellent opportunity to search for new states. For instance, quark-level $b \to c\bar{c}s$ decays have been used to search for new charmonium and charm-strange mesons and study their properties in detail. While narrow charm-strange states $D^*_{s0}(2317)$ [84] and $D_{s1}(2460)$ [85] were discovered by BaBar and CLEO, respectively, the properties of these new states were revealed by studying the B meson decays, $B \to DD^*_{s0}(2317)$ and $B \to DD_{s1}(2460)$ by Belle [86] and BaBar [87]. Another example is Dalitz plot analysis of decay $B^0_s \to \bar{D}^0 K^-\pi^+$ in which the decay to spin-3 resonance was observed for the first time [88]. One of the most significant improvements in the past decade is establishment of decays $B^+ \to D^0K^+$ and $B^+ \to D^0K^*(892)^+$ with D^0 decaying to final state common to D^0 and $\overline{D}^0$ [89]. This allows direct determination of CKM angle $\gamma(=\phi_3)$ to be $65.9^{+3.3}_{-3.5}$.

Information on B^0_s, B^+_c and Λ^0_b decays have been remarkably improved with recent studies of large samples from LHCb. Noticeable additions in B_s include decay modes to $D_s^{(*)+}D_s^{(*)-}$, $\bar{D}^0\bar{K}^0$, and $J/\psi\bar{K}^*(892)^0$. The $B^0_s \to D_s^{(*)+}D_s^{(*)-}$ decays were first observed by CDF [90], followed by Belle [91]. LHCb has improved the precision with $\mathcal{B}(B^0_s \to D_s^{(*)+}D_s^{(*)-}) = (3.07\pm0.22\pm0.33)\%$ [92], which suggests that $B^0_s \to D_s^{(*)+}D_s^{(*)-}$ decays do not saturate the CP-even modes of the B_s decays. The $B^0_s \to \bar{D}^0\bar{K}^0$ decay occurs mostly via a color-suppressed tree diagram, and has a small theoretical uncertainty in the SM, thus this mode can significantly improve the determination of the CP-violation angle ϕ_s. LHCb has observed this decay and the branching fraction is $(4.3\pm0.5\pm0.7)\times10^{-4}$ [93]. The $B^0_s \to J/\psi\bar{K}^*(892)^0$ decay can be used to constrain the penguin pollution in determining ϕ_s. LHCb has updated the branching fraction and measured the CP asymmetries of this decay, thereby constraining the penguin pollution in ϕ_s [94], although a much more stringent constraint on penguin pollution can come from $B^0 \to J/\psi\rho^0$ which has been observed by BaBar [95] and LHCb [96]. The $B^+_c \to B^0_s\pi^+$ decay is unique as the only observed mode of b-flavored hadron decays where the partner quark decays (c in this case) while the b quark remains a spectator. LHCb has observed this mode [97] and measured $\mathcal{B}(B^+_c \to B^0_s\pi^+)/\mathcal{B}(B^+_c \to J/\psi\pi^+) = (91\pm10\pm8\pm3)$ [98]. In addition, LHCb [99] and ATLAS [100] have measured $B^+_c \to J/\psi D_s^{(*)+}$, which, by comparing with $B^+_c \to B^0_s\pi^+$, provides a ratio of exclusive $b \to c$ and $c \to s$ decays of B^+_c. For $\Lambda^0_b \to \Lambda^+_c\pi^+\pi^-\pi^-$ [101], not only the total rate is measured, but also structure involving decays through excited Λ_c and Σ_c baryons.

In addition, a variety of exotic particles that do not fit the conventional meson spectroscopy have been discovered in B decays. Belle found the $X(3872)$ state by studying $B^+ \to J/\psi\pi^+\pi^-K^+$ [102], which was confirmed by CDF [103], D0 [104] and BaBar [105]. Production of $X(3872)$ has been studied by the LHC experiments, LHCb [106], CMS [107] and ATLAS [108].

