Belle II Vision in High Energy Physics

The US Belle II Collaboration

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I. INTRODUCTION

Belle II is the next-generation B-Factory or a Super B-Factory. A B-factory experiment measures fundamental weak interaction couplings and phases, QCD parameters and performs searches for physics Beyond the Standard Model (BSM) or "New Physics" at the "Rare and Precision Frontier" of high energy physics [1]. Given the absence of non-SM discoveries in direct production at the LHC, the role of flavor physics experiments has become crucial to the future of high energy physics.

Belle II reconstructs large samples of B mesons, charm hadrons, and tau leptons, and searches for the production of new particles (e.g., dark sector particles) in asymmetric energy e^+e^- collisions on and near the $\Upsilon(4S)$ resonance. Historically, the flavor physics measurements from these experiments have played critical roles in advancing our knowledge. For example, the previous-generation B factories, Belle/KEKB and BaBar/PEP-II, discovered CP violation (matter-antimatter asymmetry) in the B system, which was recognized by the 2008 Physics Nobel Prize. Belle II will make high-precision measurements of suppressed processes. If New Physics (NP) is present, its first signs may appear there. Precise measurements of suppressed decays can provide sensitivity to NP occurring at energy scales far above those that can be accessed in direct searches at high-pT hadron collider experiments. Mapping out and understanding BSM physics will require the full range of Rare and Precision Frontier and Energy Frontier experiments. The complementarity between them, and the potential for uncovering NP they collectively provide, are great strengths of the US high energy physics (HEP) program.

An e^+e^- Super B-factory has a number of advantages as compared to a fixed target or hadron collider experiment. At Belle II, $B\bar{B}$ meson pairs are produced at threshold (on the $\Upsilon(4S)$ resonance) with no additional particles. Background levels are generally low due to the small multiplicity of final state particles and the absence of pile-up. CP violation (matter-antimatter asymmetry) measurements in the B meson system using flavor-tagged and time-dependent observables can be carried out with neutral $B\bar{B}$ pairs that are produced in a coherent and entangled quantum mechanical state.

The Belle II experiment is a significant improvement over Belle and BaBar, which together have published over 1200 papers. Belle II is expected to record 50 ab^{-1} of data, which is two orders of magnitude greater than that recorded by BaBar and fifty times that of Belle. This large increase in luminosity is enabled by innovations and breakthroughs in electron-positron accelerator physics: low-emittance beams and strong vertical focusing, resulting in beam heights of only 60 nanometers - so-called "nano-beams." The new SuperKEKB accelerator is running with nano-beams and has already achieved an instantaneous luminosity (4.7×10^{34}/cm^2/sec) about 3.7 times greater than that achieved by the PEP-II accelerator at SLAC - and with a factor of five lower product of beam currents. Numerous world records for instantaneous luminosity, and integrated luminosities, have already been set by this new, innovative machine [2]. The SuperKEKB team with accelerator scientists from the US, EU and Asian laboratories are collaborating to optimize the path for realizing SuperKEKB's full potential.

The Belle II detector is state-of-the-art, incorporating advanced detector technologies. For example, it uses silicon pixels for the two innermost layers of the vertex detector. This improves the resolution on the track impact parameter and vertexing by a factor of two over those achieved at Belle and BaBar. In addition, the Belle II detector includes a new large-volume central tracker; a powerful particle identification detector (iTOP) based on Cherenkov light radiated in optically polished quartz bars; a new K_L and muon detector (KLM); and state-of-the-art readout, trigger and data acquisition systems. The US Belle II groups played a leading role in designing, constructing, and now operating the iTOP and KLM detectors [3]. These detectors, and all other Belle II detectors, are collecting data and performing close to design specifications.

Reconstruction of neutrals (i.e. photon, π^0, K_S, K_L; and subsequently η, $\rho^{\pm}$, ω, η', a_0, etc.) is relatively straightforward. For the broad Belle II program covering B, charm, τ and dark sector physics, a major advantage is that the initial state is known and the detector is nearly hermetic. Thus Belle II can reconstruct fully-inclusive final states and search for new particles via the "missing mass" technique. These searches can be performed irrespective of the lifetime of the particle or the final state into which it decays, even including "invisible" final states.

