

The Belle II experiment: status and physics program

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Abstract. The Belle II experiment at the SuperKEKB asymmetric-energy e^+e^- collider in Japan aims to search for new physics in the flavour transitions in the quark and lepton sectors. The SuperKEKB accelerator will operate at the target instantaneous luminosity of $8 \times 10^{35} \text{ s}^{-1}\text{cm}^2$. It requires a substantial upgrade of the detector subsystems which are expected to record 50 ab^{-1} of data. Such a huge data sample in clean background environment allows for probing signatures of new physics through suppressed flavour physics reactions and cross checks for deviations from the Standard Model measured at the LHCb experiment. Physics data taking at the Belle II experiment successfully started in April 2018.

1 Introduction

It is well known, the Standard Model (SM) is not a complete theory. Many New Physics (NP) scenarios have been proposed to get rid of blind spots of elementary particle physics. Experiments in high energy physics search for NP using two complementary approaches. The first, at the energy frontier, is able to discover new particles directly produced in pp -collisions. It is the Large Hadron Collider (LHC) era. Sensitivity to this production depends on the cross sections and recorded statistics. The second approach, at the intensity frontier, seeks to reveal new weak interactions in the flavor sector beyond the SM. Such interactions can occur if a new particle exists and appears in an intermediate state of rare processes. The Belle II experiment aims to discover such interactions.

There are many unique advantages of the Belle II experiment resulting in a capability to resolve the mysteries of particle physics. Relatively low background environment allows for excellent reconstruction of final system with photons in a wide energy region from neutrals, such as π^0 , η , η' and etc. Due to low track multiplicity we have high B , D and τ reconstruction efficiencies. As a result, B factories are also charm and tau factories. Since e^+e^- collisions produce a clean samples of B mesons from the initial known $\Upsilon(4S)$ state, missing mass analyses based on the energy-momentum conservation law can be performed. Detection of decay products of one of B meson allows the flavour of the rest B meson to be tagged. All these possibilities make the Belle II experiment to be unique to perform cross checks for many deviations from SM measured at the LHCb experiment.

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2 The SuperKEKB design concept

The SuperKEKB accelerator is located at High Energy Accelerator Research Organisation (KEK) in Japan. The accelerator tunnel was originally built for the TRISTAN complex [1] in eighties. It was reused for the KEKB project [2] until 2010. The length of the accelerator ring is 3 km and it is located at a distance of 11 m below the ground level.

The designed target luminosity of SuperKEKB is $8 \times 10^{35} \text{ s}^{-1}\text{cm}^2$, which is 40 times higher than that of KEKB. To achieve such increase of luminosity, a nanobeam scheme proposed by P. Riamondi for the Italian SuperB factory is applied. Reduction in the beam size at the interaction point by a factor of 20 (from $1 \mu\text{m}$ to 50 nm) and an increase of beam currents by a factor of two compared to KEKB values are the basis of this scheme. Two beams at SuperKEKB collide at a larger crossing angle which is 83 mrad instead of 22 mrad at KEKB. This choice allows for decrease of the detector background due to synchrotron radiation. A smaller beam-energy asymmetry of 7 GeV for electrons and 4 GeV for positrons in comparison of 8 GeV and 3.5 GeV at KEKB is chosen. It allows to reduce a beam loss due to Touschek effect in the lower energy beam.

Modification of the accelerator complex includes a new target of positron production, new additional damping ring for the positron beam, replacing dipoles in the low energy ring with new ones, redesigned interaction region and so on. The range of beam energies for physics studies covers the $\Upsilon(1S)$ and $\Upsilon(6S)$ resonances. A detailed description of the SuperKEKB complex can be found in Ref. [3].

3 The Belle II detector

Since the beam background for SuperKEKB is significantly higher than at KEKB, the detector systems have to be also upgraded. The modified Belle II detector includes several renovated subsystems (Fig. 1). The new vertex detector (VXD) is comprised of two devices:

