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Report of the Heavy Quarks Working Group

Conveners: J.N. Butler, Z. Ligeti, J.R. Patterson, J.L. Ritchie

N. Arkani-Hamed, D.M. Asner, A.J. Bevan, M. Blanke, G. Bonvicini, R.A. Briere, T.E. Browder, D.A. Bryman, P. Campana, R. Cenci, N.H. Christ, D. Cline, J. Comfort, D. Cronin-Hennessy, A. Datta, S. Dobbs, M. Duraisamy, J.E. Fast, R. Forty, K.T. Flood, T. Gershon, D.G. Hitlin, A. Jawahery, C.P. Jessop, A.L. Kagan, D.M. Kaplan, M. Kohl, P. Krizan, A.S. Kronfeld, K. Lee, L.S. Littenberg, D.B. MacFarlane, P.B. Mackenzie, B.T. Meadows, J. Olsen, M. Papucci, G. Paz, G. Perez, K. Pitts, M.V. Purohit, B.N. Ratcliff, D.A. Roberts, J.L. Rosner, P. Rubin, J. Seeman, K.K. Seth, A. Soni, S.R. Sharpe, B. Schmidt, A.J. Schwartz, A. Schopper, T. Skwarnicki, S. Stone, R. Sundrum, R. Tschirhart, A. Vainshtein, Y.W. Wah, R.S. Van de Water, G. Wilkinson, M.B. Wise, J. Xu, T. Yamanaka, J. Zupan

1.1 Quark Flavor as a Tool for Discovery

An essential feature of flavor physics experiments is their ability to probe very high mass scales, beyond the energy accessible in collider experiments. In addition, flavor physics can teach us about properties of TeV-scale new physics, which cannot be learned from the direct production of new particles at the LHC. This is because quantum effects allow virtual particles to modify the results of precision measurements in ways that reveal the underlying physics. (The determination of the $t-s,d$ couplings in the standard model (SM) exemplifies how direct measurements of some properties of heavy particles may only be possible in flavor physics.) Even as the Large Hadron Collider (LHC) at CERN embarks on probing the TeV scale, the ongoing and planned precision flavor physics experiments are sensitive to beyond standard model (BSM) interactions at mass scales which are higher by several orders of magnitude. These experiments will provide essential constraints and complementary information on the structure of models put forth to explain any discoveries at LHC, and they have the potential to reveal new physics that is inaccessible to the LHC.

Throughout the history of particle physics discoveries made in studies of rare processes have led to new and deeper understanding of nature. A classic example is beta decay, which foretold the electroweak mass scale and the ultimate observation of the W boson. A number of results from kaon decay experiments were crucial for the development of the standard model: the discovery of CP violation in $K_L^0 \to \pi^+\pi^-$ decay ultimately pointed toward the three-generation CKM model [1, 2], the absence of strangeness-changing neutral current decays (i.e., the suppression of $K_L^0 \to \mu^+\mu^-$ with respect to $K^+ \to \mu^+\nu$) led to the prediction of the fourth (charm) quark [3], and the measured value of the $K_L - K_S$ mass difference made it possible to predict the charm quark mass [4, 5] before charm particles were directly detected. More recently the larger than expected $B_H - B_L$ mass difference foretold the high mass of the top quark. Precision measurements of time-dependent CP-violating asymmetries in B-meson decays in the BaBar and Belle experiments firmly established the CKM phase as the leading source of CP violation observed to date in flavor-changing processes — leading to the 2008 Nobel Prize for Kobayashi and Maskawa. At the same time, corrections to the SM at the tens of percent level are still allowed, and many extensions of the SM that were proposed to solve the hierarchy problem are likely to give rise to changes in flavor physics that may be observed in the next generation of experiments.

Today, a well-planned program of flavor physics experiments — using strange, charm, and bottom quarks — has the potential to continue this history of producing paradigm-changing scientific advances.

This report from the Heavy Quarks working group responds, in the context of quark-flavor physics, to the DOE charge to the Intensity Frontier Workshop to identify experimental opportunities and to explain their potential, as well as address the needed facilities. This report is not a review of quark-flavor physics, and no attempt has been made to provide complete references to prior work.

1.2 Strange, Charm, and Bottom Quarks as Probes of New Physics

In the past decade our understanding of flavor physics has improved very significantly due to the e^+e^- B factories, BABAR, Belle, CLEO, and the Tevatron experiments. While kaon physics was crucial for the development of the SM, and has provided some of the most stringent constraints on BSM physics since the 1960s, precision tests of the CKM picture of CP violation in the kaon sector have been hindered by theoretical uncertainties in calculating direct CP violation in K decay (ϵ'). The B factories provided many stringent tests by precisely measuring numerous CP-violating and CP-conserving quantities, which in the SM are determined in terms of just a few parameters, but are sensitive to different possible BSM contributions. The consistency of the measurements and their agreement with CP violation in K^0–$\overline{K}^0$ mixing, ϵ_K, and with the SM predictions (shown in the left plot in Fig. 1-1) strengthened the "new physics flavor problem". It is the tension between the relatively low (TeV) scale required to stabilize the electroweak scale, and the high scale that is seemingly required to suppress BSM contributions to flavor-changing processes. This problem arises because the SM flavor structure is very special, containing small mixing angles, and because of additional strong suppressions of flavor-changing neutral-current (FCNC) processes. Any extension of the SM must preserve these features, which are crucial to explain the observed pattern of weak decays.

The motivation for a broad program of precision flavor physics measurements has gotten even stronger in light of the 2011 LHC data. With a hint at a particle that may be a SM-like Higgs boson, but no sign of other high-mass states, the LHC has begun to test naturalness as a guiding principle of BSM research. If the electroweak scale is unnatural, we have little information on the next energy scale to explore (except

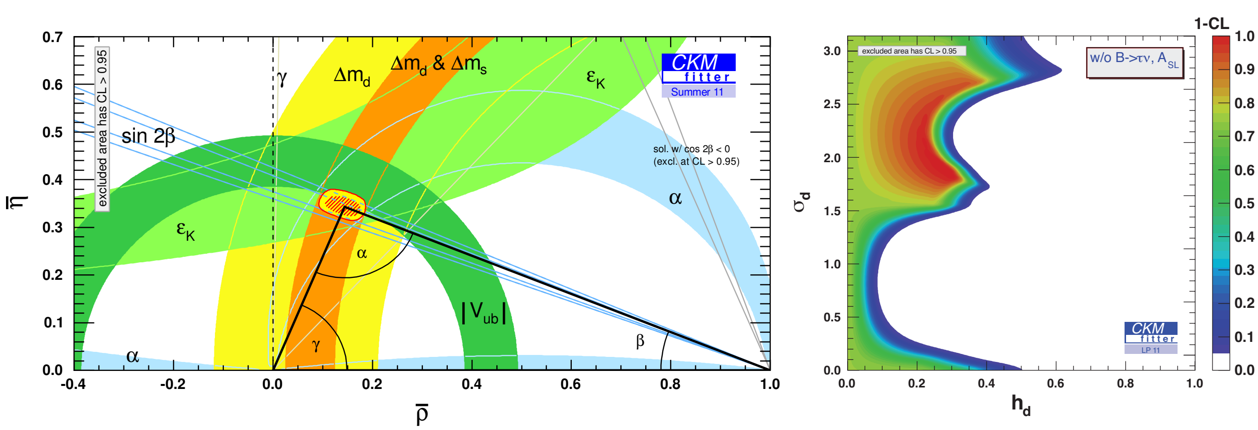

Figure 1-1. *Left: Constraints on the apex of the unitarity triangle in the $\bar{\rho}-\bar{\eta}$ plane (at 95% CL). Right: the allowed $h_d - \sigma_d$ new physics parameter space (see text) in B^0–$\overline{B}^0$ mixing. (From Refs. [6, 7].)*

Operator	Bounds on Λ [TeV] ($C = 1$)		Bounds on C ($\Lambda = 1\,\text{TeV}$)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2	2.2×10^2	7.6×10^{-5}	1.7×10^{-5}	Δm_{B_s}; $S_{\psi\phi}$
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2	7.4×10^2	1.3×10^{-5}	3.0×10^{-6}	Δm_{B_s}; $S_{\psi\phi}$

Table 1-1. *Bounds on $\Delta F = 2$ operators of the form $(C/\Lambda^2)\,\mathcal{O}$, with $\mathcal{O}$ given in the first column. The bounds on Λ assume $C = 1$, and the bounds on C assume $\Lambda = 1$ TeV. (From Ref. [8].)*

for a hint at the TeV scale from dark matter, a few anomalous experimental results, and neutrinos most likely pointing at a very high scale). The flavor physics program will explore much higher scales than can be directly probed. However, if the electroweak symmetry breaking scale is stabilized by a natural mechanism, new particles should be found at the LHC. Since the largest quantum correction to the Higgs mass in the SM is due to the top quark, the new particles will likely share some properties of the SM quarks, such as symmetries and interactions. Then they would provide a novel probe of the flavor sector, and flavor physics and the LHC data would provide complementary information. Their combined study is our best chance to learn more about the origin of both electroweak and flavor symmetry breaking.

Consider, for example, a model in which the only suppression of new flavor-changing interactions comes from the large masses of the new particles that mediate them (at a scale $\Lambda \gg m_W$). Flavor physics, in particular measurements of meson mixing and CP violation, put severe lower bounds on Λ. For some of the most important four-quark operators contributing to the mixing of the neutral K, D, B, and B_s mesons, the bounds on the coefficients C/Λ^2 are summarized in Table 1-1 (for $S_{\psi\phi}$ we use the LHCb result). For $C = 1$, they are at the scale $\Lambda \sim (10^2 - 10^5)$ TeV. Conversely, for $\Lambda = 1\,\text{TeV}$, the coefficients have to be extremely small. Therefore, there is a tension. The hierarchy problem can be solved with new physics at $\Lambda \sim 1\,\text{TeV}$. Flavor bounds, however, require much larger scales, or tiny couplings. This tension implies that TeV-scale new physics must have special flavor structures, e.g., possibly sharing some of the symmetries that shape the SM Yukawa interactions. The new physics flavor puzzle is thus the question of why, and in what way, the flavor structure of the new physics is non-generic. As a specific example, in a supersymmetric extension of the SM, there are box diagrams with winos and squarks in the loops. The size of such contributions depends crucially on the mechanism of SUSY breaking, which we would like to probe.

To be sensitive to BSM contributions to FCNC processes (where the SM is suppressed, but not absent), many measurements need to be done, and it is only their combination that can reveal a signal. (There are some exceptions, mainly processes forbidden in the SM, but considering only those would reduce the sensitivity of the program to BSM physics.) To visualize the constraints from many measurements, it is convenient to use the Wolfenstein parameterization [9] of the CKM matrix (for a review, see [10]),

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\bar{\rho} - i\bar{\eta}) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \bar{\rho} - i\bar{\eta}) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)\,. \tag{1.1}$$

It exhibits the hierarchical structure of the CKM matrix by expanding in a small parameter, $\lambda \simeq 0.23$. The unitarity of this matrix in the SM implies many relations, such as that defining the "unitarity triangle" shown in Fig. 1-1, which arises from rescaling the $V_{ud}\,V_{ub}^* + V_{cd}\,V_{cb}^* + V_{td}\,V_{tb}^* = 0$ relation by $V_{cd}\,V_{cb}^*$ and choosing two vertices of the resulting triangle to be $(0,0)$ and $(1,0)$. (We use definitions of the λ, A, $\bar\rho$ and $\bar\eta$ parameters that obey unitarity and ensure that the apex of the unitarity triangle is $(\bar\rho,\bar\eta)$ exactly [7].)