II. PHYSICS REACH

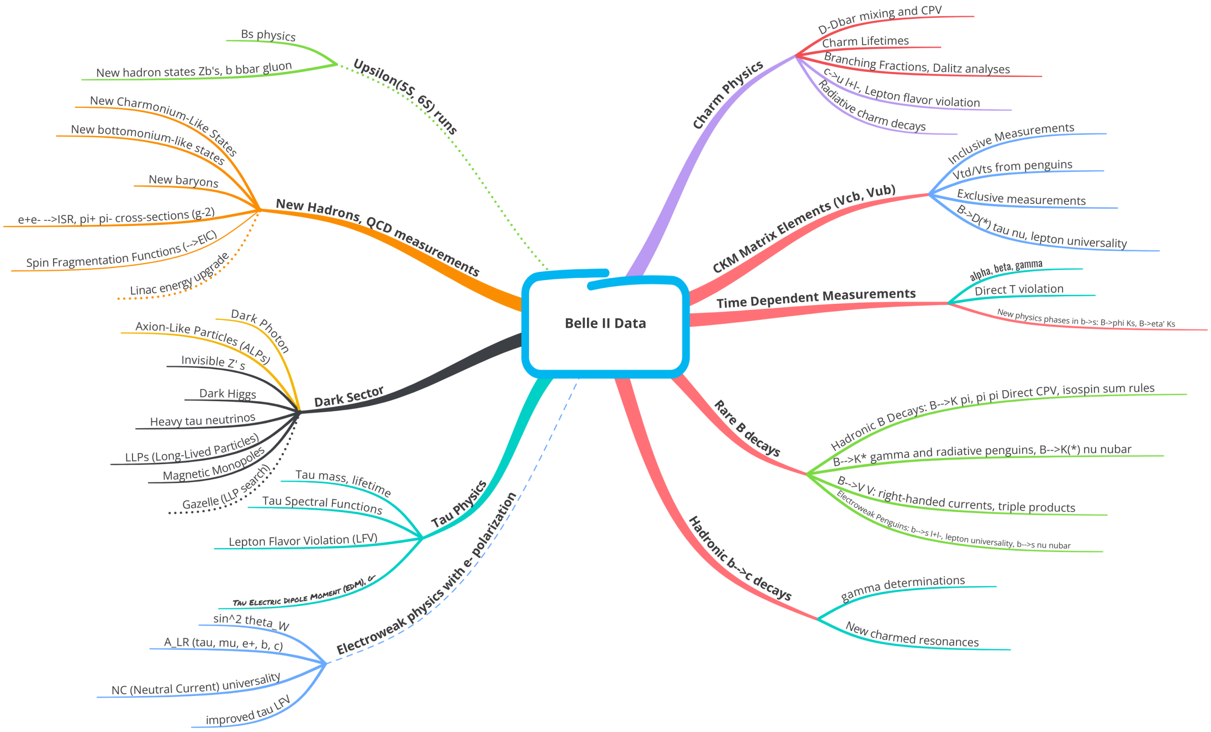

FIG. 1. Belle II physics "mind map": the dashed lines show the upgrades that could enhance the capabilities of the Belle II and SuperKEKB facility.

The goal of Belle II is to uncover new physics beyond the Standard Model. Belle II will pursue NP in many ways, as shown in FIG. 1. For example, improving the precision of weak interaction parameters, particularly the magnitudes of Cabibbo-Kobayashi-Maskawa (CKM) matrix elements and their phases, which are obtained from CP violation measurements, will more rigorously test the CKM paradigm. Belle II will measure lepton-flavor-violating parameters, perform unique searches for invisible dark sector particles, and carry out fundamental tests of quantum mechanical coherence.

As examples, the NP flavor structure with enhanced τ lepton couplings (e.g. $B \to D^{(*)}\tau\nu$) can be tested at higher precision than at a hadron collider, and the most sensitive methods to determine the CKM angle α/φ_2 require measurements of asymmetries in modes such as $B \to \rho^{\pm}\rho^{\mp}$, $B \to \rho^{\pm}\pi^{\mp}$, and $B \to \pi^0\pi^0$, which are challenging at a hadron collider. Isospin sum rules (e.g., in $B \to K\pi$ decays) can be fully tested, as all terms - including those for decays having π^0's in the final state - can be measured.

Belle II will access pure electroweak $b \to s$ penguin processes such as $B \to K^{(*)}\nu\bar{\nu}$, whose rates and CP asymmetries are especially sensitive to NP. Belle II's fully-inclusive measurements of B decay processes will have significantly reduced theory uncertainties compared to those made with exclusive final states.

Belle II's high trigger efficiency, even for events with significant missing energy allows for effective searches for dark sector particles. Belle II's measurement of the cross-section for $e^+e^- \to \pi^+\pi^-$ will more precisely determine the leading-order hadronic contribution to the muon $g-2$ anomaly.

