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Physics at the Belle II Experiment and Lattice QCD

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We present future prospect of heavy flavor physics at the SuperKEKB/Belle II experiment. The target peak luminosity is $8 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which enables us to search for New Physics through processes sensitive to presence of virtual heavy particles in decays of B and D mesons as well as τ-leptons, each produced at the rate of $O(10^{10})$ per year. In this paper, we present the physics program, status and plan of the Belle II experiment. We also discuss about crucial inputs from lattice QCD calculations, which are necessary to interpret experimental results.

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1. Introduction

The SuperKEKB accelerator, 7 GeV electron - 4 GeV positron collider under construction at KEK, is a new luminosity frontier facility with the designed peak luminosity of $8 \times 10^{35}\text{cm}^{-2}\text{s}^{-1}$, about 40 times higher than the former KEKB accelerator [1]. The Belle II experiment, located at the single collision point, aims to study decays of heavy flavor particles, such as B and D mesons as well as τ-leptons, each produced at the rate of $O(10^{10})$ per year [2]. The goal of the project is to accumulate more than 50 ab^{-1} during the first half of 2020's.

The primary motivation of the Belle II experiment is to search for New Physics (NP) through processes sensitive to presence of virtual heavy particles. In this approach, sensitivity to NP depends on the product of the mass scale and flavor violating couplings. Therefore, NP search at Belle II is complementary to direct searches in LHC high p_T programs, where the mass reach is limited by beam energies. Moreover, in heavy flavor decays, there are variety of decay modes and observables with different sensitivities to different type of NP models. This enables us not only to search for NP, but also to investigate its nature. The Belle II experiment is also complementary to the LHCb experiment. Thanks to the clean environment in e^+e^- collisions, Belle II has advantage in measurements of decay modes with photons and neutrinos in the final states.

In order to search for NP effects in decays of heavy flavor particles, precise and reliable estimates of Standard Model (SM) rates are indispensable. Lattice QCD plays important role to calculate hadronic form factors involved in decays of B and D mesons, which often dominate theoretical errors in the SM rate estimates. A few % accuracy is required in era of the Belle II experiment.

2. Physics Program at Belle II

Table 1 summarizes precision of key observables expected at Belle II [2]. The e^+e^- experiment has advantage for measurements of decay modes with ν's, γ's and π^0's in the final state. Especially, we can fully reconstruct one of a produced B meson pair, and determine the momentum vector and flavor of the other B meson ("Off-line B meson beam"). This method enables us to measure B decays with ν's in the final state, such as $B \to \pi\ell\nu$, $B \to \tau\nu$ and $B \to D^{(*)}\tau\nu$ decays. We describe some of the key measurements at Belle II in the following.

2.1 Time-dependent *CP* Violation

The Belle II experiment will provide precision measurements of time-dependent *CP* violation in different classes of decays;

- Decays dominated by tree diagram amplitude, such as $B \to J/\psi K^0_S, \psi(2S)K^0_S, J/\psi K_L$, which are SM references.
- Decays involving $b \to s s\bar{s}$ penguin loop amplitude, such as $B \to \phi K^0, K^+K^-K^0_S, K^0_S K^0_S K^0_S$, which are sensitive to NP.
- Decays involving radiative $b \to s(d)\gamma$ processes, such as $B \to K^*\gamma$ and $B \to \rho\gamma$, which are sensitive to right-handed currents.

Table 1: Measurement errors for B, D, τ decay observables achieved at the present Belle with ~ 0.5 ab^{-1} and expected at Belle II with 5 ab^{-1} and 50 ab^{-1} [2].