As a result of second-order weak interaction processes, there are transitions between the neutral meson flavor eigenstates, so the physical mass eigenstates are their linear combinations, denoted as $|B_{H,L}\rangle = p|B^0\rangle \mp q|\overline{B}^0\rangle$. (The p and q parameters differ for the four neutral mesons, but the same notation is commonly used without distinguishing indices.) In a large class of models, the BSM physics modifies the mixing amplitude of neutral mesons, and leaves tree-level decays unaffected. This effect can be parameterized by just two real parameters for each mixing amplitude. For $B^0 - \overline{B}^0$ mixing, writing $M_{12} = M_{12}^{\rm SM}\left(1 + h_d\, e^{2i\sigma_d}\right)$, the constraints on h_d and σ_d are shown in the right plot in Fig. 1-1. (Evidence for $h_d \neq 0$ would rule out the SM.) Only in 2004, after the first significant constraints on γ and α became available from *BABAR* and Belle, did we learn that the BSM contribution to B–$\overline{B}$ mixing must be less than the SM amplitude [11, 7]. The right plot in Fig. 1-1 shows that order $10 - 20\%$ corrections to $|M_{12}|$ are still allowed for (almost) any value of the phase of the new physics contribution, and if this phase is aligned with the SM ($2\sigma_d = 0 \bmod \pi$), then the new physics contribution does not yet have to be much smaller than the SM one. Similar conclusions apply to other neutral meson mixings [12, 13], as well as many other $\Delta F = 1$ FCNC transition amplitudes.

The fact that such large deviations from the SM are not yet excluded gives very strong motivations to continue flavor physics measurements in order to observe deviations from the SM predictions or establish a stronger hierarchy between the SM and new physics contributions.

In considering the future program, the following issues [14] are of key importance:

1. What are the expected deviations from the SM predictions induced by new physics at the TeV scale?
   As explained above, TeV-scale new physics with generic flavor structure is ruled out by many orders of magnitudes. However, sizeable deviations from the SM are still allowed by the current bounds, and in many scenarios observable effects are expected.
2. What are the theoretical uncertainties?
   These are highly process dependent. Some measurements are limited by theoretical uncertainties (due to hadronic, strong interaction, effects), but in many key processes the theory uncertainties are very small, below the expected sensitivity of future experiments.
3. What can be expected in terms of experimental precision?
   The useful data sets can increase by a factor of order 100 (in most cases 10–1000), and will probe effects predicted by fairly generic BSM scenarios.
4. What will the measurements reveal, if deviations from the SM are [not] seen?
   The flavor physics data will be complementary with the high-p_T part of the LHC program. The synergy of measurements can reveal a lot about what the new physics at the TeV scale is, and what it is not.

This report concentrates on the physics and prospects of a subset of measurements, for which the answers to these questions are the clearest, both in terms of theoretical cleanliness and experimental feasibility. The experiments will enable many additional measurements which are not discussed here, some due to lack of space, and some because they will be more important than can now be anticipated. (Recall that the best measurements of the CKM angles α and γ at *BABAR* and Belle were not in formerly expected decay modes.) Theoretical research, including lattice QCD, is also an important part of this program because future progress will add to the list of observables that can be used as probes for BSM physics. Nevertheless, the value of more sensitive experiments is not contingent upon theoretical progress.

1.2.1 *K* Decays

As can be seen from Table 1-1, some of the strongest constraints on BSM physics come from the measurements of the $K_L - K_S$ mass difference Δm_K and the CP violating quantities ϵ_K and ϵ'. This is because the SM suppressions are the strongest in the kaon sector, since the u and c contributions to FCNC processes are very strongly GIM suppressed, while that of the t is strongly CKM suppressed. Hence the agreement of the measurements with the SM implies that new physics must mimic the SM suppressions. While ϵ_K can be calculated precisely, the hadronic uncertainties in the SM calculation of ϵ' are particularly large, because two terms with comparable magnitude and opposite sign contribute. Progress in lattice QCD may make ϵ' tractable in the future; at present, however, we can neither rule out, nor prove, that it receives a substantial new physics contribution.

In several rare FCNC kaon decays, such as those containing a charged lepton pair in the final state, a challenge to learn about short distance physics is due to long distance contributions via one or two photons converting into the $\ell^+\ell^-$ pair. However, the decays involving a $\nu\bar{\nu}$ pair in the final state are theoretically clean, providing very interesting channels to search for BSM physics. The $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L^0 \to \pi^0\nu\bar{\nu}$ decays are determined by short distance physics, and there is a single operator (both in the SM and in most BSM scenarios) which determines the decay rates, $\mathcal{O} = X\,(\bar{s}d)_V\,(\bar{\nu}\nu)_{V-A}$. Moreover, the form factor that parameterizes the matrix element of this operator is the same as the one measured in $K \to \pi\ell\nu$ decay, in the limit of isospin symmetry. The decay rate $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ is proportional to $|X|^2$, and $\mathrm{Re}(X)$ gets a contribution from a penguin diagram with a charm loop. This contribution has been calculated to next-to-leading order, and is responsible for the slightly larger irreducible theory uncertainty in the charged than in the neutral mode. The $K_L^0 \to \pi^0\nu\bar{\nu}$ rate is even cleaner theoretically, because the final state is almost completely CP-even [15], so the decay proceeds dominantly through CP violation in the interference of decay with and without mixing [16, 17]. The rate is determined by $\mathrm{Im}(X) \propto \mathrm{Im}[(V_{td}V_{ts}^*)/(V_{cd}V_{cs}^*)]\}$. Both decay rates are proportional to $(A\lambda^2)^4$, which could, however, be canceled by taking a ratio of rates, substantially reducing the uncertainties. The constraint from a future measurement of $\mathcal{B}(K_L^0 \to \pi^0\nu\bar{\nu})$ would be two horizontal bands centered at a certain value of $\pm|\overline{\eta}|$. At present, the experimental uncertainty of $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ is $\mathcal{O}(1)$, while the bound on $\mathcal{B}(K_L^0 \to \pi^0\nu\bar{\nu})$ is 10^3 times the SM prediction, leaving a lot of room for future experiments to find unambiguous signs of BSM physics.

An important synergy with B decay measurements is due to the fact that all three observables ϵ_K, $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$, and $\mathcal{B}(K_L^0 \to \pi^0\nu\bar{\nu})$ depend on $|V_{td}V_{ts}|^2$, which is proportional to A^4, which in turn is determined by $|V_{cb}|^4$. This provides a strong motivation to improve the determination of $|V_{cb}|$ at the super flavor factories, combining the much larger data sets with theoretical improvements.

Lattice QCD is also important for the kaon program. For ϵ_K, the determination of the bag parameter, B_K, has improved in the last decade remarkably [18], and it is hoped that ϵ' may also become tractable in the future. A lattice QCD determination of the charm loop contribution to $K^+ \to \pi^+\nu\bar{\nu}$ would also be worth pursuing. And, of course, lattice QCD is important for determining $|V_{cb}|$ from semileptonic B decays.

The next generation of kaon experiments will not only measure $K \to \pi\nu\bar{\nu}$, but perform a much broader program, which includes $K \to \pi\ell^+\ell^-$, $K \to \ell\bar{\nu}$, CP-violating triple products, and many other interesting measurements sensitive to BSM physics.

1.2.2 B and B_s decays

The B physics program is remarkably broad, with many measurements sensitive to complementary ways of extending the SM (its Higgs sector, gauge sector, or fermion sector). Here the focus is on a subset of measurements which can be improved by an order of magnitude or more, and whose interpretations are definitely not limited by hadronic uncertainties. Particularly promising channels to look for new physics are in mixing and in FCNC decays, where the SM contributions are suppressed, so BSM contributions originating at a higher scale may compete. We saw that BSM contributions of order 20% of the SM ones are still allowed in most FCNC processes, and improving these constraints will be important to interpret the LHC results.

In this program, the determinations of γ and $|V_{ub}|$ are crucial, because they are obtained from tree-level processes, and hence provide a "reference" determination of the CKM matrix (i.e., $\bar\rho$ and $\bar\eta$, the apex of the unitarity triangle), to which other measurements can be compared. There is ongoing theoretical work to improve the determination of $|V_{ub}|$, using both continuum methods and lattice QCD, but it is not yet known if more than a factor-of-few improvement will be possible. At the same time, the measurement of γ from $B \to DK$ decays is only limited by statistics (the current world average is $\gamma = \left(68^{+10}_{-11}\right)^\circ$ [6]). It is arguably the cleanest measurement in terms of theoretical uncertainties, because the necessary hadronic quantities can be measured. All $B \to DK$ based analyses consider decays of the type $B \to D(\overline{D})\,K\,(X) \to f_D\,K\,(X)$, where f_D is a final state accessible in both D and $\overline{D}$ decay and X denote possible extra particles in the final state [19]. The crucial point is that the flavor of the D or $\overline{D}$ in the intermediate state is not measured, so the $b \to c\bar{u}s$ and $b \to u\bar{c}s$ decay amplitudes can interfere. Using several decay modes, one can perform enough measurements to determine all relevant hadronic parameters, as well as the weak phase γ. Thus, the theoretical uncertainties are much below the sensitivity of any foreseeable experiment. A complementary method available at LHCb, using the four time-dependent $B_s \to D_s^\pm K^\mp$ rates, has not been tried yet.

The above tree-dominated measurements will allow improvements in the CP asymmetry in $B \to J/\psi\,K_S$ and related modes, determining the angle β, to improve the constraints on BSM physics. In the B_s system, the SM prediction for CP violation in the similar $b \to c\bar{c}s$ dominated decays, such as $B_s \to J/\psi\,\phi$, is suppressed by λ^2 compared to β, yielding for the corresponding time-dependent CP asymmetry $\beta_s^{(\mathrm{SM})} = 0.0182 \pm 0.0008$. While the Tevatron measurements hinted at a possibly large value, the LHCb result, $\beta_s = -0.075 \pm 0.095$ [20], did not confirm those. The key point is that the uncertainty is still much larger than that of the SM prediction.

An important search for new physics in penguin amplitudes comes from the comparison of CP asymmetries measured in tree-level $b \to c\bar{c}s$ dominated decays with those in loop-dominated $b \to q\bar{q}s$ decays. The specific measurements that probe such effects include the difference of CP asymmetries $S_{\psi K_S} - S_{\phi K_S}$ or related modes in B_d decay, and $S_{\psi\phi} - S_{\phi\phi}$ in B_s decay.