Expected sensitivities to τ decays will be world-leading due to the production of clean $\tau^+\tau^-$ pairs at Belle II with minimal combinatorial and machine backgrounds. Many of these measurements can only be performed at Belle II, e.g., inclusive decays and absolute branching fractions are probably impractical to measure at a hadron collider [4].

In all areas, Belle II will push far beyond the first-generation measurements of Belle and BaBar. From 2015-2018, a series of workshops were held with experimentalists and theorists collaborating together to identify the most promising physics measurements for Belle II, culminating in The Belle II Physics Book [5]. These measurements address many fundamental questions of high energy physics. We list here some of the topics and corresponding measurements that Belle II is uniquely positioned to address (see the Snowmass Belle II Physics White Paper [6]).

- Testing violations of lepton flavor conservation and universality and understanding their origins
  - The ratios of branching fractions $R(D^{(\star)}) = B(B \to D^{(\star)}\tau\nu)/B(B \to D^{(\star)}\mu\nu)$ have shown some of the most significant discrepancies between SM predictions and measurements. The combined discrepancy is currently at the level of 3.2σ and indicates potential NP in leptonic couplings. Belle II will measure these ratios about three times more precisely than the current world averages. We can also probe inclusive semi-tauonic B decays, which have different theoretical uncertainties. The angular distributions of $B \to D^\star\ell\nu$ ($\ell = e, \mu, \tau$) are sensitive to NP (e.g., the difference in forward-backward asymmetries $\Delta A_{FB} = A_{FB}(B \to D^\star\mu\nu) - A_{FB}(B \to D^\star e\nu)$) and will be well measured by Belle II.
  - Belle II has good sensitivity to NP in decays involving internal loops (so-called "penguin" decays) such as $b \to s\nu\bar{\nu}$, $b \to s\ell^+\ell^-$ ($\ell = e, \mu, \tau$), and $b \to s\gamma$; the current measured value for the ratio $R_K = B(B \to K\mu^+\mu^-)/B(B \to Ke^+e^-)$ differs from the SM by 3σ. We expect Belle II to discover $B^+ \to K^+\nu\bar{\nu}$ and $B^0 \to K^{*0}\nu\bar{\nu}$, and to measure their branching fractions with about 10% uncertainty. The angular distributions of $B \to K^\star\ell^+\ell^-$ (for all lepton flavors ℓ including τ) will also be measured by Belle II and allow determinations of BSM couplings.
  - Belle II will investigate possible lepton flavor violation (LFV) with τ decays to many final states, including $\tau \to \mu\gamma$. Belle II will improve the sensitivity of this final state by an order of magnitude, while the sensitivity of about fifty other modes will be improved by up to two orders of magnitude [4]. The observation of a single LFV τ decay mode would immediately establish physics beyond the SM. Belle II can measure the electric dipole moment of the τ lepton with significantly greater precision than the current world-average; this measurement is sensitive to non-SM scalar couplings.
- Checking the unitarity of the CKM matrix to high precision
  - Belle II can measure the CKM angles β/φ_1, α/φ_2 and γ/φ_3 with high precision. The least known of the three angles, α, can be determined with B decays to $\rho\rho$, $\pi\pi$, and $\rho\pi$ final states. From the measurement of branching fractions and CP asymmetries of these decays (including those with neutral pions), Belle II can measure α with a world-leading precision of less than 1°.

  - There is a long-standing discrepancy between the value of $|V_{cb}|$ measured in inclusive semileptonic decays (i.e. $B \to X_c \ell \nu$) and that measured using exclusive semileptonic decays (e.g. $B \to D^* \ell \nu$). This 3.3σ discrepancy could indicate the presence of non-SM partial widths. A similar discrepancy exists between inclusively and exclusively measured values of $|V_{ub}|$. Belle II is in a unique position to understand and resolve these discrepancies, which are severely limiting precision measurements, as inclusive decays can only be studied in the experimentally clean e^+e^- environment.
  - $|V_{us}|$ measurements from both kaon and τ decays are systematically smaller than the CKM unitarity constraint by $\sim 3\sigma$ (the "Cabibbo angle anomaly"). Inclusive τ decays at Belle II provide an alternative way to determine $|V_{us}|$ with different systematic uncertainties than those of semileptonic kaon decay measurements.