A charged charmonium-like state $X(4430)^\pm$ that decays to $\psi(2S)\pi^\pm$ was observed by Belle in $B \to \psi(2S)K\pi^\pm$ [109]. Since it is charged, it could not be an ordinary charmonium state. A high-statistics study by LHCb confirmed the existence of the $X(4430)^\pm$ in decays $B \to \psi(2S)K\pi^\pm$ [110], demonstrated its resonance character by studying the phase motion, unambiguously determined its spin-parity, and saw evidence for another state. In a Dalitz plot analysis of $\bar{B}^0 \to J/\psi K^-\pi^+$ [111], Belle has found another state, labeled as $X(4200)^+$ in this *Review*, adding to the list of exotic charged charmonium-like states. In an amplitude analysis of the decay $\Lambda^0_b \to J/\psi pK^-$, LHCb observed exotic structures, labeled as $P_c(4380)^+$ and $P_c(4450)^+$ in this *Review*, in the $J/\psi p$ channel [112]. The subsequent analysis with significantly increased statistics observed additional state and resolved the peak at 4450 MeV/c^2 as being due to the two states close in the mass [113]. The structure in the $J/\psi p$ channel was also seen in the $B^0_s \to J/\psi p\overline{p}$ decays [114] and in the $J/\psi\Lambda$ channel in $B^+ \to J/\psi\Lambda p$ and $\Xi^-_b \to J/\psi\Lambda K^-$ decays [115]. They are referred to as charmoniumpentaquark states. More detailed discussions of exotic meson-like states and pentaquarks are given elsewhere in this *Review* [116].

73.5 Rare hadronic decays

All B-meson decays that do not occur through the $b \to c$ transition are usually called rare B decays. These include both semileptonic and hadronic $b \to u$ decays that are suppressed at leading order by the small CKM matrix element V_{ub}, as well as higher-order $b \to s(d)$ processes such as electroweak and gluonic penguin decays. In this section, we review hadronic rare B decays, while electroweak penguin decays and others are discussed in the next.

Charmless B meson decays into two-body hadronic final states such as $B \to \pi\pi$ and $K\pi$ are experimentally clean, and provide good opportunities to probe new physics and search for indirect and direct CP violations. Since the final state particles in these decays tend to have larger momenta than average B decay products, the event environment is cleaner than for $b \to c$ decays. Branching fractions are typically around 10^{-5}. Over the past decade, many such modes have been observed not only by e^+e^- collider experiments such as BaBar and Belle, but also by hadron collider experiments such as CDF ($p\bar{p}$) and LHCb (pp). In the latter cases, huge data samples of the modes with all charged final-state particles have been reconstructed by triggering on the impact parameter of the charged tracks. This has also allowed observation of charmless decays of the B_s, in final states such as $\phi\phi$ [117], K^+K^- [118, 119], and $K^-\pi^+$ [119, 120], and of charmless decays of the Λ_b^0 baryon [120]. The large samples available at LHCb experiment allow to perform also time-dependent CP violation measurements [121]. Charmless B_s modes are related to corresponding B^0 modes by U-spin symmetry, and are determined by similar amplitudes. Combining the observables from B_s^0 and B^0 modes is a further way of eliminating hadronic uncertainties and extracting relevant CKM information [122].

Because of relatively high-momenta for final state particles, the dominant source of background in e^+e^- collisions is $q\bar{q}$ continuum events; sophisticated background suppression techniques exploiting event shape variables are essential for these analyses. In hadron collisions, the dominant background comes from QCD or partially reconstructed heavy flavors, and is similarly suppressed by a combination of kinematic and isolation requirements. The results are in general consistent among the experiments.

Most rare decay modes including $B^0 \to K^+\pi^-$ have contributions from both $b \to u$ tree and $b \to sg$ penguin processes. If the size of the two contributions are comparable, the interference between them may result in direct CP violation, seen experimentally as a charge asymmetry in the decay rate measurement. BaBar [123], Belle [124], CDF [118], and LHCb [121, 125] have measured the direct CP violating asymmetry in $B^0 \to K^+\pi^-$ decays. Direct CP violation has been observed in this decay with a significance of more than 5σ. The world average value of the asymmetry is now rather precise, $A_{CP}(K^+\pi^-) = -0.0834 \pm 0.0032$. The CP asymmetry in $B^+ \to K^+\pi^0$ mode has been measured by BaBar [126], *Belle [124] and LHCb [127] with the average value $A_{CP}(K^+\pi^0) = 0.030 \pm 0.013$. These two asymmetries differ significantly, in contrast to a naive expectation based on simplified picture in the SM. For more detailed tests, there are sum rules [128] that relate the decay rates and decay-rate asymmetries between the four $K\pi$ charge states. A crucial ingredient of the sum rule test is $A_{CP}(K^0\pi^0)$. Currently, measured values are reported by both BaBar [129] and Belle [130]. Using the $A_{CP}(K^0\pi^0)$ value of Ref. [130], Belle reports the sum rule test result that is consistent with zero within 1.9σ [124]. With the future improvements via Belle II and upgraded LHCb, the measurements are expected to become precise enough to shape a definite conclusion. The CP asymmetry in the π^+K^- mode has also been measured in B_s^0 decays, by CDF [118] and LHCb [121, 125]. The combined value is $A_{CP}(B_s^0 \to \pi^+K^-) = 0.224 \pm 0.012$.