There are some intriguing hints of deviations from the SM in the current data. CP violation in neutral meson mixing, the mismatch of the CP and mass eigenstates, measured by the deviation of $|q/p|$ from 1, is simply $1 - |q/p| = 2\,\mathrm{Re}(\epsilon_K)$ in the K system. It is sensitive to BSM contributions in B mesons, since $1 - |q/p|$ is model independently suppressed by m_b^2/m_W^2, and there is an additional m_c^2/m_b^2 suppression in the SM, which new physics may violate. In B_d mixing, the SM expectation for $1 - |q/p|$ is at the few times 10^{-4} level [21], while in B_s mixing it is suppressed in addition by $|V_{td}/V_{ts}|^2$ to 10^{-5}. Thus, it is remarkable that DØ measured the CP-violating dilepton asymmetry for a mixture of B_d and B_s mesons at the 4σ level, $A^b_{\mathrm{SL}} = (7.87 \pm 1.96) \times 10^{-3} \approx 0.6\,A^d_{\mathrm{SL}} + 0.4\,A^s_{\mathrm{SL}}$ [22], where in each system $A_{\mathrm{SL}} \simeq 2(1 - |q/p|)$. It will be important at LHCb and at the super flavor factories to clarify this situation by more precise measurements. Since the hint of the signal is much above the SM, there is a lot of room to find BSM contributions.

Another interesting tension in the current data is from the measurement of the $\mathcal{B}(B \to \tau\bar\nu)$ rate, which is about 2.5σ above the prediction from the SM fit. This comparison relies on a lattice QCD calculation of the

B meson decay constant. The simplest BSM explanation would be a charged Higgs contribution, which in the type-II 2HDM is proportional to $m_b\, m_\tau \tan^2\beta/m_H^2$. It will require larger data sets at the future e^+e^- B factories (and measuring the $B \to \mu\bar{\nu}$ mode as well) to clarify the situation.

There is a nearly endless list of interesting measurements. Many are in rare decays involving leptons. LHCb will be able to search for $B_s \to \ell^+\ell^-$ down to the SM level, at few times 10^{-9}. This process received a lot of attention in the last decade, after it was noticed that a SUSY contribution is enhanced by $\tan^6\beta$. With the LHCb upgrade and many years of super flavor factory running, the search for $B_d \to \ell^+\ell^-$ may also get near the SM level. Rare decays involving a $\nu\bar{\nu}$ pair are theoretically very clean, and the next generation of e^+e^- machines should reach the SM level in $B \to K^{(*)}\nu\bar{\nu}$; the current constraints are an order of magnitude weaker. There is also a long list of interesting measurements in $b \to s\gamma$ and $b \to s\ell^+\ell^-$ mediated inclusive and exclusive decays, CP asymmetries, angular distributions, triple product correlations, etc., which will be probed much better in the future. And the $s \leftrightarrow d$ processes, with lower SM rates, will provide many other challenging measurements and opportunities to find new physics. Furthermore, there is synergy and complementarity with "hidden sector" particle searches, as explained in that working group report.

While any one of the above measurements could reveal new physics, the strongest complementary information to the LHC will come not from one measurement, but the pattern in which they do or do not show deviations from the SM. In addition, the experiments that carry out this program will also be able to search for charged lepton flavor violation at an unprecedented level, e.g., $\tau \to \mu\gamma$ and $\tau \to 3\mu$, discussed in another working group report. There is also a set of measurements for which our understanding of hadronic physics is not yet good enough, but it could improve in the next decade. A high profile example is the difference of direct CP asymmetries, $a_{K^+\pi^0} - a_{K^+\pi^-} = 0.148 \pm 0.028$, which is expected to be small if corrections to the heavy quark limit were under control. Precise measurements at the super flavor factories of other decay modes related by $SU(3)$ flavor symmetry will help to clarify this situation and also teach us about hadronic physics.

1.2.3 *D* Decays

The D meson system is complementary to K and B mesons because it is the only neutral-meson system in which mixing and rare FCNC decays are generated by down-type quarks in the SM loop diagrams. This complementary sensitivity is also present for new physics models. For example, in supersymmetric theories the gluino and neutralino contributions to FCNC K and B transitions involve down-type squarks, whereas the D system is sensitive to the mixing of the up-type squarks in loop diagrams. In the SM, since the down-type quarks are much lighter than m_W and the 2×2 Cabibbo matrix is almost unitary, FCNC charm transitions and CP violation in charm decays are expected to be strongly suppressed. Only since 2007 is there unambiguous evidence for D^0–$\overline{D}^0$ mixing, and both $x = \Delta m/\Gamma$ and $y = \Delta\Gamma/(2\Gamma)$ are at or below the 0.01 level [23] (left plot in Figure 1-2).

The values of the mixing parameters can be accommodated in the SM [24], and imply that long distance physics is important. Nevertheless, the measurement of Δm (the upper bound on it) already had important implications for BSM. For example, in supersymmetry, it was possible to suppress FCNC K and B processes by aligning the quark and squark mixing matrices [25], which predicted $x \sim \lambda^2 \sim 0.04$. The measurement of Δm implies that if the first two squark doublets are within the reach of the LHC, then they must be degenerate to some extent, since quark-squark alignment alone cannot provide enough suppression [26].

CP violation in mixing, the deviation of $|q/p|$ from 1, is very sensitive to BSM contributions in charm mixing as well. The SM expectation is below the 0.01 level, while the current uncertainty of $|q/p| - 1$ is about 0.2 (right plot in Figure 1-2; where $\arg(q/p)$ is $\arg\lambda_{K^+K^-}$). Thus, future measurements can improve the sensitivity to BSM contributions by an order of magnitude before becoming limited by hadronic uncertainties.

Direct CP violation has been observed in K and B decays, and was expected to be at or below the 10^{-3} level in charm decays. Recently LHCb announced a 3.5σ evidence for direct CP violation, a nonzero value of $\Delta a_{\rm CP} \equiv a_{K^+K^-} - a_{\pi^+\pi^-} = -(8.2 \pm 2.1 \pm 1.1) \times 10^{-3}$ [27], giving a world average $\Delta a_{\rm CP} = -(6.5 \pm 1.8) \times 10^{-3}$. In the SM, $\Delta a_{\rm CP}$ is suppressed by $|V_{cb}V_{ub}|/|V_{cs}V_{us}| \simeq 7 \times 10^{-4}$, so an order of magnitude enhancement from hadronic physics or new physics is needed to explain this central value [28, 29]. To clarify the situation, precise measurement in many modes, accessible in different experiments, will be necessary [28, 30].

There are many other important measurements in charm decays as well, which are sensitive to new physics and are important for the rest of the program. These include leptonic and semileptonic rates with much improved precision, testing lattice QCD calculations, and learning about hadronic physics from charm spectroscopy and glueball searches. Experiments producing charm at threshold can collect large samples of CP-tagged D^0 decays, which will be very useful for high precision measurements of the CKM angle γ.

1.2.4 Effective theories, hadronic physics, and exotic states

Developments in improving the sensitivity to BSM physics and understanding QCD are strongly connected. Past experience shows that whenever an order of magnitude more data becomes available, it always leads to renewed theoretical activity to understand the strong dynamics, which often results in improvements that increase the sensitivity of the measurements to new physics. The history of the field is full of unanticipated surprises that enriched this line of research.

Model-independent tools to tackle some strong interaction phenomena are provided by effective field theories, such as chiral perturbation theory (CHPT), heavy quark effective theory (HQET), and soft-collinear effective theory (SCET). Lattice QCD allows first principles calculations of certain hadronic matrix elements (often using some effective theory methods as well), and improvements in lattice QCD calculations that are projected over the next few years will substantially improve the discovery potential of future flavor physics experiments. By now, there are two or more realistic three-flavor lattice-QCD calculations of all hadronic matrix elements needed for the SM CKM fit (see, e.g., Refs. [31, 32]). The development of all of these methods was motivated to a large extent by the desire to better calculate K and B decay matrix elements, and they have provided

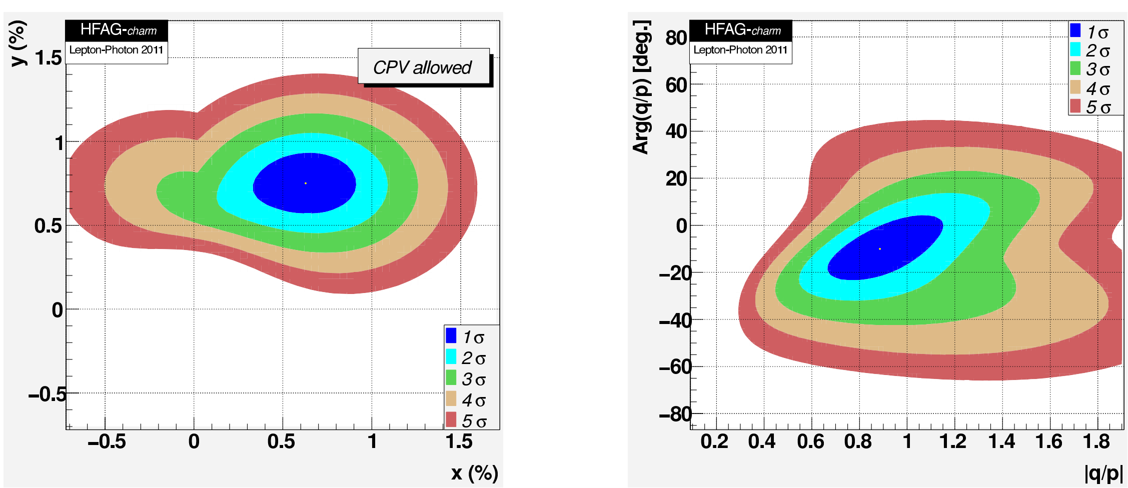

Figure 1-2. *Results on charm mixing parameters x and y, showing clear evidence for mixing (deviation from $x = y = 0$) (left); and the magnitude and phase of q/p (right). (From Ref. [23].)*

fundamental insights into the dynamics of QCD. These techniques are important in other parts of particle physics as well; e.g., SCET is being applied to jet physics to aid discoveries at the LHC, and lattice QCD is being applied to the determination of matrix elements for dark-matter detection cross sections.

The spectrum of states containing heavy quarks has provided some of the most important insights into the dynamics of QCD. After decades, when heavy quark spectroscopy was thought to amount to finding previously unobserved states anticipated from the quark model picture, *BABAR* and Belle discovered a large number of unexpected states, as well as states with unexpected masses. An important open question is whether states other than mesons composed of $q\overline{q}$ and baryons composed of qqq are realized in nature. Possible "unconventional" combinations include four-quark mesons, $q\overline{q}q\overline{q}$ (tetraquarks), five quark baryons, $qqqq\overline{q}$ (pentaquarks), "hybrids" consisting of "valence" quarks and gluons, "glueballs" that are composed of gluons (with no quarks), and hadronic "molecules". Some of these states can have exotic quantum numbers, e.g., isospins, hypercharges, or values of J^{PC} that cannot be produced in the quark model by $q\overline{q}$ or qqq constituents. Lattice QCD calculations reproduce the spectrum of charmonium and bottomonium states and predict the glueball spectrum. Many phenomenological models have also been developed to explain various aspects of these states, and the recent experimental results triggered lots of new theoretical research.

1.3 A World-wide Program of Quark Flavor Experiments

1.3.1 Kaon Experiments

As accelerators and detectors have advanced, the sensitivity of rare kaon decay experiments has also improved. In the past the U.S. led in this arena. Kaon experiments which took data more than a decade ago at the Brookhaven AGS approached the 10^{-11} level of branching fraction sensitivity [33, 34], and in one case the 10^{-12} level [35]. With current and future accelerators, substantial improvements will be possible. Experiments are now underway in Europe at CERN and Frascati, and in Japan at J-PARC. While no experiments are underway in the U.S., existing facilities at Fermilab can support world-leading experiments today, and Project X has the potential to make further significant improvements possible. A summary of the forseeable experimental progress is given in Table 1-2, while the individual experimental initiatives are discussed below.