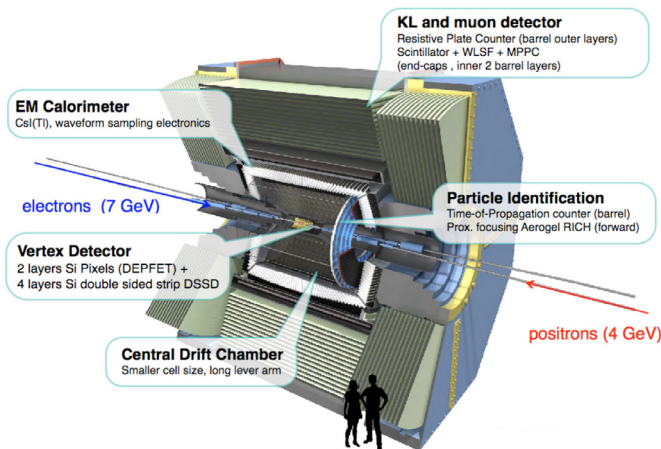


Figure 1. Overview of the Belle II detector.

a Pixel Vertex Detector (PXD) including two layers of pixalated sensors based on DEpleted P-channel Field Effect Transistor (DEPFET) technology and a double-sided Silicon strip Vertex Detector (SVD) with four layers of silicon strip sensors. Significant improvement of the

vertex resolution by a factor of 2 compared to the Belle detector is expected. The central tracking system is a large volume Central Drift Chamber (CDC) surrounding the VXD. To be able to operate at high event rates, CDC has been modified with smaller cells. A particle identification system includes the Time-Of-Propagation (TOP) system in the barrel region which is a kind of Cherenkov detector and Aerogel Ring Image Cherenkov (ARICH) detector in the forward region. In the TOP system the time of propagation and the impact position of a Cherenkov photon are measured. In the ARICH detector the number of Cherenkov photons is detected. The Electromagnetic Calorimeter (ECL) based on CsI(Tl) crystals is used to detect photons and identify electrons. New calorimeter electronics has been implemented to decrease the large level of pile-up noise. The K-Long and Muon (KLM) detector located outside the superconducting solenoid has been equipped by layers of scintillator strips with silicon photomultipliers to be able to operate with significantly higher neutron fluxes. The Belle II detector is described in Ref. [4].

4 Belle II schedule

The Belle II schedule includes two main phases before full physics commissioning which will start in February 2019. These periods known as Phase 1 and Phase 2 were scheduled in 2016 and 2018, respectively.

During Phase 1, the solenoid was not active and no collisions took place. The Belle II detector was in a roll-out position and a system of radiation detectors called as BEAST II (Beam Exorcism for A Stable Belle II experiment) has been placed at the interaction region. The BEAST II detectors collected beam background data to validate the Monte Carlo simulation of the beam backgrounds in the detector. The possible beam-induced backgrounds at SuperKEKB are Touschek effect which is an intrabunch scattering, beam gas scattering which is a Coulomb scattering with the residual gas in the vacuum beam pipe, synchrotron radiation, radiative Bhabha and two-photon processes.

During Phase 2, the Belle II detector was rolled to the beam line but without the full vertex system. Only one octant of the PXD and SVD, consisting of 2 and 4 layers, respectively, was included. The main aim of Phase 2 is the SuperKEKB accelerator commissioning and BEAST II background studies. All of outer detector systems (CDC, ECL, TOP, ARICH and KLM) were included in Phase 2. It is also a good possibility to debug Data Acquisition (DAQ) system stability. Belle II successfully recorded the first beam collision events on 26 April 2018. It is the most important milestone! Many known resonances have been rediscovered from Phase 2 collision data. We show the invariant mass distribution of $\pi^0 \rightarrow \gamma\gamma$ in 5 pb^{-1} of collisions data in Fig. 2. The photons forming π^0 candidates are required to have a minimum energy of 150 MeV and to be within the CDC acceptance. Calibration and resolution fit studies are ongoing.

After integration of the full vertex system in summer 2018, the Belle II detector will have the full systems for physics commissioning stage.

5 Belle II physics program

The Belle II experiment focuses on precision measurements and search for NP hints in rare events with large data statistics. The "Belle II Theory interface Platform" (B2TiP) [5] is organised to study the potential physics topics for Belle II. In my talk, I cover only a few of them.