In addition to $B_{(s)} \to K\pi$ modes, significant ($> 3\sigma$) non-zero CP asymmetries have been measured in several other rare decay modes: $A_{CP}(B^+ \to \rho^0 K^+) = 0.37 \pm 0.10$ [131], $A_{CP}(B^+ \to \eta K^+) = -0.37 \pm 0.08$ [132], $A_{CP}(B^0 \to \eta K^{*0}) = 0.19 \pm 0.05$ [133], and $A_{CP}(B^+ \to f_2(1270)K^+) = -0.68^{+0.19}_{-0.17}$ [131]. In at least the first two cases, a large direct CP violation might be expected since the penguin amplitude is suppressed so the tree and penguin amplitudes may have comparable magnitudes. There are also measurements by LHCb of CP asymmetries in several 3-body modes: $A_{CP}(B^+ \to \pi^+\pi^-\pi^+) = 0.057 \pm 0.013$, $A_{CP}(B^+ \to K^+\pi^-\pi^+) = 0.027 \pm 0.008$, $A_{CP}(B^+ \to K^+K^-\pi^+) = -0.122 \pm 0.0021$, and $A_{CP}(B^+ \to K^+K^-K^+) = -0.033 \pm 0.008$ [134]. Many of these analyses now include Dalitz plot treatments with many intermediate resonances.

BaBar [135] and Belle [124, 136] have observed the decays $B^+ \to \overline{K}^0 K^+$ and $B^0 \to K^0\overline{K}^0$. The world-average branching fractions are $\mathcal{B}(B^0 \to K^0\overline{K}^0) = (1.21 \pm 0.16) \times 10^{-6}$ and $\mathcal{B}(B^+ \to \overline{K}^0 K^+) = (1.31 \pm 0.17) \times 10^{-6}$. These are the first observations of hadronic $b \to d$ transitions, with significance bigger than 5σ for all four measurements. CP asymmetries have been measured for these modes, but with large errors. LHCb has observed $B^0 \to K^+K^-$ mode which occurs via a weak-annihilation process and is the rarest hadronic B-meson decay thus far observed, with $\mathcal{B}(B^0 \to K^+K^-) = (7.80 \pm 1.52) \times 10^{-8}$ [137]. $B_s^0 \to K^+K^-$ decay mode, which occurs mostly via $b \to s$ penguin process, has been observed by Belle [138], CDF [139] and LHCb [119]. The average branching fraction is $\mathcal{B}(B_s^0 \to K^+K^-) = (26.6 \pm 2.2) \times 10^{-6}$. Belle has also observed $B_s^0 \to K^0\overline{K}^0$ [140] which also occurs via $b \to s$ penguin transition in the SM. This was recently confirmed by LHCb [141]. The average branching fraction is $(1.76 \pm 0.31) \times 10^{-5}$.