KLOE-2

The KLOE-2 experiment [36] will run at the upgraded DAΦNE e^+e^- storage ring at the Frascati Laboratory, and it will extend the results of the earlier KLOE experiment. The upgraded DAΦNE will achieve a factor of three increase in instantaneous luminosity with a crab waist at the interaction point, one of the innovations that will also be used to achieve large luminosity gains for the super flavor factories. A number of detector improvements are being made for KLOE-2, including a new $\gamma\gamma$ tagging system, a new inner tracker, new small angle calorimeters, improved front-end electronics, and updated computing and software. Ultimately KLOE-2 aims to collect integrated luminosity of $25\,\mathrm{fb}^{-1}$, an order of magnitude more than KLOE.

The KLOE-2 physics program exploits the correlated production of K and $\overline{K}$ mesons in a $J^{PC} = 1^{--}$ state from ϕ decays, rather than achieving high sensitivity to rare decays (which is the domain of experiments using kaon beams at proton accelerators). KLOE-2 will be able to improve neutral kaon interference measurements, leading to improved tests of CPT and quantum mechanics and refined measurements of mass and mixing

Observable	SM Theory	Current Expt.	Future Experiments
$\mathcal{B}(K^+ \to \pi^+ \nu\overline{\nu})$	7.8×10^{-11}	$1.73^{+1.15}_{-1.05} \times 10^{-10}$	∼10% measurement from NA62 ∼5% measurement from ORKA ∼2% with Project X
$\mathcal{B}(K_L^0 \to \pi^0 \nu\overline{\nu})$	2.43×10^{-11}	$< 2.6 \times 10^{-8}$	1st observation from KOTO ∼5% measurement with Project X
$\mathcal{B}(K_L^0 \to \pi^0 e^+ e^-)_{SD}$	1.4×10^{-11}	$< 2.8 \times 10^{-10}$	∼10% measurement with Project X
$\mathcal{B}(K_L^0 \to \pi^0 \mu^+ \mu^-)_{SD}$	3.5×10^{-11}	$< 3.8 \times 10^{-10}$	∼10% measurement with Project X
$\vert P_T \vert$ in $K^+ \to \pi^0 \mu^+ \nu$	$\sim 10^{-7}$	< 0.0050	< 0.0003 from TREK < 0.0001 with Project X
$R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$	2.477×10^{-5}	$(2.488 \pm 0.080) \times 10^{-5}$	$\pm 0.054 \times 10^{-5}$ from TREK $\pm 0.025 \times 10^{-5}$ with Project X
$\mathcal{B}(K_L^0 \to \mu^\pm e^\mp)$	$< 10^{-25}$	$< 4.7 \times 10^{-12}$	$< 2 \times 10^{-13}$ with Project X

Table 1-2. *A summary of the reach of current and proposed experiments for some key rare kaon decay measurements, in comparison to standard model theory and the current best experimental results.*

parameters (Γ_L, Γ_S, Δm) and CP-violation parameters. It will also make a wide range of measurements of non-leptonic and radiative K and η/η' meson decays.

NA62

The NA62 experiment [37] has the goal of making a measurement of the $K^+ \to \pi^+ \nu\overline{\nu}$ branching fraction with uncertainty approaching 10%. It will run in the CERN SPS north area extraction line that housed the NA48 detector array, some components of which (in particular, the liquid krypton calorimeter) are being reused. NA62 will utilize a high-intensity (750 MHz) unseparated charged beam (about 6% K^+'s) to search for $K^+ \to \pi^+ \nu\overline{\nu}$ decays in flight. It will be the first decay-in-flight experiment to search for this mode. The projected sensitivity of the experiment would allow about 55 $K^+ \to \pi^+ \nu\overline{\nu}$ events to be collected per year at the SM branching fraction, with signal/noise of about 7/1.

Background rejection in this experiment requires precise measurements of the incoming K^+ and outgoing π^+. The former measurement is challenging in a high-intensity beam, so that NA62 is developing a so-called gigatracker using silicon pixel detectors. The latter measurement will be performed by straw tracking chambers operated in vacuum, in order to minimize multiple scattering the decay region. High-efficiency for vetoing photons from π^0 decays is assisted by the relatively high beam energy and will be accomplished using a combination of different calorimeter technologies in different regions. Very good π:μ separation is also required and will be achieved with a RICH counter in combination with an instrumented hadron absorber.

Construction of the NA62 detector systems [38] has been underway for about three years, and an engineering run of representative elements is scheduled for the second half of 2012. Data-taking is expected to begin in 2014, depending on the LHC upgrade schedule (since the SPS will only be run when the LHC is running).

KOTO

The KOTO experiment [39] will search for the $K_L^0 \to \pi^0 \nu\overline{\nu}$ at J-PARC. It will reuse parts of the detector of the E391a experiment that ran at the KEK PS, along with significant modifications. E391a set the best upper limit [40] so far for this decay (2.6×10^{-8}), which is three orders of magnitude larger than the SM branching fraction. The goal of KOTO is to close that gap and to make the first observation of $K_L^0 \to \pi^0 \nu\overline{\nu}$.

The $K_L^0 \to \pi^0 \nu\overline{\nu}$ mode is particularly challenging because the only observable particles are the two photons from the π^0 decay and there are copious other sources of photons. To obtain a kinematic constraint, KOTO will have a tightly collimated neutral beam (a "pencil beam") so that the reconstructed π^0 momentum component transverse to the beam direction can be used as a constraint. Imposing a requirement that the transverse momentum be relatively large forces missing photons from background sources to have higher energies, which makes them easier to detect. Neutron interactions must be suppressed, so most beam and detector volumes are evacuated. Excellent efficiencies for detecting photons and charged particles from background decays are achieved by surrounding the entire decay volume with active photon veto counters.

The KOTO experiment has many improvements over the E391a experiment. At J-PARC the K_L^0 flux will be higher by a factor of up to 40, while the n/K_L^0 ratio is expected to be lower by a factor of at least three due to an improved neutral beamline. The CsI calorimeter has been replaced with smaller and longer CsI crystals from the Fermilab KTeV experiment, to suppress backgrounds, and the data acquisition system is being upgraded. An engineering run and first physics running are planned for 2012. Running with 100 kW beam power will not take place before 2014; subsequently annual runs of approximately four months duration are expected. To achieve sufficient sensitivity to observe a few events at the SM branching fraction, it will be necessary for KOTO to run for several years.

TREK

The TREK experiment [41] will run at J-PARC. The primary goal of TREK is a search for T-violation in the decay $K^+ \to \pi^0 \mu^+ \nu$ via observation of muon polarization in the direction transverse to the $\pi-\mu$ decay plane with 20 times better precision than the prior best limit ($|P_T| < 0.005$) [42], which is from KEK-PS experiment E-246. TREK will use the E-246 spectrometer after both detector and data acquisition upgrades. The experiment will use stopped-K^+'s (i.e., a low-energy K^+ beam enters the detector and a fraction of the K^+'s are brought to rest via dE/dx at the center of the detector in a scintillating fiber target). Charged decay products of the K^+ are subsequently detected in a toroidal spectrometer, combined with a calorimeter with large solid angle to detect photons. Muons from $K^+ \to \pi^0 \mu^+ \nu$ stop inside a muon polarimeter, which detects the direction of the positron in the $\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$.

The TREK design calls for a beam power of 270 kW for 30 GeV protons, which will not be available for several years. Other measurements are possible with less beam. The ratio of decay rates $R_K = \Gamma(K^+ \to e^+\nu)/\Gamma(K^+ \to \mu^+\nu)$ tests lepton-flavor universality. The SM ratio depends only on kinematics (i.e., masses) and small radiative corrections. The current world average result for R_K (from NA62 and KLOE) agrees with the SM expectation with an uncertainty of 0.4%. TREK expects to improve this comparison to the 0.2% level. TREK also has the ability to search for a heavy sterile neutrino (N) in the decay $K^+ \to \mu^+ N$ down to a branching ratio 10^{-8}.

TREK requires slow extraction from J-PARC and is expected to begin data-taking in 2014 with beam power of 50 kW, which is adequate for the R_K measurement and the heavy neutrino search.

ORKA

The $K^+ \to \pi^+\nu\overline{\nu}$ decay has only been observed so far in Brookhaven experiments E787 and E949, which used stopped K^+'s. E949 was an upgrade of E787. These experiments ran at the AGS in several short runs between 1988 and 2002 (usually 10 to 16 weeks of running in a given year, which was typical of AGS operations). Ultimately these experiments observed seven signal events [33] (with background 0.93 ± 0.17 events). In the end E949 did not reach its goal, since it was terminated early due to lack of funding. Nonetheless, E949 demonstrated background rejection at the 2×10^{-11} level, which is sufficient for a high-statistics measurement of $\mathcal{B}(K^+ \to \pi^+\nu\overline{\nu})$.

The ORKA experiment [43] at Fermilab would apply the same technique demonstrated in E787/E949, while taking advantage of the longer running time per year and the higher beam flux possible with the Main Injector and also large acceptance gains which are possible using updated detector technologies and modern data acquisition systems. The ORKA detector will be a completely modernized version of the original E949 detector and will benefit from several improvements. These include increasing the length of the detector to increase geometrical acceptance, a larger magnetic field to improve tracking resolution, new and improved range stack scintillator with higher light yields, a thicker photon veto system to improve photon detection efficiency, deadtimeless electronics, and a modern high-throughput data acquisition system. Estimates of ORKA's sensitivity are based on extrapolations from E949's measured performance, rather than simulations. Background rejection does not need to be better than in E949 for ORKA to reach its goal.

The ORKA proposal received Stage I approval at Fermilab in December 2011. The time scale for receiving final approval is not yet known. If approved and funded soon, it should be possible to complete detector construction and begin first data-taking by the end of 2016. The projected sensitivity would allow ORKA to collect about 200 $K^+ \to \pi^+\nu\overline{\nu}$ events per year (at the SM level), enabling a branching fraction measurement with 5% uncertainty after five years of running. This would be a strong test for new physics, since the theory uncertainty in the SM branching fraction will be at the same level of uncertainty.

Opportunities with Project X

Project X at Fermilab [44] could provide extremely high intensity kaon beams with a very well controlled time-structure. The beam power available to produce kaons (1500 kW) will be higher by an order of magnitude than any other kaon source in the world. Since the proton kinetic energy would be around 3 GeV, the kaon energy will be low. While this may not be well-matched to all experiments, for some it will be nearly optimal [45]. In particular, Project X provides the most promising opportunity advanced so far to make a high-statistics measurement of the $K^0_L \to \pi^0\nu\overline{\nu}$ branching fraction.