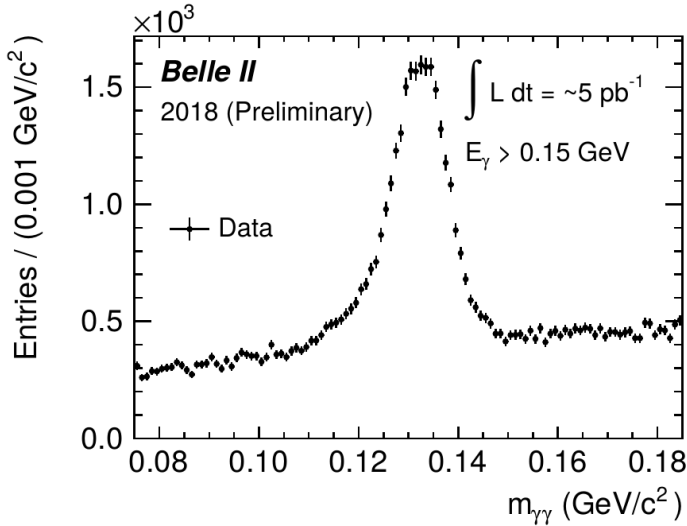


Figure 2. The invariant mass distribution $m_{\gamma\gamma}$ for π^0 candidates from Belle II first collision data.

5.1 $B^+ \rightarrow \tau^+ \nu_\tau$

The branching fraction (BF) of the leptonic B -decay $B \rightarrow l^+ \nu_l$ ($l = e, \mu, \tau$) is

$$\mathcal{B}(B^+ \rightarrow l^+ \nu_l) = \frac{G_F^2}{8\pi} f_B^2 |V_{ub}|^2 m_B \tau_B m_l^2 \left(1 - \frac{m_l^2}{m_B^2}\right)^2, \quad (1)$$

where G_F is the Fermi constant; V_{ub} is the Cabibbo-Kobayashi-Maskawa (CKM) element; f_B is the B -decay constant; τ_B is the B meson lifetime; and m_l and m_B are masses of the lepton and B meson, respectively. The leptonic width in Eq. 1 is proportional to the squared mass of the charged lepton m_l^2 due to the helicity suppression. The largest BF corresponds to the τ lepton. Taking $|V_{ub}| = (3.55 \pm 0.12) \times 10^{-3}$ [6] and $f_B = (186 \pm 4)$ MeV [7], the SM prediction for the $B^+ \rightarrow \tau^+ \nu_\tau$ decays calculated from Eq. 1 is $\mathcal{B}_\tau = (7.7 \pm 0.6) \times 10^{-5}$. The uncertainty comes from the V_{ub} CKM element determined from exclusive semileptonic B decays and the B weak decay constant from lattice calculations. Single measurements from the B -factories find a significance less than 5σ . NP particles (charged Higgs-like bosons, leptoquarks, ...) can contribute to the matrix element in Eq. 1 modifying the probability of the decay. To search for these contributions, further improvement of experimental accuracy is required.

Measurements of leptonic decays are performed using either the untagged method where the missing momentum of neutrino is determined from the whole event or tagged method where the other B meson in the event is reconstructed in well-defined decays in hadronic or semileptonic modes. Unfortunately, none of them is optimal. They compete to achieve the best purity of the signal sample or efficiency. To reconstruct a τ lepton, leptonic ($\tau \rightarrow l \nu_l$) and hadronic ($\tau \rightarrow \pi(\rho)\nu$) decay modes are used. We expect that the $B^+ \rightarrow \tau^+ \nu_\tau$ process will be observed with much larger than 5σ significance at the Belle II experiment.

5.2 $\bar{B} \rightarrow D^{(*)} \tau^- \bar{\nu}_\tau$

The $\bar{B} \rightarrow D^{(*)} \tau^- \bar{\nu}_\tau$ decays are described by the tree-level diagram that proceeds in the SM through the exchange of virtual W boson. The Lepton Flavour Universality (LFU) ratio

$$\mathcal{R}_{D^{(*)}} = \frac{\mathcal{B}(B \rightarrow D^{(*)} \tau \nu_\tau)}{\mathcal{B}(B \rightarrow D^{(*)} l \nu_l)}, \quad (2)$$

where $l = e$ or μ , is a useful quantity to search for NP contributions as theoretical uncertainties in transition form factors $B \rightarrow D^{(*)}$ as well as $|V_{cb}|$ CKM element cancel out. Measurements of $\mathcal{R}_{D^{(*)}}$ from Belle [8, 9], BaBar [10] and LHCb [11] show a combined tension with the SM prediction [12] at the 4σ level. The current precision can be significantly extended at Belle II. Existing average and expected Belle II constraints are shown in Fig. 3. With the