The decay $B^0 \to \pi^+\pi^-$ can be used to extract the CKM angle α (for details see elsewhere in this *Review* [142]). This is complicated by the presence of significant contributions from penguin diagrams. An isospin analysis [143] can be used to untangle the penguin complications. The decay $B^0 \to \pi^0\pi^0$ is crucial in this analysis. Both BaBar and Belle have observed $B^0 \to \pi^0\pi^0$, with a mild tension in the measured branching fractions: $(1.83 \pm 0.25) \times 10^{-6}$ for BaBar [123] and $(1.31 \pm 0.26) \times 10^{-6}$ for Belle [144]. It turns out that the amount of penguin pollution in the $B \to \pi\pi$ system is rather large. In the past few years, measurements in the $B^0 \to \rho\rho$ system have produced more precise values of α, since penguin amplitudes are generally smaller for decays with vector mesons. An important ingredient in the analysis is the $B^0 \to \rho^0\rho^0$ branching fraction. The average of measurements from BaBar [145] and Belle [146] yields a branching fraction of $(0.96 \pm 0.15) \times 10^{-6}$. This is only 3% of the $\rho^+\rho^-$ branching fraction, much smaller than the corresponding ratio ($\gtrsim 20\%$) in the $\pi\pi$ system.

Since $B \to \rho\rho$ has two vector mesons in the final state, the CP eigenvalue of the final state depends on the longitudinal polarization fraction f_L for the decay. Therefore, a measurement of f_L is needed to extract the CKM angle α. Both BaBar and Belle have measured f_L for the decays $\rho^+\rho^-$ [147] and $\rho^+\rho^0$ [148] and in both cases the measurements show $f_L > 0.9$, making a complete angular analysis unnecessary. In $B^0 \to \rho^0\rho^0$, f_L is measured by BaBar [145], Belle [146] and LHCb [149], with the average value being $0.71^{+0.08}_{-0.09}$.

By analyzing the angular distributions of the B decays to two vector mesons, we can learn a lot about both weak- and strong-interaction dynamics in B decays. Decays that are penguin-dominated surprisingly have values of f_L near 0.5. The list of such decays has now grown to include $B \to \phi K^*(892)$, $B \to \rho K^*(892)$, and $B \to \omega K^*(892)$. The reasons for this "polarization puzzle" are not fully understood. A detailed description of the angular analysis of B decays to two vector mesons can be found in a separate mini-review [150] in this *Review* .

73.6 Electroweak penguin decays

Electroweak penguin decays are one-loop FCNC decays proceeding through penguin or box Feynman diagrams with final state including real photon or pair of leptons. Such decays were first observed by CLEO experiment when it observed decay $B \to K^*(892)\gamma$ [74]. Since then significant amount of experimental information was obtained. Branching fractions for these decays are 10^{-5} or less, which makes them excellent candidates for searches for new physics beyond SM. Often several observables are available, which allows for stringent tests of the SM.

Starting with radiative decays, experimentally easiest to study are exclusive decays with a fully reconstructed final state. The best studied decay in this class is $B \to K^*(892)\gamma$ seen by CLEO, Belle, BaBar experiments [151, 152] with world average branching fraction $\mathcal{B}(B^0 \to K^*(892)^0\gamma) = (41.8 \pm 2.5) \times 10^{-6}$. Decays through several other kaon resonances such as $B \to K_1(1270)\gamma$, $K_2^*(1430)\gamma$, *etc.* were studied at B-factories [153, 154]. It is worth to mention decay $B^+ \to K^+\pi^+\pi^-\gamma$ for which besides measurements of the branching fraction [154, 155] one can also use the angular distribution to access photon polarization. Such a measurement was done by the LHCb experiment, which was able to clearly demonstrate that the photon in $B^+ \to K^+\pi^+\pi^-\gamma$ decay is polarized [156]. Unfortunately given non-trivial hadronic structure, more work is needed before turning this into test of the SM. The exclusive radiative decays $B_s^0 \to \phi\gamma$ was seen by the Belle and LHCb experiments [157] with an average branching fraction of $(3.4 \pm 0.4) \times 10^{-5}$ and more recently also decay $\Lambda_b \to \Lambda\gamma$ was observed by LHCb [158].

Compared to $b \to s\gamma$, the $b \to d\gamma$ transitions such as $B \to \rho\gamma$, are suppressed by the CKM elements ratio $|V_{td}/V_{ts}|^2$. Both Belle and BaBar have observed these decays [75, 76]. The world average $\mathcal{B}(B \to (\rho, \omega)\gamma) = (1.30 \pm 0.23) \times 10^{-6}$. This can be used to calculate $|V_{td}/V_{ts}|$ [159]; the measured values are $0.195^{+0.025}_{-0.024}$ from Belle [75] and $0.233^{+0.033}_{-0.032}$ from BaBar [76].