A challenge for $K^0_L \to \pi^0\nu\overline{\nu}$ is the unknown momentum of the incident K^0_L. As discussed in the context of KOTO, some compensation for this can be achieved by limiting the beam aperture so that at least the K^0_L direction of flight is known to good precision. In addition to this, the precisely controlled beam pulses which can be delivered by a CW-linac make it possible to measure the K^0_L momentum using time-of-flight information. The 500 MeV K^0_L's typical of Project X energies are ideal for this measurement. This provides a strong kinematic constraint which significantly improves background rejection while maintaining larger acceptance than the pure pencil-beam technique. Initial estimates indicate that it may be possible to collect as many as 200 $K^0_L \to \pi^0\nu\overline{\nu}$ events per year in a Project X experiment, making possible a measurement at the 5% level after about five years of data taking.

The existence of Project X will surely stimulate initiatives focusing on other rare modes, such as the lepton-flavor violating decays $K^0_L \to \mu e$ and $K^+ \to \pi^+\mu e$. Several rare K decay measurements would be possible, some involving subtle effects, such as interference measurements vs proper time of K^0_L and K^0_S decaying into a common $\pi^0 e^+ e^-$ final state. Such interference measurements can possibly isolate the directly CP-violating component of the decay amplitude and provide complementary handles to interpret new physics which may be observed in $K^0_L \to \pi^0 \nu\overline{\nu}$ decays. The unprecedented intensity of a stopped K^+ beam from Project X can be exploited to extend the TREK research program now at J-PARC to a sensitivity limited by theoretical uncertainties. This ultra-bright stopped K^+ source can also enable other precision measurements sensitive to new physics, such as anomalous polarization of muons in $K^+ \to \pi^+ \mu^+ \mu^-$ decays and more precise studies of $K^+ \to \pi^+ \nu\overline{\nu}$ decays, including the measurement of the π^+ spectrum which can be used to test the underlying matrix element.

Exploiting the opportunities provided by Project X will also require detector improvements, so that R&D is needed. Some areas of importance are: ultra-low-mass tracking detectors which can operate at high rates and in vacuum; fine-grained fast scintillator-based shower counters read out with high quantum efficiency photodetectors that can operate in high magnetic fields and in vacuum; large-scale system time-of-flight resolution better than 20 ps; high-rate γ-pointing calorimetry; and fully streaming “triggerless” data-acquisition technologies.

1.3.2 *B*-meson Experiments

Super Flavor Factories

When Kobayashi and Maskawa shared the Nobel Prize in 2008 for “the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature,” it was widely acknowledged that the B-factory experiments — *BABAR* at SLAC and Belle at KEK — had provided the essential experimental confirmation. The spectacular successes of the B-factories KEKB and PEP-II rested on two important features of these accelerators: unprecedented high luminosities which allowed the experiments to collect data samples on the $\Upsilon(4S)$ resonance consisting of several hundred million $B\overline{B}$ pairs, and asymmetric beam energies which made it possible to measure rate asymmetries in B and $\overline{B}$ decays as a function of the proper decay time difference. In addition, e^+e^- collisions provide a relatively clean environment so that complex final states can be reconstructed (including those with several daughters, π^0’s, K^0_L’s, and even ν’s), thereby enabling a broad program of measurements.

KEKB achieved peak luminosity of $2.1 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and an integrated luminosity of $1040\,\mathrm{fb}^{-1}$ (i.e., just over $1.0\,\mathrm{ab}^{-1}$). PEP-II achieved a peak of $1.2 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and integral of $550\,\mathrm{fb}^{-1}$, before its running was terminated early due to a funding crisis in the U.S. in 2008. Achieving these high luminosities required accelerator advances in a number of areas, including very high-current stored beams ($> 3\,\mathrm{A}$), very large numbers of bunches (> 1000), bunch-by-bunch feedback systems, high-power RF systems, and operational advances such as continuous injection; KEKB also enhanced its luminosity by using crab cavities to achieve head-on collisions.

Innovations in the last few years, in part resulting from linear collider studies and light source development, make it possible to achieve instantaneous luminosity close to $1 \times 10^{36}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. This has led to plans for “super flavor factories”. SuperKEKB will be built as an upgrade to KEKB in Japan. The new Italian Cabibbo Laboratory, located near Frascati, will host a green field project to build the Super$B$ collider. These machines will achieve dramatic luminosity gains by making the beams very small at the collision point and, in the case of Super$B$, by implementing a crab waist crossing. Beam currents will be higher than in the B factories, but only by a factor of about two so that beam-associated backgrounds will not follow the gains in luminosity. These machines will collect data-sets of 50–75 ab^{-1}. The cross section on the $\Upsilon(4S)$ is 1.1 nb,

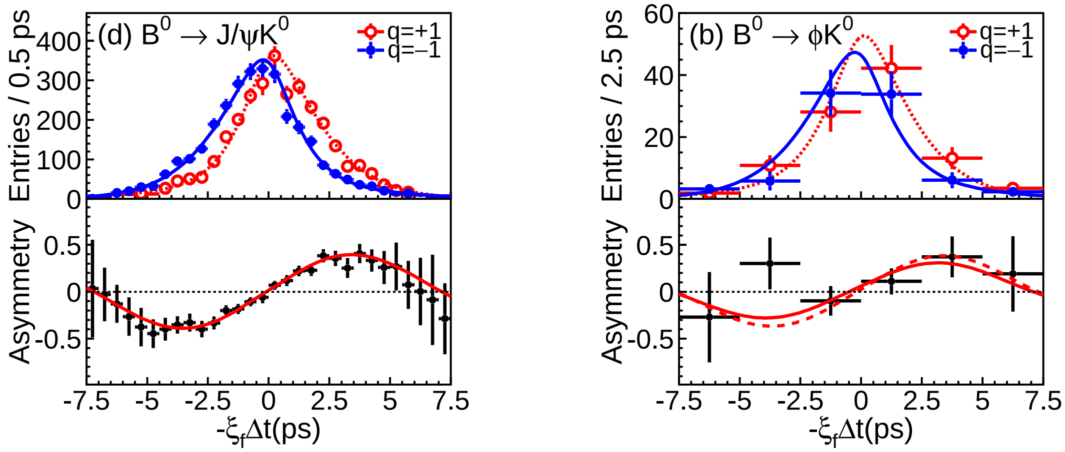

Figure 1-3. *Belle measurements [48] of the time-dependent CP asymmetry versus Δt for $B \to J/\psi K^0$ (left) and $B \to \phi K^0$ (right). $\sin(2\beta)$ is determined from the amplitude of the oscillations evident in the lower plots. Super flavor factory experiments will obtain statistics for $B \to \phi K^0$ (and other loop-dominated modes) as good as was obtained for $B \to J/\psi K^0$ in Belle and BABAR.*

so the super flavor factory experiments will have access to over 5×10^{10} $B\overline{B}$ pairs. This will open the door to precise measurements of a large number of processes which have the potential to reveal new physics.

Physics Reach of Super Flavor Factories

Complete discussions of the physics programs of the super flavor factory experiments exist [46, 47]. Only a few highlights are discussed here.

One strength of the super flavor factory experiments will be their ability to search for non-SM sources of CP violation. The $B\overline{B}$ pairs produced at the $\Upsilon(4S)$ are in a coherent quantum state, which allows the decay of one B to tag the state of the other. Since B^0 and $\overline{B}^0$ may decay to the same CP eigenstate, the difference of B^0 and $\overline{B}^0$ decay rates to a common final state is an observable for CP violation. When measured versus time, the decay rate asymmetry is sensitive to CP violation that occurs in the interference between two amplitudes — those for $B^0 \to f_{\rm CP}$ and $B^0 \to \overline{B}^0 \to f_{\rm CP}$, where $f_{\rm CP}$ is the CP eigenstate and in the second instance the B^0 "oscillates" into $\overline{B}^0$ before decaying. This interference provides direct access to underlying CKM parameters, since the decay rate asymmetry versus time is a simple sine function whose amplitude is $\sin(2\beta)$, or equivalently $\sin(2\phi_1)$ in the notation favored in Japan. The precision measurement of $\sin(2\beta)$ is one of the keystone achievements of the B-factory experiments; $\sin(2\beta) = 0.678 \pm 0.020$ is the average [23] of Belle and BABAR from decay modes resulting from the quark level process $b \to c\bar{c}s$, such as $B^0 \to J/\psi K^0$. Since the $b \to c\bar{c}s$ decay is dominantly tree level, this is effectively the SM value of $\sin(2\beta)$. However, an analogous $\sin(2\beta)$ measurement can be made using $b \to s\bar{s}s$ decays, such as $B^0 \to \phi K^0$ and $B^0 \to \eta' K^0$, which only occur through loops (i.e., penguin diagrams). Loop processes open the door to additional amplitudes (and complex phases) from new heavy particles. Comparison of such measurements from BABAR and Belle to the $b \to c\bar{c}s$ value is statistically limited and inconclusive, as illustrated in Figure 1-3. Belle and BABAR averages [23] for $\sin(2\beta)$ from $B^0 \to \phi K^0$ and $B^0 \to \eta' K^0$ are 0.56 ± 0.17 and 0.59 ± 0.07, respectively. The super flavor factory experiments can reduce the errors on these measurements by an order of magnitude.

Dramatically improved tests for direct CP violation in numerous modes will also be possible at the super flavor factories. One example is $B \to X_{s+d}\gamma$, which results from electromagnetic penguin diagrams for the quark level processes $b \to s\gamma$ and $b \to d\gamma$; X_{s+d} represents the hadronic system in these decays. In a fully inclusive measurement (i.e., one that detects the γ but does not reconstruct the hadronic system in order to avoid losing complicated final states), the net flavor of the X_{s+d} is not determined. In the standard model there is a robust expectation that direct CP violation is negligible; that is, the decay rate for $B \to X_{s+d}\gamma$ equals that for $\overline{B} \to X_{s+d}\gamma$ to a very good approximation. Any detected difference must be an indication of new physics, and differences of up to 10% appear in some non-SM scenarios. The best measurement with existing B-factory data is consistent with no difference and has a 6% error. Super flavor factory experiments can reduce the error to below 1%.

Many rare B decays which have either not been observed by Belle or *BABAR*, or which have been observed with only marginal statistics, will become accessible in super flavor factor experiments. An example is $B \to \tau\nu$, which in the SM results from a simple W-exchange diagram and has branching fraction of $(1.1 \pm 0.2) \times 10^{-4}$. This mode is sensitive to supersymmetric models or others that predict the existence of a charged Higgs. The current average branching fraction from *BABAR* and Belle is $(1.64 \pm 0.34) \times 10^{-4}$, in loose agreement with the SM expectation. Super flavor factory experiments can reduce the error to about 0.04×10^{-4}. This mode, which has multiple neutrinos in the final state, is a good example of the power of e^+e^- experiments for B physics. The technique of reconstructing the 'other' B in the event can be very effective in reducing backgrounds for modes in which the signal B is impossible to reconstruct.

Rare decay modes in which the underlying quark-level process is $b \to s\ell^+\ell^-$ or $b \to d\ell^+\ell^-$ (where ℓ represents e or μ) provide excellent sensitivity to new physics because they occur through loop diagrams; the former have branching fractions of order 10^{-6} and the latter of order 10^{-8}. Some of these modes, such as $B^0 \to K^{*0}\mu^+\mu^-$, can be collected in very large numbers in hadronic production experiments, making a good measurement of the lepton forward-backward asymmetry $A_{\rm FB}$ possible. However, a full exploration of these decays can only be accomplished in the e^+e^- environment. Examples of important measurements at which the super flavor factories will excel include the *inclusive* decay rates versus dilepton mass, comparisons of e^+e^- modes to $\mu^+\mu^-$ as tests of universality, and searches for CP violation in these decays.