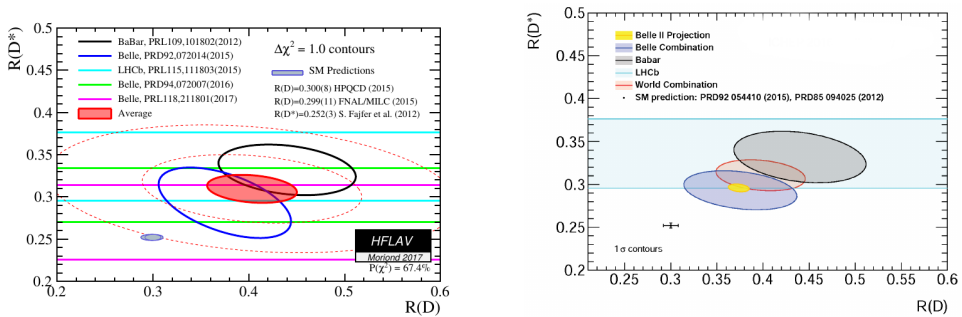


Figure 3. Measurements on \mathcal{R}_D and \mathcal{R}_{D^*} . The left side shows the current average from [6]. The right side shows the Belle II sensitivity with the full data set.

Belle II data set the NP effects will be tested from differential distributions of momentum transfer to the lepton pair and polarization of the τ lepton. The latter can be measured from the helicity distribution of the hadronic τ decay mode. The current Belle measurement [9] of the τ lepton polarization in the decay $\bar{B} \rightarrow D^* \tau^- \bar{\nu}_\tau$ is in agreement with the SM value of -0.497 ± 0.013 [13] within its uncertainty.

5.3 $\bar{B}^0 \rightarrow \pi^+ \tau^- \bar{\nu}_\tau$

Since experimental measurements of \mathcal{R}_D and \mathcal{R}_{D^*} are off the SM expectation, it is therefore natural to search for similar effects in the transition of b quark to up quark, i.e. measuring of \mathcal{R}_π . The SM value of \mathcal{R}_π is 0.641 ± 0.016 . The Belle collaboration [14] observed no signal but the upper limit of 2.5×10^{-4} has been obtained at 90% confidence level. This result has already disfavoured NP contributions larger than those of SM. To evaluate the Belle II sensitivity to the mode under consideration, the central value identical to the SM prediction is assumed and uncertainties are extrapolated from the Belle measurement. Assuming the Belle II integrated luminosity of 50 ab^{-1} , the \mathcal{R}_π expectation from the Belle II is 0.64 ± 0.09 .

5.4 $B \rightarrow K^{(*)} l^+ l^-$, $l = e, \mu$

B decays to K or K^* in pair with leptons $l^+ l^-$ ($l = e, \mu$) proceed through Flavour Changing Neutral Currents (FCNC) at loop level in SM. Again, the LFU ratio

$$\mathcal{R}_{K^{(*)}} = \frac{\mathcal{B}(B \rightarrow K^{(*)} \mu^+ \mu^-)}{\mathcal{B}(B \rightarrow K^{(*)} e^+ e^-)} \quad (3)$$

could be appropriate to test for NP because theoretical uncertainties cancel out in the ratio and the SM prediction is very close to unity. So, any deviation from the SM value would be a sign of NP. Current measurements of ratios \mathcal{R}_K and \mathcal{R}_{K^*} deviate from the SM expectation by 2.6σ and 2.4σ , respectively, giving us a complementary information. The deviation observed for \mathcal{R}_{K^*} requires a painstaking analysis of the angular distributions in the $B \rightarrow K^*l^+l^-$ channel. Such analysis with optimised observables is a powerful tool to search for NP effects. The LHCb measurements [15] show a tension in the optimised observable P'_5 for $B \rightarrow K^*\mu^+\mu^-$ with 3.3σ discrepancy from the SM.

The Belle II experiment is a unique place where it is possible to perform the cross-checks with LHCb for \mathcal{R}_K , \mathcal{R}_{K^*} and P'_5 . Independent validation of these deviations is very important. Belle II has also a great sensitivity to $B \rightarrow K^*e^+e^-$ decay due to a high reconstruction efficiency for electrons. It is also expected that Belle II can increase statistics in the low q^2 -region ($q^2 = M_{\mu^+\mu^-}^2$ is the invariant mass squared of a muon pair) for the P'_5 variable due to identification of low momentum muons in TOP and ARICH systems. Belle II measurements will be statistically limited with an uncertainty of about 3% for the full Belle II data set.