The observed radiative penguin branching fractions can constrain a large class of SM extensions [160]. However, due to the uncertainties in the hadronization, only the inclusive $b \to s\gamma$ rate can be reliably compared with theoretical calculations. This rate can be measured from the endpoint of the inclusive photon spectrum in B decay. By combining the measurements of $B \to X_s\gamma$ from the CLEO, BaBar, and Belle experiments [161, 162], HFLAV obtains the average: $\mathcal{B}(B \to X_s\gamma) = (3.49 \pm 0.19) \times 10^{-4}$ [59] for $E_\gamma \geq 1.6$ GeV, averaging over B^+ and B^0. Consistent but less precise results have been reported by ALEPH for inclusive b–hadrons produced at the Z, which includes also contribution from B_s^0 and Λ_b^0 hadrons. Using the sum of seven exclusive final states, the BaBar experiment measured the branching fraction of inclusive $b \to d\gamma$ decays to be $(9.2 \pm 2.0 \pm 2.3) \times 10^{-6}$ [163]. The measured branching fraction can be compared to theoretical calculations. Recent calculations of $\mathcal{B}(b \to s\gamma)$ at NNLO level predict for the $E_\gamma \geq 1.6$ GeV values of $(3.36 \pm 0.23) \times 10^{-4}$ for $b \to s\gamma$ and $(1.68 \pm 0.17) \times 10^{-5}$ for $b \to d\gamma$ decays [164].

The CP asymmetry in $b \to s\gamma$ is extensively studied theoretically both in the SM and beyond [165]. According to the SM, the CP asymmetry in $b \to s\gamma$ is smaller than 1%, but some non-SM models allow significantly larger CP asymmetry ($\sim 10\%$) without altering the branching fraction. The current world average is $A_{CP} = 0.015 \pm 0.011$, again dominated by BaBar and Belle [166, 167]. In addition to the CP asymmetry, BaBar and Belle also measured the isospin asymmetry $\Delta_{0-} = -0.005 \pm 0.020$ in $b \to s\gamma$ measured using sum of exclusive decays [166, 168]. An alternative measurement using full reconstruction of the companion B in the hadronic decay modes yields a consistent, but less precise result [169]. Both Belle and BaBar experiments measured the isospin asymmetry in exclusive $B \to K^*(892)\gamma$ decay with average of $6.3 \pm 1.7\%$ [152] and therefore providing evidence for the non-zero isospin asymmetry.

In addition, experiments have measured the inclusive photon energy spectrum for $b \to s\gamma$, and by analyzing the shape of the spectrum they obtain the first and second moments for photon energies. Belle has measured these moments covering the widest range in the photon energy ($1.7 < E_\gamma < 2.8$ GeV) [162]. The measurement by BaBar has slightly smaller range with lower limit at 1.8 GeV [170]. These results can be used to extract non-perturbative HQET parameters that are needed for precise determination of the CKM matrix element V_{ub} (see further discussion elsewhere in this *Review* [171]).

Additional information on FCNC processes can be obtained from $b \to s\ell^+\ell^-$ decays. These processes are studied as a function of dilepton invariant mass squared, q^2. Different q^2 regions are sensitive to different physics. Starting at the very low q^2 decays exhibit sensitivity to the same physics as the radiative decays. Then for the q^2 in region 1.1 to 6.0 GeV^2/c^4 the SM and new physics have best chance to compete. At the high q^2 above the $\psi(2S)$ mass, the interference of SM and new physics is to some extend complementary to that in lower q^2. Regions around J/ψ and $\psi(2S)$ is normally excluded from measurements as these are dominated by the $b \to c$ transitions to charmonia. For exclusive decays, theory predictions require calculations of hadronic form factors. With current theory predictions, the most useful are measurements within the q^2 regions 1.1 to 6.0 GeV^2/c^4 and from 16.0 GeV^2/c^4 up to the kinematic limit. From this reason in the listing we provide results mainly in those two regions.