The processes discussed above provide only a glimpse of the rich menu of incisive measurements that will be made by the super flavor factory experiments from running on the $\Upsilon(4S)$. By running on the $\Upsilon(5S)$, the super flavor factories also will have access to B_s physics. This may be important if LHCb makes a measurement that is inconsistent with the SM; that is, experimental confirmation of important B_s results may be needed. Also, some interesting B_s measurements will not be possible in the hadronic environment, such as $B_s \to \gamma\gamma$ or other decays with neutral particles or neutrinos in the final state.

Belle II at SuperKEKB

The SuperKEKB project [49] in Japan is under construction. Commissioning of the accelerator is expected to begin in 2014. The design luminosity is $8 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (40 times larger than KEKB), which will allow an integrated luminosity of $50\,\mathrm{ab}^{-1}$ to be accumulated in five years of running.

The Belle II detector will be an upgraded version of Belle that can handle the increased backgrounds associated with higher luminosity. The inner vertex detector will employ DEPleted Field Effect (DEPFET) pixels, inside tracking layers that will consist of double-sided silicon strips with high-speed readout. There will also be a new small-cell drift chamber. The particle identification system will be a ring-imaging Cherenkov (DIRC-type) detector. The CsI calorimeter will be retained, but it will be instrumented with waveform sampling readout. The outer K_L^0/μ detector will be upgraded to use scintillator to accommodate the higher rates. Belle II should be ready to roll in by the end of 2015, after commissioning of SuperKEKB is completed. The U.S. groups on Belle II are focusing their efforts on the particle identification and K_L^0/μ systems.

Observable	SM Theory	Current Expt.	Super Flavor Factories
$S(B \to \phi K^0)$	0.68	0.56 ± 0.17	± 0.03
$S(B \to \eta' K^0)$	0.68	0.59 ± 0.07	± 0.02
γ from $B \to DK$		$\pm 11^\circ$	$\pm 1.5^\circ$
A_{SL}	-5×10^{-4}	-0.0049 ± 0.0038	± 0.001
$S(B \to K_S \pi^0 \gamma)$	< 0.05	-0.15 ± 0.20	± 0.03
$S(B \to \rho\gamma)$	< 0.05	-0.83 ± 0.65	± 0.15
$A_{\mathrm{CP}}(B \to X_{s+d}\gamma)$	< 0.005	0.06 ± 0.06	± 0.02
$\mathcal{B}(B \to \tau\nu)$	1.1×10^{-4}	$(1.64 \pm 0.34) \times 10^{-4}$	$\pm 0.05 \times 10^{-4}$
$\mathcal{B}(B \to \mu\nu)$	4.7×10^{-7}	$< 1.0 \times 10^{-6}$	$\pm 0.2 \times 10^{-7}$
$\mathcal{B}(B \to X_s\gamma)$	3.15×10^{-4}	$(3.55 \pm 0.26) \times 10^{-4}$	$\pm 0.13 \times 10^{-4}$
$\mathcal{B}(B \to X_s\ell^+\ell^-)$	1.6×10^{-6}	$(3.66 \pm 0.77) \times 10^{-6}$	$\pm 0.10 \times 10^{-6}$
$\mathcal{B}(B \to K\nu\overline{\nu})$	3.6×10^{-6}	$< 1.3 \times 10^{-5}$	$\pm 1 \times 10^{-6}$
$A_{\mathrm{FB}}(B \to K^*\ell^+\ell^-)_{q^2<4.3\,\mathrm{GeV}^2}$	-0.09	0.27 ± 0.14	± 0.04

Table 1-3. *A summary of the reach of the planned super flavor factory experiments for some key B decay measurements, in comparison to standard model theory and the current best experimental results. Normally Belle II assumes* $50\,\mathrm{ab}^{-1}$ *for such comparisons, while SuperB assumes* $75\,\mathrm{ab}^{-1}$*. For this table,* $50\,\mathrm{ab}^{-1}$ *has been assumed.*

Super*B* in Italy

The Super*B* project [50] has been approved by the Italian government and will be sited at the new Cabibbo Laboratory, which is at the University of Rome Tor Vergata near Frascati. The design luminosity will be $1 \times 10^{36}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. It is hoped to begin commissioning in 2016.

The Super*B* detector is based on the *BaBar* detector, and large parts of *BaBar* will be re-used: the superconducting coil and steel flux return, the quartz bars from the DIRC, and the barrel CsI crystals. New tracking detectors will be build, including a silicon strip vertex detector whose inner layer (very close to the beam) will initially be silicon striplets, which will be upgraded to pixels for high-luminosity running after the first few years, and a new central drift chamber. The DIRC readout will utilize faster photodetectors, and the CsI barrel calorimeter will be augmented by a forward calorimeter using LYSO crystals which are much faster and more radiation hard than CsI. The flux return will be augmented with additional absorber to improve the muon identification.

While large U.S. contributions to Super*B* are planned in the form of PEP-II components and *BaBar* components, the status of U.S. physicist participation is currently unsettled.

B Physics at Hadron Colliders

Hadron colliders have great potential for studying the decays of particles containing charmed and bottom quarks. The production cross sections are quite large and the machine luminosities are very high so that more than 10 kHz of b-hadrons can be produced per second. This is a much higher production rate than can be achieved even in the next generation e^+e^- B factories. All species of b-flavored hadrons, including B_s, B_c, and b baryons are produced. However, compared to e^+e^- b and charm factories, the environment is much more harsh for experiments. At hadron colliders, the b quarks are accompanied by a very high rate of background events; they are produced over a very large range of momenta and angles; and even in b-events of interest there is a complicated underlying event. The overall energy of the center of mass of the hard scatter that produces the b quark, which is usually from the collision of a gluon from each beam particle, is not known so that the overall energy constraint that is so useful in e^+e^- colliders is not available. These features translate into difficult challenges in triggering, flavor tagging, and particle identification, and limit the overall efficiency and background rejection that can be achieved.

The CDF and DØ experiments at the Fermilab Tevatron demonstrated that these problems could be successfully addressed using precision silicon vertex detectors and specialized triggers. While these experiments were mainly designed for high-p_T physics, they nevertheless made major contributions to bottom and charm physics [51, 52]. Highlights of their B-physics program include the first measurement of B_s mixing [53]; possible deviations from the SM predictions for the asymmetry between $\mu^+\mu^+$ and $\mu^-\mu^-$ from the semileptonic decays of B mesons from the DØ experiment [54]; observation of many B_s and b-baryon decay modes and measurement of the B_s and Λ_b lifetimes; bottomonium spectroscopy; and the first observation of the B_c meson and the measurement of its lifetime [55, 56].

The LHC produced its first collisions at 7 TeV center of mass energy at the end of March 2010. The b cross section at the LHC is a few hundred μb, a factor of three higher than at the Tevatron, and approximately, 0.5% of the inelastic cross section. When the LHC reaches its design center of mass energy of 14 TeV in 2015, the cross section will be a factor of two higher.

B Physics at LHCb

The LHC program features for the first time at a hadron collider a dedicated B-physics experiment, LHCb [57]. LHCb covers the forward direction from about 10 mr to 300 mr with respect to the beam line. B hadrons in the forward direction are produced by collisions of gluons of unequal energy so that the center of mass of the collision is Lorentz boosted in the direction of the detector. Because of this, the b-hadrons and their decay products are produced at small angles with respect to the beam and have momenta ranging from a few GeV/c to over a hundred GeV/c. Because of the Lorentz boost, even though the angular range of LHCb is small, its coverage in pseudorapidity is from about 2 to about 5 and both b hadrons travel in the same direction, making b flavor tagging possible. With the small angular coverage, LHCb can stretch out over a long distance along the beam without becoming too large transversely. A silicon microstrip vertex detector (VELO) only 8 mm from the beam provides precision tracking that enables LHCb to separate weakly decaying particles from particles produced at the interaction vertex. This allows the measurement of lifetimes and oscillations due to flavor mixing. A 4 Tm dipole magnet downstream of the collision region, in combination with the VELO, large area silicon strips (TT) placed downstream of the VELO but upstream of the dipole, and a combination of silicon strips (IT) and straw tube chambers (OT) downstream of the dipole provides a magnetic spectrometer with excellent mass resolution. There are two Ring Imaging Cherenkov counters, one upstream of the dipole and one downstream, that together provide K–π separation from 2 to 100 GeV/c. An electromagnetic calorimeter (ECAL) follows the tracking system and provides electron triggering and π^0 and γ reconstruction. This is followed by a hadron calorimeter (HCAL) for triggering on hadronic final states. A muon detector at the end of the system provide muon triggering and identification.

LHCb has a very sophisticated trigger system that uses hardware at the lowest level (L0) to process the signals from the ECAL, HCAL and muon systems. The L0 trigger reduces the rate to $\sim$1 MHz followed by the High Level Trigger (HLT), a large computer cluster, that reduces the rate to $\sim$3 kHz for archiving to tape for physics analysis. LHCb is able to run at a luminosity of 4.0×10^{32} cm^{-2}s^{-1}. This is about 10% of the current peak luminosity achieved by the LHC and is about 3% of the LHC design luminosity. The luminosity that LHCb can take efficiently is currently limited by the 1 MHz bandwidth between the Level 0 trigger system and the trigger cluster. Therefore, the physics reach of LHCb is determined by the detector capabilities and not by the machine luminosity. In fact, the LHC implemented a "luminosity levelling" scheme in the LHCb collision region so that LHCb could run at its desired luminosity throughout the store while the other experiments, CMS and ATLAS, could run at higher luminosities. This mode of running will continue until 2017 when a major upgrade of the LHCb trigger and parts of the detector and front end electronics will increase the bandwidth to the HLT and permit operation at a factor of 10 higher luminosity.

There have been two runs of the LHC. In the first "pilot" run in 2010, LHCb recorded 35 pb^{-1}, which was enough to allow it to surpass in precision many existing measurements of B decays. In 2011, the LHC delivered more than 5 fb^{-1} to CMS and ATLAS. Since this luminosity was more than LHCb was designed to handle, the experiment ran at a maximum luminosity that was 10% of the LHC peak luminosity. The total integrated luminosity was about 1 fb^{-1}.

The decay $B_s \to J/\psi\phi$ has been used to measure the CKM angle $\phi_s = -2\beta_s$ [20]. The result, using also the decay mode $B_s \to J/\psi f_0$ first established by LHCb [58], is $\phi_s = 0.07 \pm 0.17 \pm 0.06$ rad [59]. The difference in the width of the CP-even and CP-odd B_s mesons is $\Delta\Gamma_s = (0.123 \pm 0.029 \pm 0.008)$ ps^{-1}. These results are consistent with the SM, resolving a slight tension with earlier measurements from the Tevatron [60], which deviated somewhat from the SM predictions.

