Snowmass 2021 Letter of Interest: B Physics at Belle II

on behalf of the U.S. Belle II Collaboration

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Abstract:

The Belle II experiment is expected to record 5×10^{10} $B\overline{B}$ pairs over the next decade produced in the asymmetric-energy e^+e^- collisions provided by the SuperKEKB facility. Parts of Belle II's diverse physics program are the search for new physics and the precise determination of Standard Model parameters in B meson decays. The main B physics goals in the areas of semileptonic and leptonic decays, radiative and electroweak loop decays, and time-dependent and direct CP violation measurements are summarized here.

The Belle II experiment has a diverse physics program. Here, we provide an overview of the potential of Belle II's B physics program to both significantly improve the precision of many CKM parameters as well as search for possible New Physics (NP) contributions in B decays to final states which are very rare and/or difficult to reconstruct. Belle II's measurements in other physics areas, as well as upgrades to the Belle II detector and the SuperKEKB accelerator are described in separate LoIs.

Belle II is expected to record a total integrated luminosity of 50 ab^{-1} over the next decade in the clean environment of the asymmetric-energy e^+e^- collisions provided by the SuperKEKB facility. The majority of the events will be produced near the $\Upsilon(4S)$ resonance corresponding to a sample of 5×10^{10} $B\overline{B}$ pairs, roughly 30× the size of the combined data sample of the B Factories BABAR and Belle. Belle II has an excellent sensitivity to B physics measurements in part due to a new vertex tracker and particle identification system. Measurements of B decays with one or more neutrinos or other invisible particles in the final state benefit from the hermeticity of the detector and a novel reconstruction method of the *other* B in the event. The sensitivity estimates quoted in this LoI are based on studies summarized in the Belle II Physics Book[1].

Belle II will improve the precision of the magnitudes of the CKM matrix elements V_{ub} and V_{cb} through measurements of leptonic and semileptonic B decays. These CKM matrix elements are related to the sides of the Unitarity Triangle (UT), and complement measurements of CP asymmetries in B decays in testing the CKM sector of the Standard Model (SM). Belle II's experimental environment provides two conditions that are favorable to study decays with one or more neutrinos in the final state. The initial state of a single $B\overline{B}$ pair is well determined and the detector is nearly hermetic. This allows the application of several experimental techniques (for example, hadronic and semileptonic tagged, untagged, and partially-reconstructed events). Belle II is expected to measure V_{ub} with an experimental uncertainty of around 1%, which is comparable to the expected theoretical uncertainty. The branching fraction $\mathcal{B}(B^- \to \tau^- \nu_\tau)$ will be measured with an uncertainty of about 3% in both hadronically-tagged and semileptonically-tagged events. Current tensions with SM predictions in $B \to D^{(*)}\tau\nu$ decays will already be confirmed or refuted with the first 5 ab^{-1} of Belle II data and more precisely measured with the full Belle II dataset.

Belle II will make crucial measurements of rare, radiative and electroweak $b \to s$ and $b \to d$ processes. These transitions proceed through one-loop diagrams in the SM and are particularly sensitive to NP. Belle II will measure inclusive $B \to X_{s,d}\gamma$ and $B \to X_{s,d}\ell^+\ell^-$ decays, and decays with photons or neutrinos in the final state such as $B_{d,s} \to \gamma\gamma$, $B \to K^{(*)}\nu\overline{\nu}$, $B_{d,s} \to \tau^+\tau^-$, and $B \to K^{(*)}\tau^+\tau^-$. Belle II is the only experiment that can provide detailed information on FCNC processes with photon pairs, neutrinos, or taus in the near future, and is expected to observe the decays $B_d \to \gamma\gamma$ and $B \to K^{(*)}\nu\overline{\nu}$ for the first time. Another important goal of the Belle II physics program is to provide independent tests of the anomalies recently measured in the decay angular analysis of $B \to K^*\ell^+\ell^-$ as well as in the ratios $\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)/\mathcal{B}(B \to K^{(*)}e^+e^-)$. Belle II is uniquely suited for the latter measurements due to its dedicated charged-lepton identification subsystems with nearly equal reconstruction efficiencies for electrons and muons.