Similar as for radiative decays, also for the $b \to s\ell^+\ell^-$ decays the inclusive measurements provide some benefits. Both Belle and BaBar performed such measurement without reconstructing hadronic part exclusively and measure a branching fraction of $(5.8 \pm 1.3) \times 10^{-6}$ [172]. Unfortunately this measurement is not trivially possible at hadron colliders and also does not easily allow the angular distributions of the decay products to be exploited. One alternative is to extract information on the inclusive decay as sum of exclusive decays. Such a measurement was performed by Belle [173], but in this case the difficulty lies in extrapolation for the missing hadronic states.

Turning to the exclusive decays, the initial measurements performed by B-factories typically averaged between charged and neutral B mesons as well as between e^+e^- and $\mu^+\mu^-$ finals states. The experiments CDF, LHCb, ATLAS and CMS are much better suited for the $\mu^+\mu^-$ finals states compared to the e^+e^- final states. As such most measurements at hadron colliders are done only with $\mu^+\mu^-$ pairs and by separating charged and neutral B mesons. Recently, however, with much increased statistics, LHCb measured several final states with e^+e^-, to make a series of tests of e/μ universality in $B \to K^{(*)}\ell^+\ell^-$ decays. At hadron colliders other b hadrons are produced and as such CDF and LHCb experiments did observe also $B^0_s \to \phi\mu^+\mu^-$ [174, 175], $\Lambda^0_b \to \Lambda\mu^+\mu^-$ [174, 176] and $\Lambda^0_b \to pK^-\mu^+\mu^-$ decays [177]. The averages of the total branching fractions integrated over whole q^2 regions are $(5.6 \pm 0.6) \times 10^{-7}$ for $B^+ \to K^+e^+e^-$, $(4.53 \pm 0.35) \times 10^{-7}$ for $B^+ \to K^+\mu^+\mu^-$, $(1.03^{+0.19}_{-0.17}) \times 10^{-6}$ for $B^0 \to K^*(892)^0e^+e^-$ and $(0.94 \pm 0.05) \times 10^{-6}$ for $B^0 \to K^*(892)^0\mu^+\mu^-$ decays [178–182]. The total branching fractions for $B^0_s \to \phi\mu^+\mu^-$ and $\Lambda^0_b \to \Lambda\mu^+\mu^-$ decays are $(8.4 \pm 0.4) \times 10^{-7}$ [174, 175, 183] and $(1.08 \pm 0.28) \times 10^{-6}$ [174, 176] respectively. With increased precision of $B^0 \to K^*(892)^0\ell^+\ell^-$ decay, there is a question on what fraction of the seen branching fraction is due to the $K^*(892)^0$ resonance and what fraction is due to the $K\pi$ in s-wave. This has been studied by LHCb which found that the $K\pi$ in s-wave fraction varies between 1% and about 10% depending on the q^2 region [182]. It should be noted, that for all relevant B meson decays the branching fractions so far studied are consistently below the SM expectation.

In the $b \to s\ell^+\ell^-$ decays angular distributions offer rich source of information. The full angular analysis was performed for decays $B^+ \to K^+\ell^+\ell^-$, $B^0 \to K^0\ell^+\ell^-$, $B^+ \to K^*(892)^+\ell^+\ell^-$, $B^0 \to K^*(892)^0\ell^+\ell^-$, $B^0_s \to \phi\mu^+\mu^-$ and $\Lambda^0_b \to \Lambda\mu^+\mu^-$ decays [184–192]. An attempt to increase sensitivity to the NP was made by constructing observables, which have reduced theory uncertainties and measurements of these are done. Most notably the observable called P'_5 [193] shows a discrepancy with the SM in the q^2 region which is highly sensitive to new physics [186–188]. Measurements of the CP asymmetries [177, 178, 181, 194, 195] and the isospin asymmetry [179–181, 194] were also performed. All these measurements are well consistent with the small A_{CP} and small isospin asymmetry expected in the SM [196]. With statistics available at the LHC, the measurement of phase difference between long- and short-distance contribution in $B^+ \to K^+\mu^+\mu^-$ decays became possible [197].

With the data samples available at LHC, the lepton universality in $b \to s\ell^+\ell^-$ can be tested.