The rare decay $B_s \to \mu^+\mu^-$ is predicted in the SM to have a branching fraction that is 3×10^{-9}. A higher branching fraction would be an indicator for new physics beyond the SM. LHCb has now produced the best limit on this decay mode. While the current upper limit is now approaching the SM value, there is still room for a substantial contribution from new physics. CMS is also a contributor to this topic. The overall experimental situation and the combined limit [61, 62, 63] from LHCb and CMS is shown in Fig. 1-4. For the LHC experiments, this represents about 1/4–1/3 of the data already taken. Updated results are expected from both experiments soon using the full 2011 data sets. This measurement will continue and if no new physics appears, the SM value will be observed some time between 2015 and 2017, based on the current LHC midterm schedule and luminosity projections.

LHCb has also produced results on the key decay $B^0 \to K^{*0}\mu^+\mu^-$ [64] that could reveal evidence for new physics. The forward-backward asymmetry of the μ^- relative to the direction of the parent B^0 meson in the dimuon center of mass vs the q^2 (dimuon invariant mass) is shown in Fig. 1-5. The SM prediction crosses over through zero in a narrow range of q^2 due to the interference between the SM box and electroweak pengin diagrams. New physics can remove the crossover or displace its location. Indications from low statistics at Belle, *BABAR*, and CDF seemed to indicate that this might be happening. The new LHCb results are the most precise so far and are in good agreement with the SM.

Many other decays are being studied, including all hadronic decays such as $B_s \to \phi\phi$, $B \to D\pi$, $B \to DK$, and states with photons such as $B_s \to \phi\gamma$.

LHCb will run at a luminosity of 4.0 $\times10^{32}\text{cm}^{-2}\text{s}^{-1}$ for several years, limited by the bandwidth between the Level 0 trigger and the HLT. A substantial upgrade [65] that will enable LHCb to run at much higher rates is being developed. It will be installed in a long shutdown planned for the LHC in 2018. Between now and then, LHCb will accumulate about 1 fb^{-1} per operating year so a total of about 5 fb^{-1} will be obtained. The sensitivity will increase by more than this because the LHC will run for at least 3 years of this period at 14 TeV, with a correspondingly higher B cross section. After the upgrade is installed, LHCb will integrate about 5 fb^{-1} per year so that about 50 fb^{-1} will be obtained over the decade following 2018. The expected senstivity to selected important decays during each phase of LHCb running is shown in Table 1-4.

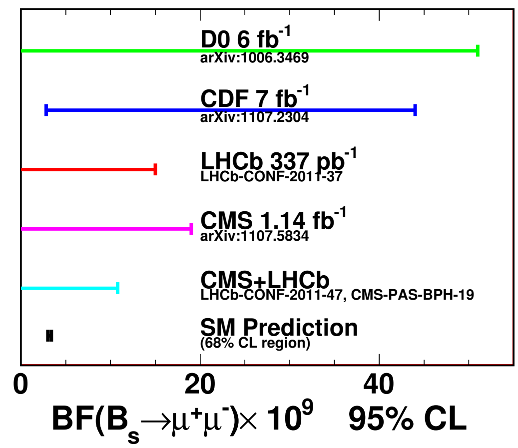

Figure 1-4. *The 95% confidence level upper limits on the $B_s \to \mu^+\mu^-$ branching fraction from CDF, DØ, LHCb, CMS, and the combined value from LHCb and CMS. The SM prediction for this decay is also shown. The integrated luminosity used in each measurement is shown. All four experiments are analyzing additional data.*

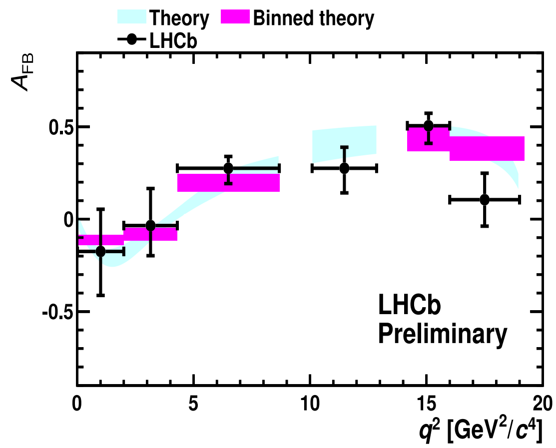

Figure 1-5. *A_{FB} for $B^0 \to K^{*0}\mu^+\mu^-$ as a function of the dimuon mass, q^2. The SM prediction is given by the cyan (light) band, and this prediction rate-averaged across the q^2 bins is indicated by the purple (dark) regions. No SM model predictions are shown in the two mass regions dominated by J/ψ and ψ' dimuon decays.*

B Physics at CMS and ATLAS

Two detectors, CMS and ATLAS, are designed to explore high mass and high-p_T phenomena to look for new physics at the LHC. They must operate at luminosities of up to $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which implies the need to handle an average event pileup of $\sim$20. This demands that the detectors cover a large area with very high granularity. They both have tracking coverage up to $|\eta| = 2.5$ and have silicon pixel detectors capable of separating B-decays from the main interaction vertex. The detectors also have other features that are needed to do B physics, including precise mass reconstruction, electron, photon, and muon identification, and sophisticated triggering capability. However, they lack some important characteristics that are necessary to carry out a broad program of B physics. They have only limited charged hadron identification. In addition, as general-purpose detectors they must operate in high-luminosity conditions with trigger configurations that are more oriented to high transverse momentum events. Consequently, they have only limited ability to trigger on low-p_T B hadrons, which comprise most of the B cross section.

Both experiments can implement muon triggers with relatively low thresholds of a few GeV/c. However, the rate of low-p_T muons from B decays competes for scarce resources with the many other trigger signatures that could contain direct evidence of new physics. The high muon rate at all levels of the trigger system in the LHC environment must be controlled as the luminosity increases, by requiring double muon signatures for low p_T muons, raising thresholds, applying invariant mass and lifetime cuts in high level triggers, restricting signatures to certain regions of the detector and as a last resort, prescaling. These measures limit the ability to collect large statistics of certain B-decays and means that those which are collected have a higher transverse momentum overall than those collected by LHCb.

On the other hand, both experiments can successfully record certain b decays with reasonable efficiency. These typically involve final states that contain dimuons. One example of this, discussed above, is the rare decay $B_{d,s} \to \mu^+\mu^-$, where CMS and ATLAS can be competitive, because of clever triggering and because they can compensate for lower efficiency as they can run at more than an order of magnitude

Observable	Precision as of 2011	LHCb ($5\ \mathrm{fb}^{-1}$)	Upgrade ($50\ \mathrm{fb}^{-1}$)
$\phi_s(B_s \to J/\psi\phi)$	0.16	0.019	0.006
$S(B_s \to \phi\phi)$	—	0.08	0.02
$S(B_s \to K^{*0}\bar{K}^{*0})$	—	0.07	0.02
$\beta(B^0 \to J/\psi K^0)$	1°	0.5°	0.2°
$S(B^0 \to \phi K^0_S)$	0.17	0.15	0.03
$\gamma(B \to D^{(*)}K^{(*)})$	$\sim 20^\circ$	$\sim 4^\circ$	0.9°
$\gamma(B \to D_s K)$	—	$\sim 7^\circ$	1.5°
$B(B_s \to \mu^+\mu^-)$	—	30%	8%
$B(B^0 \to \mu^+\mu^-)/B(B_s \to \mu^+\mu^-)$	—	—	~35%
$S(B_s \to \phi\gamma)$	—	0.07	0.02
$A^{\Delta\Gamma_s}(B_s \to \phi\gamma)$	—	0.14	0.03
$A_T^2(B^0 \to K^{*0}\mu^+\mu^-)$	—	0.14	0.04
$s_0 A_{FB}(B^0 \to K^{*0}\mu^+\mu^-)$	—	4%	1%

Table 1-4. *Sensitivity of LHCb to key observables. The current sensitivity is compared to that expected after 5 fb^{-1} and that achievable with 50 fb^{-1} by the upgraded experiment, all assuming $\sqrt{s} = 14$ TeV. Note that at the upgraded LHCb, the yield in fb^{-1} in hadronic B and D decays will be higher on account of the software trigger. (Adapted from Table 2-1, p13, of reference [65].)*

higher luminosity than LHCb. If ATLAS and CMS can maintain their triggering efficiency as the LHC luminosity and eventually its energy increase, they can continue to be competitive in this study. The decay $B^0 \to K^*\mu^+\mu^-$ presents more problems. The muons are softer and more difficult to trigger on and the limited K–π separation increases the background to the K^*. It is still hoped that these two experiments can play a oncfirming role to LHCb in this study. Despite their limitations, these two experiments will collect large numbers of b-decays and should be able to observe many new decay modes and perhaps new particles containing b and charmed quarks [66, 67].

1.3.3 Charm Experiments

In the SM, many charm decay modes involving loop diagrams are suppressed. Therefore, CP violating and rare decays of charmed particles are promising places to look for new physics since new phenomena could make observable contributions to such decays. In the future, information on charm decays will come from:

- BES [68], an e^+e^- collider dedicated to the study of systems containing charmed quarks;
- The two super flavor factories; and
- LHCb, the dedicated heavy quark experiment at the LHC, which is described above, with perhaps some additional results in a few favorable decay modes from CMS and ATLAS.

A fourth source of information on charm could come from fixed target experiments, of which the only currently approved example is PANDA [69] at the FAIR facility at Darmstadt, which will collide antiprotons in a storage ring with gas, solid, or liquid targets. The ability of that experiment to contribute will depend on the cross section for charm production by low energy antiprotons, a quantity that has not been measured and whose theoretical estimates vary from 1μb to 10μb, and the amount of time dedicated to the charm program, which competes with other aspects of the program that require the machine to operate below or close to the bare charm production threshold.

For the experiments, the challenge will be to observe small effects. For theory, the task will be to pin down the size of the long range contributions so that observations can be correctly identified as new physics or conventional physics.

Charm Physics at Charm Factories

The BES program carried out a major upgrade to a two-ring machine optimized for running at center of mass energies of 3–4 GeV. The accelerator/storage ring, now called BEPCII, is designed for a peak luminosity of $1{\times}10^{33}$ cm^{-2}s^{-1}. An all new and improved detector, BESIII [70], has been built to exploit the opportunity afforded by the higher luminosity. The upgraded machine began to run in July of 2008 and has achieved so far about 2/3 of the design luminosity. BESIII has now collected data at the center of mass energy of significant $c\overline{c}$ resonances, including the ψ', the J/ψ, the $\psi(3770)$, and also at center of mass energy of 4010 MeV (0.3 nb of $D_s^+D_s^-$). BESIII has now integrated about 3.5 times more data than CLEO-c on the $\psi(3770)$. By studying charm particle properties on the $\psi(3770)$ resonance which is very near D–$\overline{D}$ threshold, BESIII has large and relatively clean source of D mesons with tightly constrained kinematics. This provides powerful flavor tagging capability, unique access to leptonic and semileptonic decay modes, and enables the study of decays that include neutrinos. The two D mesons are produced in the CP-odd state. This quantum correlation can be used to study CP violation and strong phases and will extend the work carried out by CLEO-c. BESIII also collected 400 pb^{-1} in 2011 at 4010 MeV and in 2013 will take data at 4170 MeV, which is above $D_s^*D_s$ threshold (0.9 nb cross section), and which has been previously studied by CLEO-c. These data, taken all together, will represent a significant advance in our understanding of the D_s meson.