Type	Observables	Belle (0.5ab^{-1})	Belle II (5ab^{-1})	Belle II (50 ab^{-1})
CPV in $b \to s$ penguin	$\Delta S(\phi K^0)$	0.22	0.073	0.029
	$\Delta S(\eta' K^0)$	0.11	0.038	0.020
	$\Delta S(\phi K^0)$	0.33	0.105	0.037
Right-handed currents	$\Delta S(K_s \pi^0 \gamma)$	0.32	0.10	0.03
	$A_{CP}(X_s \gamma)$	0.058	0.01	0.005
E/W penguin	$C_9(A_{FB}(K^* \ell\ell))$		11%	4%
	$C_{10}(A_{FB}(K^* \ell\ell))$		13%	4%
	$\mathscr{B}(B^+ \to K^+ \nu\bar{\nu})$	$< 9 \times \mathscr{B}_{\rm SM}$	33 ab^{-1} for 5 σ discovery	
Charged Higgs	$\mathscr{B}(B^+ \to \tau^+ \bar{\nu})$	3.5 σ	10%	3%
	$\mathscr{B}(B^+ \to \mu^+ \bar{\nu})$	$< 2.4 \times \mathscr{B}_{\rm SM}$	4.3 ab^{-1} for 5 σ discovery	
	$\mathscr{B}(B \to D \tau^+ \bar{\nu})$		7.9%	2.5%
LFV τ decays	$\mathscr{B}(\tau^+ \to \mu^+ \gamma)$	< 45	< 30	< 8
	$\mathscr{B}(\tau^+ \to \mu^+ \eta)$	< 65	< 20	< 4
	$\mathscr{B}(\tau^+ \to 3\mu)$	< 209	< 10	< 1
Unitarity triangle	$\Delta \sin 2\phi_1$	0.026	0.016	0.012
	$\Delta\phi_2(\rho\pi)$	$68° - 95°$	3°	1°
	$\Delta\phi_3$(Dalitz)	20°	7°	2.5°
	$\Delta V_{ub}(incl.)$	7.3%	6.6%	6.1%

Compared to the previous Belle detector, the Belle II detector has $\sim$ 30% larger acceptance for K_S^0 decays, because of the vertex detector extending to larger outer radius. It also has improved vertex resolution, $\sigma_Z \sim 18\mu$m ($\sim 61\mu$m at Belle), by using pixel detectors and a beam pipe with smaller radius. Figure 1 shows the expected precision of $\sin 2\phi_1^{\rm eff}$ for $b \to s s\bar{s}$ and $b \to s(d)\gamma$ processes.

2.2 Electroweak *B* Decays

Electroweak Penguin decays, $b \to s\ell^+\ell^-$, is one of the most sensitive observables to New Physics. Especially, recent results from LHCb indicate deviations from SM in $b \to s\ell\ell$ transition; 3.7 σ deviation in the P_5' observable in the $B \to K^*\mu\mu$ decay [3], 3.5 σ deviation in the branching fraction of the $B_s \to \phi\mu\mu$ decay [4], and 2.6 σ deviation in the ratio of $B^+ \to K^+\mu\mu$ to $B^+ \to K^+ ee$ (lepton non-universality) [5]. Belle II can provide precise data for these exclusive decay modes, and also for inclusive rate $B \to X_s\ell\ell$, which has less theoretical systematic error.

2.3 Charged Higgs Search with Tauonic *B* decays

B decays with the τ lepton in the final state, such as $B \to \tau\nu$ and $B \to D\tau\nu$, are sensitive to