While in the SM decays to electron-positron and muon pairs are expected to be same up to small corrections due to the different masses of leptons, in extensions of the SM this does not have to hold. The angular analysis of $B^0 \to K^*(892)^0 e^+e^-$ decays was performed by LHCb at low dilepton invariant masses [198] and Belle in several regions over whole q^2 range [188]. The LHCb measurement yields the most stringent constraint on the photon polarization. The result on lepton universality test which over past few years attracted most attention is the ratio of branching fractions between $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$ and between $B^0 \to K^*(892)^0\mu^+\mu^-$ and $B^0 \to K^*(892)^0e^+e^-$ decays [179,199]. The measurements by LHCb showed mild discrepancy from the SM, with significance of $3.1\,\sigma$ for $B^+ \to K^+\ell^+\ell^-$ and about $2.4\,\sigma$ for $B^0 \to K^*(892)^0\ell^+\ell^-$. The latest analysis in Ref. [200] identified previously missed hadronic misidentification background. With better handling of such background the results are now consistent with the SM. LHCb experiment performed similar test with $\Lambda_b^0 \to pK^-\ell^+\ell^-$ decays [201], $B^0 \to K_S^0\ell^+\ell^-$ and $B^+ \to K^*(892)^+\ell^+\ell^-$ [202].

While $b \to d\ell^+\ell^-$ decays are further suppressed, they recently became accessible. Signals were observed for $B^+ \to \pi^+\mu^+\mu^-$ [77], $B^0 \to \pi^+\pi^-\mu^+\mu^-$ [203] and $\Lambda_b^0 \to p\pi^-\mu^+\mu^-$ [204] decays. Search for the $B_s^0 \to \overline{K}^*(892)^0\mu^+\mu^-$ at LHCb is complicated by large background from $B^0 \to K^*(892)^0\mu^+\mu^-$ and current significance for the decay is 3.4σ [205]. The total branching fractions are only quantities measured and these are about 2×10^{-8} for the meson decays and about 7×10^{-8} for the Λ_b^0 decay.

A closely related process is $B \to X_s\nu\overline{\nu}$. Since the neutrinos are not detected, the final state is a strange hadron system X_s plus missing energy-momentum. Depending on X_s, the SM branching fraction is $\mathcal{O}(10^{-6})$. New physics effects beyond SM, e.g. those from dark sector models can greatly enhance the yield of X_s plus missing energy. BaBar [206], Belle [207], and Belle II [208] have searched for these decays and determined the upper limits in the range $\mathcal{O}(10^{-5})$.

Finally the decays $B_{(s)}^0 \to e^+e^-$ and $\mu^+\mu^-$ are interesting since they only proceed at second order in weak interactions in the SM, but may have large contributions from supersymmetric loops, proportional to $(\tan\beta)^6$. First limits were published more than 30 years ago and since then experiments at Tevatron, B-factories and LHC gradually improved those and effectively excluded whole models of new physics and significantly constrained allowed parameter space of others. For the decays to $\mu^+\mu^-$, Tevatron experiments pushed the limits down to roughly factor of 5-10 above the SM expectation [209]. The long journey in the search for these decays culminated in 2012, when first evidence for $B_s^0 \to \mu^+\mu^-$ decay was seen [210]. Subsequently, LHC experiments ATLAS [211], CMS [212] and LHCb [213] observed statistically significant signal for $B_s^0 \to \mu^+\mu^-$ decay. The average branching fraction is found to be $(3.01 \pm 0.435) \times 10^{-9}$. In experiments at hadron colliders searches for $B^0 \to \mu^+\mu^-$ decays are performed at the same time. The $B(B^0 \to \mu^+\mu^-)$ is extracted in simultaneously with $B(B_s^0 \to \mu^+\mu^-)$ and is found to be $(0.07^{+0.13}_{-0.11}) \times 10^{-9}$. The limits for the e^+e^- modes are: $< 9.4 \times 10^{-9}$ and $< 2.5 \times 10^{-9}$, respectively, for B_s^0 and B^0 [214]. The searches for decays to $\tau^+\tau^-$ are more challenging with current best limits of $B(B^0 \to \tau^+\tau^-) < 2.1 \times 10^{-3}$ and $B(B_s^0 \to \tau^+\tau^-) < 6.8 \times 10^{-3}$ at 95% C.L. [215]. All existing measurements of B^0 and B_s^0 decays to same flavour dilepton pair is consistent with SM expectation [216]. With $B_s^0 \to \mu^+\mu^-$ decay observed, it was suggested that the effective lifetime is useful further test of the decay [217]. Attempt was made by LHCb and CMS experiments, but its precision is not yet sufficient to provide test of the SM [212, 213]. It will take couple of years until interesting precision is reached. The searches were also performed for lepton flavour violating decays to two leptons with best limits in $e^\pm\mu^\mp$ channel, where limits are $< 1.3 \times 10^{-9}$ for B^0 and $< 6.3 \times 10^{-9}$ for B_s^0, at 95% confidence level [218].