5.5 $\Upsilon(6S)$ physics

The operating point at the $\Upsilon(6S)$ resonance is the excellent first Belle II physics opportunity. The Belle detector collected only 5.6 fb^{-1} at $\Upsilon(6S)$ but not all "on-peak". A search for $\Upsilon(6S)$ closed-flavour decays is interesting for bottomonium(like) studies. It is interesting to understand the relative production of multiquark $Z_b(10610)$ and $Z_b(10650)$ states in $\Upsilon(6S) \rightarrow \pi^\pm Z_b^\mp$ decays with final decays to $h_b(1P, 2P)$ and $\Upsilon(1S, 2S, 3S)$. It may also be possible to search for W_{bJ} states in $\Upsilon(6S) \rightarrow \gamma W_b^0$ and $\Upsilon(6S) \rightarrow \pi^+\pi^- W_b^0$ decays with $W_b \rightarrow \eta_b\pi, \chi_b\pi, \Upsilon\rho$ as well as isoscalar X_{bJ} states in $\Upsilon(6S) \rightarrow \gamma X_b$ and $\Upsilon(6S) \rightarrow \pi^+\pi^- X_b$ decays with $X_b \rightarrow \omega\Upsilon(1S)$. New conventional $h_b(3P)$ and $\Upsilon(2D)$ states can be also found.

5.6 Dark sector

Belle II is a good place to search for dark sector mediators decaying into invisible and visible particles. A vector gauge singlet, dark photon A' , couples to the SM electromagnetic current with a coupling strength ϵ arising from kinetic mixing of the hypercharge and the vector field strength. A search for a dark photon decaying into the light Dark Matter (DM) particles requires an efficient single photon trigger which was not realised at Belle but would be at Belle II. The background is dominated by high cross section Quantum ElectroDynamics (QED) processes that produce one or more photons. If the charged tracks in the radiative Bhabha scattering $e^+e^- \rightarrow e^+e^-\gamma$ or additional photons in the $\gamma\gamma$ processes $e^+e^- \rightarrow \gamma\gamma, \gamma\gamma\gamma$ are not detected, they can fake single-photon events. A simulation shows it occurs due to non-negligible photon detection inefficiencies in the ECL. Figure 4 shows the Belle II sensitivity to the production of a dark photon A' decaying to DM particles with a 20 fb^{-1} data set.

6 Summary

The Belle II experiment is expected to collect a unique data set of 50 ab^{-1} , which will greatly extend our current knowledge of flavour physics.

The SuperKEKB collider has successfully completed the commissioning Phase 2 in July 2018. The Phase 2 was extremely useful: many background studies and detector checkouts have been performed. The first data taking runs for physics analyses have been recorded. First physics studies are ongoing. Many known resonances and processes have been rediscovered.

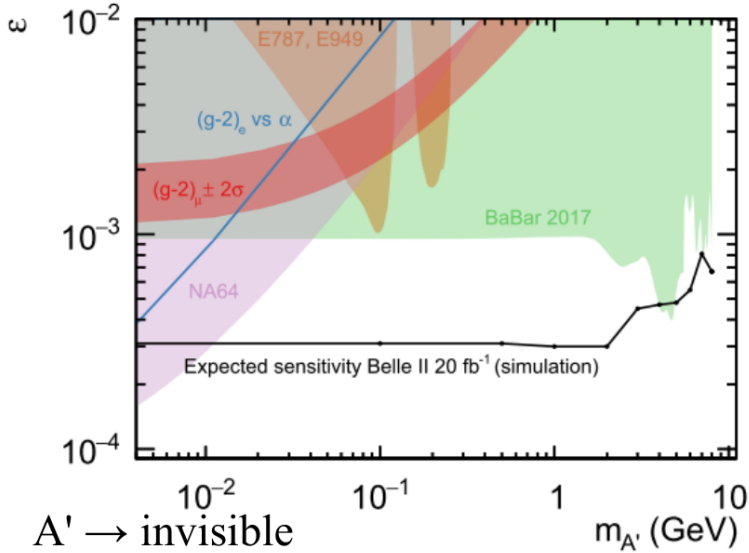


Figure 4. Expected Belle II sensitivity to the dark photon searches from monophoton events. Sensitivity to ϵ coupling vs. dark photon mass $m_{A'}$ is shown.

The physics commissioning stage with the full Belle II systems is expected to start in early 2019.

Belle II physics potential is enormous. Most of the Belle II sensitivity studies have been prepared within the B2TiP platform where theorists and experimentalists developed an optimal physical strategy for the Belle II experiment. The Belle II aims to search for NP hints currently observed and maybe more.

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