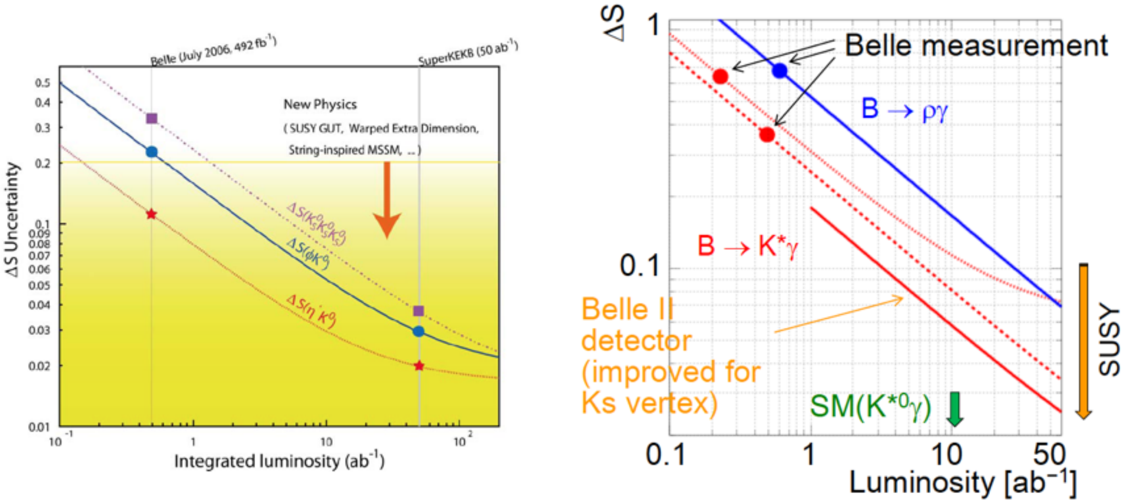

Figure 1: Expected precision of $\sin 2\phi_1^{\rm eff}$ for $b \to s s \bar{s}$ (left) and $b \to s(d)\gamma$ (right) processes.

charged Higgs ($H^{\pm}$). If $H^{\pm}$ exists, the branching fraction for $B \to \tau\nu$ is modified as [6],

$$\mathscr{B}(B \to \tau\nu) = \mathscr{B}(B \to \tau\nu)_{\rm SM} \times (1 - m_B^2/m_H^2 \cdot \tan^2\beta)^2 \tag{2.1}$$

in the Type II Higgs Doublet Model (HDM), where the SM branching fraction $\mathscr{B}(B \to \tau\nu)_{\rm SM}$ is calculated as,

$$\mathscr{B}(B \to \tau\nu)_{\rm SM} = \frac{G_F^2 m_B m_\tau^2}{8\pi}(1 - \frac{m_\tau^2}{m_B^2})^2 f_B^2 |V_{\rm ub}|^2 \tau_B \quad . \tag{2.2}$$

A simiar modification of the branching fraction is predicted also for $B \to D^{(*)}\tau\nu$ by several authors [7]. Recently, the $B \to D^{(*)}\tau\nu$ decay has attracted much attention since the BaBar experiment observed 3.4σ excess over the SM prediction [8]. More recent measurements of $B \to D^*\tau\nu$ by LHCb [9] and of $B \to D\tau\nu$ and $B \to D^*\tau\nu$ by Belle [10] show slight excesses, while they are consistent to SM within the large errors. At Belle II, we will be able to measure these decays with a few % error. Important inputs from lattice QCD calculations are the B decay constant f_B and the $B \to D^{(*)}$ form factor. Figure 2 shows constraint on $H^{\pm}$ in the ($\tan\beta$, m_H) plane from $B \to \tau\nu$ data at present and in future (Type-II HDM) [11].

2.4 τ Decays

The SuperKEKB collider produces not only $B\overline{B}$ pairs but also the similar amount of $\tau^+\tau^-$ pairs ("Super τ Factory"). They provide unique opportunity to search for Lepton-Flavor-Violating (LFV) decays, such as $\tau \to \ell\gamma$ and $\tau \to \ell\ell\ell$ ($\ell = \mu, e$), which may proceed via the SUSY loop and the Higgs exchange diagrams, respectively. These two classes of decays have different sensitivity to different BSM models. Figure 3 shows the sensitivity of Belle II (in terms of 90% C.L. upper limits) as a function of the integrated luminosity. The Belle II experiment will enable us to search for τ LFV decays at $O(10^{-9})$, and even at $O(10^{-10})$ for $\tau \to \ell\ell\ell$, which suffers from less background [2].