With these exposures, BESIII could well be the leader in the use of the charm system as a QCD laboratory. BESIII should excel in the measurements of leptonic and semileptonic D and D_s decays. These determine $|V_{cd}|$ and $|V_{cs}|$ (without assuming CKM unitarity) when combined with lattice-QCD calculations, and can also check lattice QCD with high precision, so that similar calculations can be trusted when applied to the B system, to extract CKM matrix elements and look for BSM physics. These results, many of them from data already in hand, should precede by a few years any data that could come from a super flavor factory running on a boosted $\psi(3770)$, as discussed below.

Charm Physics at e^+e^- super flavor factories

The major effort at the upgraded B factories, SuperKEKB and Super$B$, is to learn about new physics by carrying out precision measurements of mixing and CP violation and searching for rare decays of B_d and B_u mesons, primarily by running on the Υ(4S). However, massive statistics on charm decays will be gathered from the charm meson and baryon daughters of the B decays as well as direct charm production from the continuum background under the resonance. Most of the charm sensitivity will be obtained from this mode of running.

A new possibility is being studied by Super$B$. They are considering a run of 1 ab^{-1} on the $\psi(3770)$. The energies of the two rings will be chosen so that $\beta\gamma$ is between 0.24 and 0.6. This choice provides good acceptance and precision measurements of the time dependence of the decays. The results will occur after the BES results but will exceed them by a factor of 100 in integrated luminosity. For Super$B$ this might make sense in the early phase of running when the luminosity is still low. This would allow them to carry out

Observable	Current Expt.	LHCb ($5\ \mathrm{fb}^{-1}$)	Super Flavor Factories ($50\ \mathrm{ab}^{-1}$)	LHCb Upgrade ($50\ \mathrm{fb}^{-1}$)
x	$(0.63 \pm 0.20)\%$	$\pm 0.06\%$	$\pm 0.02\%$	$\pm 0.02\%$
y	$(0.75 \pm 0.12)\%$	$\pm 0.03\%$	$\pm 0.01\%$	$\pm 0.01\%$
y_{CP}	$(1.11 \pm 0.22)\%$	$\pm 0.02\%$	$\pm 0.03\%$	$\pm 0.01\%$
$\lvert q/p \rvert$	0.91 ± 0.17	± 0.085	± 0.03	± 0.03
$\arg(q/p)$	$(-10.2 \pm 9.2)^\circ$	$\pm 4.4^\circ$	$\pm 1.4^\circ$	$\pm 2.0^\circ$

Table 1-5. *Sensitivities of super flavor factories and LHCb to charm mixing related parameters, along with the current results for these measurements (here $\arg(q/p)$ means $\arg \lambda_{K^+K^-}$). The second column gives the 2011 world averages. The remaining columns give the expected accuracy at the indicated integrated luminosities. For this table, $50\,\mathrm{ab}^{-1}$ has been assumed for super flavor factory experiments (usually SuperB assumes $75\,\mathrm{ab}^{-1}$, while Belle II assumes $50\,\mathrm{ab}^{-1}$). (Adapted from Table 1, p13, of reference [71].)*

charm studies that take advantage of the production at threshold and quantum coherence with the added advantage that they would be able to study the time dependence of the decays.

Charm Physics at the LHC

LHCb, the dedicated B physics experiment at the LHC, also has significant capability to study charm decays. The B decays recorded by LHCb are themselves a copious source of charmed particles. Direct production of charm at the LHC is a few percent of the total cross section so the direct charm rate is enormous and actually has to be suppressed since it competes with B physics for precious resources such as output bandwidth between the Level 0 trigger and the higher level trigger. Even with this suppression, LHCb records a very high rate of directly produced charm. LHCb should be a leader in the spectroscopy and decay properties of charmed baryons and in the study of rare and lepton flavor and lepton number violating decays. It should be able to carry out a large number of detailed decay studies including Dalitz plot analyses and time-dependent Dalitz plot analyses. It does not have an overall energy constraint so the study of many decays that involve neutrinos in the final state will be difficult to do. LHCb's ability to do states with photons and π^0's efficiently is still to be demonstrated.

After LHCb is upgraded, with more events reaching the HLT, a much more targeted selection of events to record will be possible. This should benefit the LHCb charm program and permit it to improve or at least maintain its efficiency for charm as the luminosity of the LHC increases.

The basic CP-violating parameters in charm can be measured by LHCb and the super flavor factories. A summary of the sensitivity for these quantities is given in Table 1-5. These measurements may reveal new physics beyond the Standard Model and will help in discriminating among the various models of new physics that might be employed to explain results from the LHC.

1.3.4 Exotic States

Recently, there has been an explosion of new results on heavy meson spectroscopy. The *BABAR* and Belle experiments, in addition to advancing the field of bottomonium spectroscopy by observing the $b\bar{b}$ ground state η_b and other missing $b\bar{b}$ states, have observed 18 states in the mass range 3872 MeV to 4700 MeV. These so-called "XYZ" states do not easily fit into the expected spectrum of charmonium states. An example is the very narrow $X(3872)$, first observed by Belle, but confirmed by *BABAR*, CDF, DØ, and now also by CMS and LHCb. Many models have been proposed to explain this state, including that it may be a $\overline{D}^0 D^{*0}$ molecule.

In addition to searching for additional states, the experimental agenda includes the measurement of masses and widths, branching fractions, and quantum numbers of the observed states.

The super flavor factories study charmonium states in the decay of B mesons. They may also directly produce charmonium and bottomonium states that have 1^{--} quantum numbers. The e^+e^- charm factories can study 1^{--} charmonium resonances. The LHC experiments may produce charmonium states directly or observe them in B-meson decays. They can also study bottomonium states. The PANDA experiment at the new $\overline{p}$ facility, FAIR in Darmstadt, can study charmonium. The $\overline{p}$ experiments can produce charmonium states exclusively by annihilation or in association with other particles. In particular for narrow-width meson resonances that can be produced by annihilation in $p\overline{p}$ collisions at FAIR, the measurement of the mass and width ($\Gamma \simeq 50$ KeV) can be obtained very accurately from machine scans across the resonances.

These studies complement the ability of these experiments to probe high mass scales. They provide an opportunity to study one of nature's fundamental interactions, QCD, in a regime where it is poorly understood. A large community of both theorists and experimentalists are focused on these topics.

1.4 The Need for New Experiments and Facilities

Before looking forward, it provides useful context to briefly review some history. In the 1990's, the U.S. was the leader both on the Energy Frontier and in quark flavor-physics experiments at the Intensity Frontier. B physics was still dominated by the CLEO experiment for most of that decade. The most sensitive rare K decay experiments performed to date were then underway at the Brookhaven AGS, and direct CP violation in $K_L^0 \to \pi\pi$ decays was the focus of a fixed-target experiment using the Tevatron at Fermilab. Toward the end of that decade, the asymmetric e^+e^- B factories began running at SLAC and KEK, leading to increases in the size of B meson datasets by two orders of magnitude and also opening the door to measurements of time-dependent CP asymmetries, which provided the experimental basis for the 2008 Nobel Prize. In the midst of this success, a number of new and aggressive quark-flavor initiatives were put forward in the U.S. These included the BTeV proposal which would have used the Tevatron collider for B physics, the CKM proposal which would have made the first high-statistics measurement of $K^+ \to \pi^+\nu\overline{\nu}$ using the Fermilab Main Injector, and the RSVP proposal which included an experiment (KOPIO) to measure $K_L^0 \to \pi^0\nu\overline{\nu}$ at the Brookhaven AGS. After lengthy consideration in an enviroment characterized by flat budgets and a predilection for a fast start on the International Linear Collider on U.S. soil, all of these initiatives were ultimately terminated. Also, as accelerator breakthroughs capable of increasing B-factory luminosity by more than another order of magnitude were made, the opportunity to upgrade the PEP-II B factory at SLAC was not pursued; subsequently, the proponents coalesced around what is now the Italian super flavor factory planned to be built at the new Cabibbo Lab near Rome. This history is relevant in order to stress that the U.S. has been a leader in flavor-physics experiments — involving a vigorous community — until very recently. Nonetheless, this sequence of events inevitably encouraged many in the flavor-physics community in the U.S. to migrate elsewhere, most often to ATLAS or CMS at the LHC.

In spite of these developments in the U.S., a rich heavy-quark flavor physics program is flourishing around the world. Kaon experiments, B-physics experiments, and charm experiments are running and under construction in Asia and Europe. Indeed, CERN — the laboratory that now owns the Energy Frontier — is also the home of a running B-physics experiment (LHCb), which has a clear upgrade path, and a rare K decay experiment (NA62) which is under construction. This reflects the world-wide consensus that flavor-physics experiments are critical to progress in particle physics, as described in Section 1.2.

Looking forward, it is clear — based on this workshop — that there continues to be strong interest and a potentially substantial community in the U.S. for an Intensity Frontier flavor-physics program. Indeed, U.S. physicists are participants in almost all the offshore experiments, although on a modest scale. Two conclusions are obvious: U.S. participation in offshore Intensity Frontier experiments should be supported on a scale sufficient to make significant impact on those experiments, and facilities are needed in the U.S. that can support a leadership role at the quark-flavor Intensity Frontier.

The basic motivation for this program can be described very simply. If the LHC observes new high-mass states, it will be necessary to distinguish between models proposed to explain them. This will require tighter constraints from the flavor sector, which can come from more precise experiments using strange, charm, and bottom quark systems. If the LHC does not make such discoveries, then the ability of precision flavor-physics experiments to probe mass scales far above LHC, through virtual effects, is the best hope to see signals that may point toward the next energy scale to explore. Therefore, a healthy U.S. particle physics program must include a vigorous flavor-physics component.

A few conclusions from this working group can be summarized briefly:

- Intensity Frontier experiments using strange, charm, and bottom quark systems are an essential component of a balanced world-wide particle physics program. The U.S., which led in this area only a few years ago, should endeavor to be among the leaders in the future.
- The compelling case for flavor-physics experiments, as described in this report, is not predicated on future theoretical progress. Nonetheless, theoretical progress, including improvements in lattice-QCD calculations, will strengthen the program by increasing the set of observables that can be used to search for new physics. Continued support of the theory community engaged in this research is important.
- Several Intensity Frontier experiments using strange, charm, and bottom quark systems are underway and are planned at laboratories around the world (including KEK and J-PARC in Japan, BESIII in China, and at the CERN and Frascati/Cabibbo laboratories in Europe). The U.S. needs to be involved in these experiments on a significant scale in order to exploit the expertise gained over the many years that U.S. facilities led in these areas and to share in possible new discoveries.
- At the present time, no Intensity Frontier experiments using strange, charm, or bottom quark systems are underway in the U.S., in spite of the fact that existing facilities at Fermilab provide powerful capabilities. In particular, world-leading rare kaon decay experiments can be mounted at Fermilab, using the Main Injector, with relatively modest investment. The ORKA experiment, if it proceeds, would exploit this opportunity.
- Kaon beams from Project X can provide a singular opportunity for Intensity Frontier flavor physics experiments. These experiments comprise an important element within the world-wide flavor-physics program, and their physics case is compelling.
- To exploit the potential that Project X can provide, improved detectors will be needed. Therefore, an active program of detector R&D focused on the key issues is critical.

A well-planned program of flavor physics experiments — using strange, charm, and bottom quarks — has the potential to produce new paradigm-changing scientific advances.

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