Several theory groups performed global analysis of electroweak decays concluding that significant tension between data and SM is present [219]. The tension can be relieved by new physics beyond SM. For more detailed reviews see e.g. Ref. [220].

73.7 Summary and Outlook

The study of B mesons continues to be one of the most productive fields in particle physics. With the two asymmetric B-factory experiments Belle and BaBar, we now have a combined data sample of well over 1 ab^{-1}. CP violation has been firmly established in many decays of B mesons. Evidence for direct CP violation has been observed. Many rare decays resulting from hadronic $b \to u$ transitions and $b \to s(d)$ penguin decays have been observed, and the emerging pattern is still full of surprises. Despite the remarkable successes of the B-factory experiments, many fundamental questions in the flavor sector remain unanswered.

At Fermilab, CDF and D0 each has accumulated about 10 fb^{-1}, which is the equivalent of about 10^{12} b-hadrons produced. In spite of the low trigger efficiency of hadronic experiments, a selection of modes have been reconstructed in large quantities, giving a start to a program of studies on B_s and b-flavored baryons, in which a first major step has been the determination of the B_s oscillation frequency.

As Tevatron and B-factories finished their data taking few year ago, the experiments at the LHC have become very active. LHCb has collected about 1 fb^{-1} at 7 TeV, 2 fb^{-1} at 8 TeV, and close to 5.9 fb^{-1} at 13 TeV during LHC Runs 1 and 2. CMS and ATLAS have collected each about 5 fb^{-1} of data at $\sqrt{s} = 7$ TeV, 20 fb^{-1} at 8 TeV and about 150 fb^{-1} at 13 TeV during LHC Runs 1 and 2. The latest LHC Run 3 at 13.6 TeV started in summer 2022, with upgraded detectors. By the time of the writing (summer 2023), LHC has delivered about 70 fb^{-1} to ATLAS and CMS experiments. LHCb, which is dedicated to the studies of b- and c-hadrons, has a data sample that is for many decays larger than the sum of all previous experiments. With it, we are entering to regime of precision physics even for many rare decays, which allows much more detailed measurements.

The Belle II experiment at the SuperKEKB has started recording data in 2019 and has by summer 2022 collected about 428 fb^{-1} of data, when their long shutdown 1 started. The aim to increase sample to ~ 50 ab^{-1} will make it possible to explore the indirect evidence of new physics beyond the SM in the heavy-flavor particles (b, c, and τ), in a way that is complementary to the LHC. The LHCb Collaboration is commissioning upgrade of its detector and is planning on nominal running from 2024. The aim of the upgrade was to increase flexibility of the trigger, which will allow about a factor of five increase in instantaneous luminosity and of about a factor of two in efficiencies on triggering on purely hadronic decays. The plan is to integrate about 50 fb^{-1} of data during LHC runs 3 and 4.

These experiments promise a rich spectrum of rare and precise measurements that have the potential to fundamentally affecting our understanding of the SM and CP-violating phenomena.

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[5] Currently two different notations (ϕ_1, ϕ_2, ϕ_3) and (α, β, γ) are used in the literature for CKM unitarity angles. In this mini-review, we use the latter notation following the other mini-reviews in this *Review*. The two notations are related by $\phi_1 = \beta$, $\phi_2 = \alpha$ and $\phi_3 = \gamma$.

[6] See the "CP Violation in Meson Decays" by D. Kirkby and Y. Nir in this *Review*.

[7] See the "CKM Quark Mixing Matrix," by A. Cecucci, Z. Ligeti, and Y. Sakai, in this *Review*.

[8] See the note on "$B^0 - \overline{B}^0$ mixing," by O. Schneider in this *Review*.

[9] See the "Determination of $|V_{cb}|$ and $|V_{ub}|$," by R. Kowalewski and T. Mannel in this *Review*.

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