In the SM, the CKM UT angles ϕ_1, ϕ_2, and ϕ_3 depend on the single CP-violating phase of the CKM matrix. NP could provide additional phases and be revealed through inconsistencies in the constraints of the UT. Belle II will provide a precision measurement of the time-dependent CP-asymmetry in the golden decay $B \to J/\psi\, K_S^0$ and thereby reduce the uncertainty in the current world average of the CP-asymmetry parameter $S_{J/\psi K_S^0}$ from 0.022 to 0.0052. Belle II will measure the ϕ_1-related CP-asymmetries in penguin-dominated B decays ϕK^0, $\eta' K^0$, ωK_S^0, $K_S^0\pi^0$, and $K_S^0\pi^0\gamma$ which are sensitive to NP in the penguin loop. The uncertainties in the world averages of the CP asymmetries in these modes are expected to be reduced by a factor of 2 already with 5 ab^{-1}. Belle II can measure time-dependent asymmetries in subsets of $B \to J/\psi K_S^0$ and $B \to J/\psi K_L^0$ decays as well as in charmless B decays to CP eigenstates to substantially increase the precision on direct tests of T violation as pioneered by BABAR[2].

Belle II will reduce the uncertainty in ϕ_2 through time-dependent CP-asymmetry and branching fraction measurements in the final states $B \to \pi\pi$, $B \to \pi^+\pi^-\pi^0$, and $B \to \rho\rho$ and reduce the corresponding experimental errors by factors between 2 and 10 depending on the sources of systematic uncertainties. Only an e^+e^- experiment such as Belle II can measure all three $B \to \pi\pi$ and $B \to \rho\rho$ decay modes (due to the presence of π^0's in the final states), which is required to perform the isospin decompositions needed to determine ϕ_2. Belle II's measurement of the CP-asymmetry in $B \to \pi^0\pi^0$ will reduce the discrete ambiguities in ϕ_2. The measurements of $B \to \pi\pi$ and $B \to \rho\rho$ are expected to reduce the world average uncertainty in ϕ_2 from 4.2° to 0.6° (assuming theoretical uncertainties in SM predictions can be sufficiently controlled).

Belle II will perform many measurements in B decays to charmed final states with specific emphasis on the measurement of the UT angle ϕ_3 in $B \to D^{(*)}K^{(*)}$ decays. The underlying interference of only tree-level amplitudes in these decays allows the extraction of ϕ_3 with negligible theoretical uncertainties. Belle II will measure ϕ_3 in decays where the D decays to CP eigenstates, Cabibbo-favored and doubly Cabibbo-suppressed decays, self-conjugate modes, and singly Cabibbo-suppressed decays. The uncertainty in ϕ_3 with 50 ab^{-1} of data and strong phase measurements from BESIII is expected to be 1.6°.

Another area where Belle II will study CP violation are B decays to charmless hadronic final states. These decays proceed through CKM-suppressed $b \to u$ tree-level transitions or $b \to s$ hadronic penguin loops and CP violation is a result of the interference of two amplitudes with a weak and a strong phase difference between them. Belle II will be able to answer many questions that have resulted from the measurements of $B_{(s)}$ decays by BABAR, Belle, and LHCb. The decays $B \to K^{(*)}\pi$ and $B \to K^{(*)}\rho$ are sensitive to NP contributions. Belle II's can carry out isospin analyses of these decays by measuring the corresponding CP asymmetries and branching fractions for all final states, and may resolve the $K\pi$ CP puzzle. The large Belle II data sample will allow full angular analyses of B decays to vector-vector final states and to search for CP asymmetries in three-body $B \to 3h$ decays with (multiple) neutral particles in the final state. A subset of the Belle II dataset will be taken near the $\Upsilon(5S)$ resonance. This data will provide a sizable sample of B_s decays, including B_s decays to neutral-particles final states such as $K^0\overline{K}^0$, $\eta^{(\prime)}\eta^{(\prime)}$, and $\phi\pi^0$. Many such decays are unexplored and provide promising ways to constrain NP contributions.

In summary, Belle II will exploit its large sample of $B\overline{B}$ events to produce a comprehensive set of precision measurements of crucial B physics parameters. Studies of leptonic and semileptonic B decays, radiative and electroweak loop decays, and time-dependent and direct CP violation will provide much improved sensitivity to SM parameters such as the CKM UT angles and rare decay branching fractions, while at the same time tightly constraining potential contributions from NP.

References

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