- Identifying new weak (CP-violating) phases in the quark sector
  - CP asymmetries in decays proceeding via the penguin loop transitions $b \to s$ and $b \to d$ have high sensitivity to new weak interaction phases from BSM physics. Such asymmetries will be measured at Belle II in a variety of charged and neutral final states. Examples are the CP violating asymmetries in $B^0 \to \eta' K^0_S$ and $B^0 \to \phi K^0_S$, which Belle II will measure with unique precision.
  - Measurements of the branching fraction ratio of charged and neutral $B \to K\pi$ decays deviate significantly from SM expectations (the "$K\pi$ puzzle"). Whether this discrepancy arises from additional SM contributions or from NP can be probed with an isospin sum rule involving $B \to K\pi$ branching fractions and CP asymmetries. Belle II can determine all terms with high precision, including the difficult-to-measure CP asymmetries in $B^0 \to K^0_S \pi^0$ that dominate the sensitivity of the sum rule (in fact, probably only Belle II can measure this asymmetry). As $B \to K\pi$ decays proceed via loop diagrams they can help identify non-SM contributions to electroweak penguin amplitudes.
  - Belle II will measure time-dependent CP violation in exclusive $b \to s\gamma$ decays (e.g., in $B \to K^0_S \pi^0 \gamma$) that can arise from right-handed currents. We will also measure triple-product CP asymmetries in $B \to VV$ decays. Belle II will search for CP violation in many charm hadron decays, e.g., in $D^+ \to \pi^+ \pi^0$, where a nonzero CP asymmetry would unambiguously identify NP.

- Probing the existence of dark-sector particles at MeV to GeV mass scales
  - A number of theoretical models predict a rich structure of dark-matter particles, axion-like-particles, and new gauge bosons in the MeV to GeV energy range. Such particles can be directly produced in e^+e^- collisions at Belle II, but the experimental signatures can be challenging to identify, e.g., $e^+e^- \to \gamma + \text{nothing}$. Belle II has implemented new trigger algorithms (such as a single photon trigger) to capture these elusive events. With such triggers, and using the missing-mass technique, Belle II has a unique ability to uncover these dark-sector particles [7], [8].

- Reducing the uncertainty in the theory prediction for the muon $g - 2$ anomaly
  - An important measurement of the US high energy physics program is that of the gyromagnetic ratio g of the muon, typically parameterized as the "anomaly" $a_\mu = (g - 2)/2$. The current experimental value differs from the SM prediction by 4.2σ using data driven predictions. The dominant theoretical uncertainty (from hadronic vacuum polarization terms) can be reduced by a more precise measurement of the cross-section $\sigma(e^+e^- \to \pi^+\pi^-)$. The increased statistics at Belle II allows one to reduce the systematic uncertainty in this measurement.

- Understanding the role of QCD in the production and binding of new hadronic states of matter
  - Exotic QCD states such as tetraquarks and QCD molecules can be produced at Belle II in several ways: near resonance by tuning the machine energy; through initial state radiation; or in B decays

such as $B \to X(3872)K$ and $B \to Z(4430)K$. With the ability to reconstruct essentially all neutral and charged particles, Belle II will play a unique role in the search for exotic states; especially for $b\bar{b}$ states that are currently accessible only at SuperKEKB and will be in the foreseeable future[9].

- Unique studies in nuclear physics
  - Measurements of di-hadron spin-momentum correlations at B factories, such as the discovery of the Collins effect, have provided crucial input to the imaging of the partonic structure of nucleons. Precision data from Belle II will enable the extension of this physics program to multi-dimensional correlations of spin and momenta [10]. Such measurements will provide important input to the design of a future electron-ion collider.