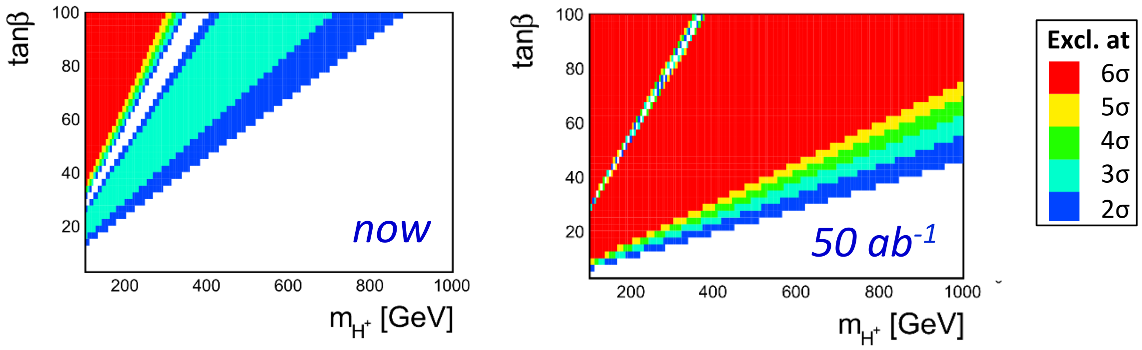

Figure 2: Constraint on the charged Higgs boson from the branching fraction of $B \to \tau\nu$ (Type-II HDM); (left) constraint from the present result and (right) constraint expected with 50 ab^{-1} data at Belle II.

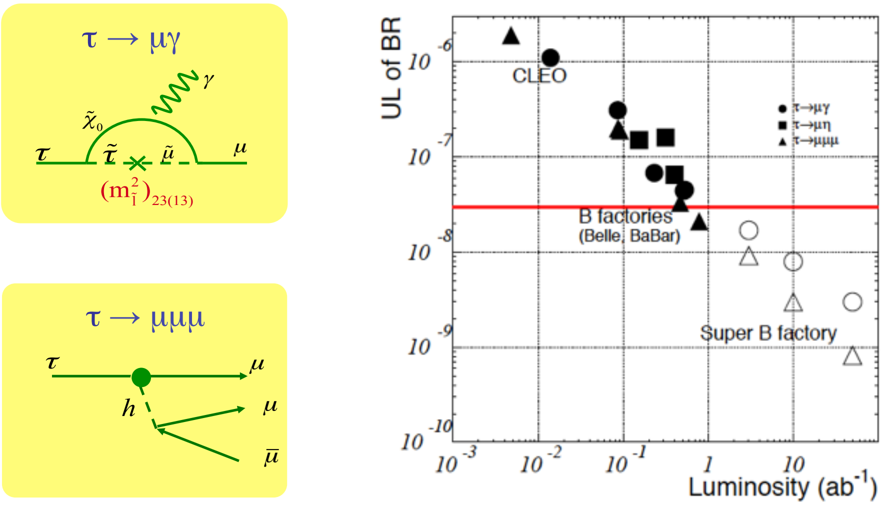

Figure 3: Feynman diagram of LFV τ decays, and projected sensitivity for them as a function of the integrated luminosity.

2.5 Precision CKM

While the former B factory experiments, BaBar and Belle, demonstrated that the Kobayashi-Maskawa phase is the primary source of CP violation phenomena observed in K and B decays, there still remains a room for sub-leading contribution from NP at $O(0.1)$. Belle II will pin down the three internal angles of the Unitarity Triangle (UT) with ultimate precision; ~ 0.001 for Δsin $2\phi_1$, 1° for $\Delta\phi_2$ and 2.5° for $\Delta\phi_3$. In such precision CKM measurements, we can constrain the apex of UT with tree dominated processes, ϕ_3 (γ) and $|V_{\rm ub}|$, and then compare the result with sin $2\phi_1$ measurement (see Figure 4). Then it will constrain relative amplitude (h_d) and phase (σ_d) of possible NP contribution in the $B-\bar{B}$ mixing, parameterized as $M_{12}^d = (M_{12}^d)_{\rm SM} \times (1 + h_d e^{2i\sigma_d})$. Figure 4 demonstrates that most of the (h_d, σ_d) space are constrained by Belle II 50ab^{-1} and LHCb 50 fb^{-1} data [12].

One of the crucial input is $|V_{\rm ub}|$. In the past several years, there have been persistence tensions between the inclusive and exclusive measurements. At Belle II, we can extract very clean sample of $B \to \pi \ell \nu$ decays by using the tagging method, as described above, and measure the rate with a few % error with $O(10)\mathrm{ab}^{-1}$ data. It is required that lattice QCD provides the $B \to \pi$ form factor with similar precision for the critical test of CKM.

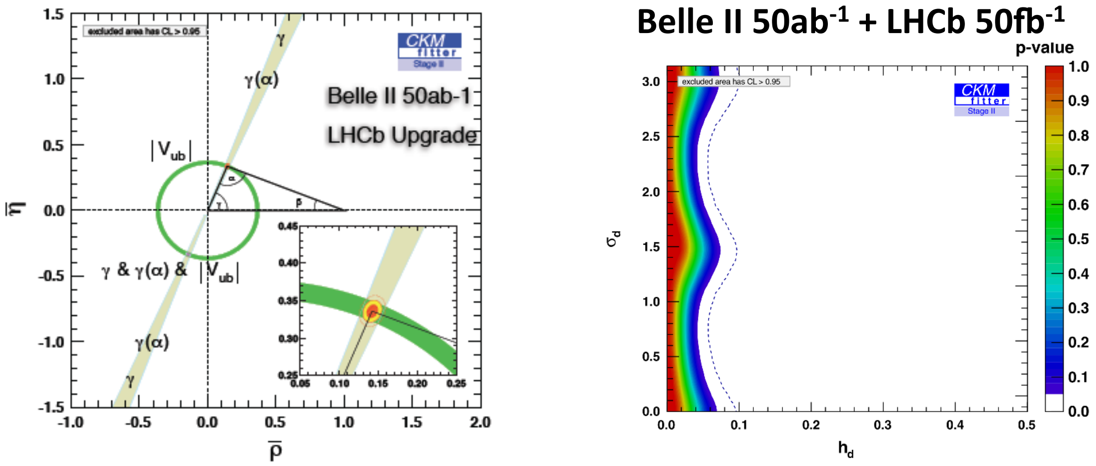

Figure 4: Constraints in the $(\bar{\rho},\bar{\eta})$ plane (left) and in the (h_d,σ_d) plane (right) with $50\mathrm{fb}^{-1}$ LHCb data and $50\ \mathrm{ab}^{-1}$ Belle II data.

2.6 Hadron Spectroscopy

The Belle II experiment provides opportunities not only to search for BSM physics in electroweak processes, but also to improve our understandings in low-energy QCD phenomena. The previous Belle experiment has brought many discoveries of new hadronic states, denoted collectively as “XYZ”, such as $X(3872)$ and $Z^+(4430)$. The Belle experiment found also the bottomonium counter-parts of Z^+, $Z_b^+(10510)$ and $Z_b^+(10560)$, in $e^-e^+ \to \Upsilon(nS)\pi^+\pi^-$ $(n = 1,2,3)$ and $e^-e^+ \to \eta_b\pi^+\pi^-$ reactions [13]. Some of them have mass, decay properties and electric charge, which cannot be understood with the conventional quark model, therefore, could be states involving (at least) four quarks as constituents. The Belle II experiments will enable us to search for new states and to study their detailed properties (J^{PC}, decay modes etc.). Lattice QCD is also a powerful tool to understand the nature of such exotic hadron states.

3. Importance of Lattice QCD for Belle II

Lattice QCD provides crucial inputs for precision test of the SM and hence maximizing sensitivity to NP effects of the Belle II experiment. As an illustration, Table 2 summarizes the quantities needed be calculated by lattice QCD, relevant CKM elements, and corresponding experimental accuracy at present and future. Here are some notes from the experimental point of views [2].