III. TIMELINE

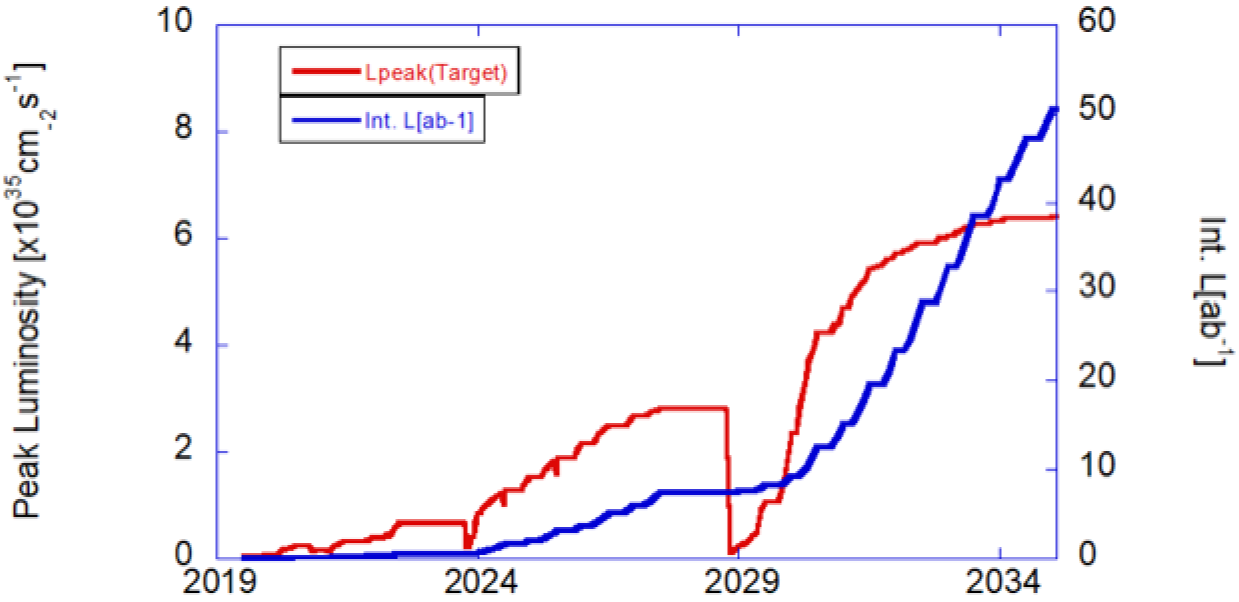

FIG. 2. The SuperKEKB/Belle II luminosity profile over the next decade and beyond. The two flat regions refer to long shutdown 1 and 2 (LS1 and LS2, respectively), which are reserved for detector and accelerator upgrades.

Belle II began its initial physics run in 2019. Since then, SuperKEKB has carried out significant accelerator development, continuously improved its performance during the pandemic, and delivered 428 fb^{-1} of integrated luminosity (comparable to the final BaBar/PEP-II data sample).

Belle II's goal is to integrate 50 ab^{-1} of data by 2035, as shown in FIG. 2. This schedule includes two long shutdowns (LS1 and LS2) for detector upgrades. During LS1, which is in progress, Belle II plans to complete the installation of the second layer of the pixel-based inner vertex detector and replace some of the photo-detectors in the barrel particle identification system. In addition, there are upgrades to SuperKEKB such as the installation of the NLC (non-linear collimator) system and improvements to the linac injector complex. For LS2, major upgrades to the Belle II detector are being considered [11], along with extensive upgrades to the accelerator. A number of planned upgrades of the SuperKEKB accelerator are described elsewhere [12].

We are exploring an upgrade to the accelerator that would result in polarization of the electron beam [13]. A polarized beam would open up a new and unique program of high-precision electroweak measurements. For example, the neutral current couplings of the b quark, c quark and muon can be measured several times more precisely than the current world averages. This "chiral Belle II" upgrade could potentially be implemented before reaching the full 50 ab^{-1} of data. Running with a polarized electron beam could allow Belle II to measure the anomalous magnetic moment of the τ lepton, which would be of great interest if the inconsistency between experiment and theory observed for the muon's magnetic moment persists.

Studies are beginning on technical advances in accelerator R&D and the machine detector interface. These are synergistic with the FCC-ee project at CERN and could lead to instantaneous luminosities as high as $2 \times 10^{36}/\text{cm}^2/\text{sec}$. Such an increase in luminosity would require a major R&D program for the detector, in order to improve its radiation hardness and its ability to reject backgrounds.

IV. SUMMARY

Belle II has outstanding potential for discovering BSM physics over the next decade. We strongly agree with the assessment of the European Strategy Group that "The quest for dark matter and the exploration of flavor and fundamental symmetries are crucial components in the search for new physics." In addition, if unambiguous non-SM physics signals are observed in flavor-physics measurements made at other experiments, independent measurements at Belle II will be important. Given the BSM discovery potential of Belle II, and the track record of the preceding Belle experiment, the US investment in Belle II represents a very high value.

The broad program of fundamental weak interaction measurements, the current hints of non-SM flavor signals including the so-called "flavor anomalies" in B physics, muon and kaon physics, as well as the exciting possibility of BSM discoveries in searches unique to Belle II warrant enhanced US investment in the Belle II experiment, SuperKEKB and their upgrades. For the longer term future, when non-SM physics is observed in B, D, or τ decays, or a dark sector particle is discovered, Belle II will continue its physics program to explore such phenomena in depth.

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