- Determination of $|V_{\mathrm{cb}}|$ from branching fractions of the exclusive $B \to D^*\ell\nu$ decays requires calculation of the form factor $B \to D^*$ form factors. At Belle II, thanks to improved silicon tracking, it will be possible to reduce experimental systematic uncertainties, such as those associated with reconstruction of the slow-momentum pions from D^* decays. The expected experimental error, including both statistical and systematic errors, will be 1.5 (1.2) % at the integrated luminosity of 5 (50) ab^{-1}.

- In era of the Belle II experiment, precision for the exclusive $B \to D\ell\nu$ decay will be comparable to that for $B \to D^*\ell\nu$. Therefore, lattice QCD calculation for the $B \to D$ form factor will also be useful and important.

- To obtain the best possible $|V_{\rm ub}|$, the lattice QCD numerical form factor for the $B \to \pi$ transition must be extended to the full kinematic range. The expected total experimental error for the total branching fraction of the $B \to \pi\ell\nu$ decay at 5 (50) ab^{-1} will be 2.6 (1.3) % with hadronic tags, and 1.5 (0.9) % without tags.

- The B decay constant f_B is the most crucial parameter to deduce $|V_{\rm ub}|$ from purely leptonic decays, such as $B \to \tau\nu$ and $B \to \mu\nu$. The expected total experimental error for the $B \to \tau\nu$ branching fraction at 5 (50) ab^{-1} will be 7.9 (3.2) % with hadron tags. A similar precision is expected also with semileptonic tags.

- Precise calculations of $B \to D^{(*)}$ form factors and f_B are mandatory also for deducing new physics contribution such as the charged Higgs boson in tauonic B decays, $B \to D^*\tau\nu$ and $B \to \tau\nu$.

It is far important that lattice QCD provides these quantities with errors small enough compared to the expected experimental errors.

Table 2: Quantities needed be calculated by lattice QCD, relevant CKM elements, their experimental accuracy at present and at Belle II with 5 ab^{-1} and 50ab^{-1}. Note that the experimental errors are shown for branching factions, therefore, need be divided by 2 for corresponding rates.

Quantity	CKM element	Present lattice error	Belle (711 fb^{-1})	Belle II (5 ab^{-1})	(50 ab^{-1})
$B \to D^*\ell\nu$ form factor	$\lvert V_{\rm cb}\rvert$	1.8%	3.1%	1.5%	1.2%
$B \to \pi\ell\nu$ form factor	$\lvert V_{\rm ub}\rvert$	8.7%	3.5%	1.5%	0.9%
B decay constant ($B \to \tau\nu$)	$\lvert V_{\rm ub}\rvert$	2.5%	20.4%	7.9%	3.2%

4. SuperKEKB

How do we achieve the high luminosity of $8 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$? The basic concept is the so-called "nano-beam scheme", invented first by Pantareo Raimondi for the Italian Super-B project [14]. In the luminosity formula,

$$L = \frac{\gamma_\pm}{2er_e}(1+\frac{\sigma_y^*}{\sigma_x^*})\frac{I_\pm\xi_{\pm y}}{\beta_y^*}(\frac{R_L}{R_y}) \quad , \tag{4.1}$$

there are three important ingredients; the vertical β function at IP (β_y^*), the beam currents (I) and the beam-beam parameter (ξ_y). In case of the upgrade from KEKB to SuperKEKB, about 40 times higher luminosity will be achieved by reducing β_y^* ($\times 20$) and increasing the beam current ($\times 2$), while assuming no improvement in ξ_y. Table 3 compares the machine parameters. Note that the Crab waist scheme is not applied to the SuperKEKB design. Compared to KEKB/PEP II, we introduce large crossing angle, and less energy asymmetry in order to achieve longer Touschek lifetime in LER.

Figure 5 shows layout of the superKEKB, which will be built in the same tunnel as the KEKB. The upgrade includes a damping ring to inject low emittance positrons, new lattice designs for both rings to reduce the emittance, addition/modification of RF systems to circulate higher beam currents, and installation of new beam pipes with ante-chambers to avoid instability due to electron cloud produced by synchrotron radiation hitting the beam pipe. The final focusing system is composed of 8 superconducting final focusing (FF) magnets, and is designed with a half crossing angle of 41.5 mrad, larger than 11mrad at the present KEKB.

Table 3: Machine Parameters of KEKB and SuperKEKB

		KEKB		SuperKEKB	
Parameter	units	LER(e^+)	HER(e^-)	LER(e^+)	HER(e^-)
E_b (energy)	GeV	3.5	8.0	4.0	7.0
ε_x (horizontal emittance)	nm	18	24	3.2	4.6
β_y at IP	mm	5.9	5.9	0.27	0.30
β_x at IP	mm	1200	1200	32	25
Half crossing angle	mrad	11		41.5	
I_b (beam current)	A	1.6	1.2	3.6	2.6
Lifetime	min.	130	200	~ 10	
L (luminosity)	cm^{-2}s^{-1}	2.1×10^{34}		80×10^{34}	

4.1 Belle II detector

Upgrade of the Belle detector is also in progress to deal with higher background ($\times(10-20)$), radiation damage, higher occupancy, and higher event rates (up to 30 kHz at Level 1), as shown in Figure 6. Detector construction is made by an international collaboration, consisting of more than 600 researchers from 98 institutes from 23 countries/regions. The detector upgrade from Belle to Belle II includes,

- Replacement of the 4-layer silicon vertex detector (SVD) with the vertex detector system, consisting of 2-layer silicon pixel (PXD) and 4-layer doubles-sided silicon strip (SVD) detectors.
- Replacement of the central drift chamber (CDC) with the one having smaller cell size and larger outer diameter, providing better momentum resolution with longer lever arms.

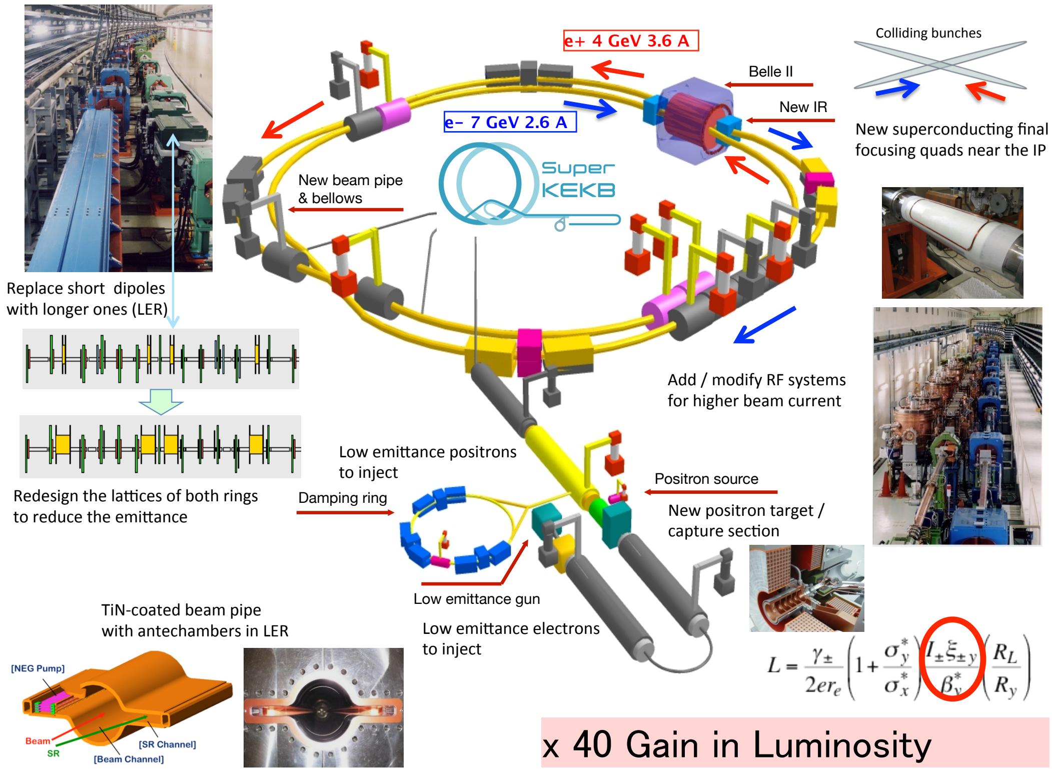

Figure 5: Layout of the SuperKEKB

- Replacement of particle identification system based on threshold aerogel Cherenkov counters (BACC, EACC) with novel ring imaging Cherenkov counters: Time-Of-Propagation (TOP) counter for the barrel and Aerogel RICH for the endcap part.

- Introduction of waveform sampling readout electronics for the electromagnetic calorimeter (ECL). Introduction of pure CsI crystals to the endcap parts are also anticipated.

- Replacement of the Resistive Plate Chambers (RPC) with scintillator based counters read out by Silicon Photomultiplier (Si-PM) for the endcap KLM and the innermost 2 layer of the barrel KLM.

- Introduction of custom trigger/DQ system based on an optical fiber data transmission (”Belle2link”) from the front-end electronics to the back-end ”COPPER” boards, a timing distribution system (”FTSW (Frontend Timing SWitch)”) etc.

In order to process large data produced with high luminosity and also generate Monte Carlo events, a grid computing network and an analysis framework are also being prepared.

5. Plan & Summary

As reported in this paper, the Belle II experiment at SuperKEKB aims to find New Physics with ultimate precision measurement of heavy flavor decays at the order of 10^{10} samples per year.

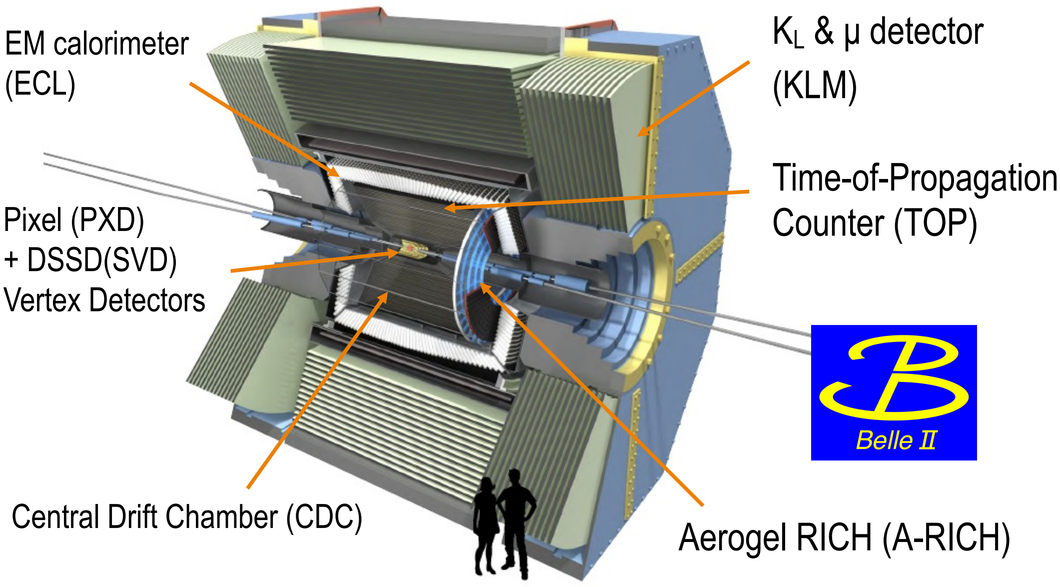

Figure 6: Belle II detector

Lattice QCD provides crucial inputs to extract physics from the results. We need precise enough calculations timely. We will start commissioning of SuperKEKB in early 2016. Belle II physics run will start in 2017 without the vertex and in 2018 with the full detector. These facilities will provide us with unique data sets to test and elucidate BSM physics in a TeV scale. Let us prepare for exciting future in heavy flavor physics!

Acknowledgments

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