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The Belle II Experiment: Status and Prospects

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Abstract. The Belle II experiment is a substantial upgrade of the Belle detector and will operate at the SuperKEKB energy-asymmetric e^+e^- collider. The accelerator has already successfully completed the first phase of commissioning in 2016. First electron positron collisions in Belle II have been delivered in April 2018. The design luminosity of SuperKEKB is 8x$10^{35}cm^{-2}s^{-1}$ and the Belle II experiment aims to record 50 ab^{-1} of data, a factor of 50 more than the Belle experiment. This large data set will be accumulated with low backgrounds and high trigger efficiencies in a clean e^+e^- environment. This contribution will review the detector upgrade, the achieved detector performance and the plans for the commissioning of Belle II.

1 Introduction

Even though the Standard Model is currently the best description of the subatomic world, it does not explain the complete picture. The theory incorporates only three out of the four fundamental forces, omitting gravity. Moreover there are also important questions that it does not answer, such as the matter anti-matter asymmetry in the number of quark and lepton generations. Many New Physics (NP) scenarios have been proposed. 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 (ATLAS, CMS). 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. The advantages of the Belle II experiment with respect to a hadron-collider experiment are:

1. full solid angle detector coverage;
2. relatively clean environment of e^+e^- collisions w.r.t. hadronic environment;
3. the possibility to completely reconstruct the final state.

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'. Due to low track multiplicity we have high B, D and τ reconstruction efficiencies. As a result, B factories are also charm and τ factories.

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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. Belle II also exploit the detection of decay products of one of B meson to be tagged. All these possibilities make the Belle II experiment to be unique to perform NP measurements and important cross checks for many deviations from SM measured at the LHCb experiment.

2 The SuperKEKB design concept

The SuperKEKB accelerator [1]is upgraded from KEKB as shown in Figure 1. The target luminosity is 8x$10^{35}cm^{-2}s^{-1}$ and it is higher than that of KEKB by factor 40. The beam energies for the High Energy Ring (HER) and the Low Energy Ring (LER) are 7 GeV and 4 GeV, respectively. The energy of the LER has been increased to obtain larger dynamic acceptance. The designed HER and LER beam currents are 2.6 A and 3.6 A, respectively. Several upgrades were performed to achieve those performances. The most important one is the nano-beam collision scheme. The lower emittance and the smaller vertical β^* in the interaction point (IP) are critical. New lattice design has been applied to the HER and totally new ring was built for the LER to reach the low emittance. A pair of new superconductive final focusing magnets were designed and fabricated. In this framework it is essential to squeeze the beams. To achieve this purpose quadrupole magnets, compensation solenoid magnets and correction magnets in the single cryostat have been installed. Moreover new TiN-coated beam pipes with the antechamber structure were designed and constructed to reduce the photoelectron cloud in the LER. A new damping ring was built in the injection linac section to meet the request for the LER with the smaller acceptance. Moreover higher bunch current and shorter bunch length might cause hardware troubles due to higher heat load of the Higher Order Mode (HOM) loss. Therefore, the bunch luminosity in KEKB 1.2x$10^{31}cm^{-2}s^{-1}$ was rather low if compared with other accelerators. But, due to the double ring design, around 1600 bunches could be stored in each ring and the world highest luminosity could be achieved. The storage of more bunches is relatively straightforward to get higher luminosity. However, the RF frequency limits number of bunches to about 5000 thus allowing only a factor three should the KEKB collision scheme be used. Figure 2 shows the collision image for KEKB and SuperKEKB. The overlap region is rather large in KEKB even for the small crossing angle. The collision spot is much smaller in SuperKEKB due to the smaller horizontal beam

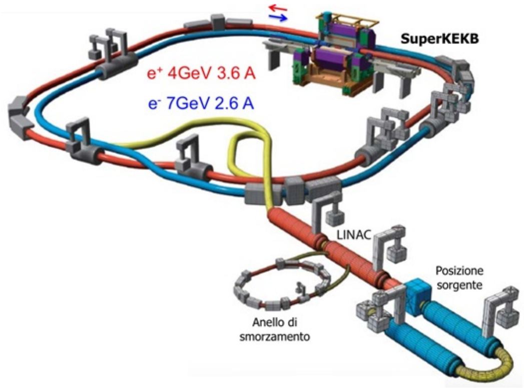

Figure 1. Schematic view of the SuperKEKB accelerator.

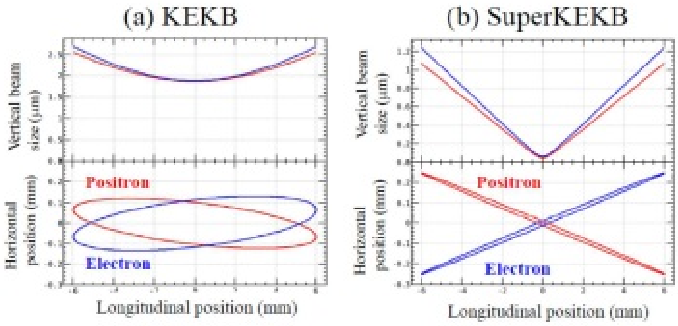

Figure 2. The vertical beam size and the collision image for both beams at KEKB (a) and SuperKEKB (b).

size (lower emittance) and the larger crossing angle, thus allowing us to treat each bunch as many subdivided "non interacting" bunches. In this way, the nano-beam collision scheme can be exploited to reach the bunch limit luminosity.

3 The Belle II experiment

Belle II is an hermetic magnetic spectrometer and is a major upgrade of the Belle experiment that operates at the B-factory SuperKEKB, located at the KEK laboratory in Tsukuba, Japan [2]. The SuperKEKB facility is designed to collide electrons and positrons at center-of-mass energies in the region of the Υ resonances. Most of the data will be collected at the $\Upsilon(4S)$ resonance ($\sqrt{s} = 10.58$ GeV), which is just above threshold for B-meson pair production. In the case of $B\overline{B}$ production hence no additional fragmentation particles are produced. The accelerator is designed with asymmetric beam energies to provide a boost to the center-of-mass system and thereby allow for time-dependent CP violation measurements. The boost is slightly lower than that at KEKB, which is advantageous for analyses with neutrinos and missing energy in the final state, that require a good detector hermeticity. SuperKEKB has a design luminosity of $8\text{x}10^{35}cm^{-2}s^{-1}$, about 40 times larger that of KEKB, with the aim to collect 50 ab^{-1} of data in 8 years. The first data taking runs for physics analyses have started in April 2018, with a lower luminosity than the designed one. In this particular running condition, (called Phase 2) which serves mainly for machine commissioning and beam background studies, we have reached a peak luminosity of $5\text{x}10^{33}cm^{-2}s^{-1}$ and collected about $500pb^{-1}$ of data by the end of July 2018. A new data taking phase (phase 3) will start in February 2019, luminosity is expected to increase to its designed value and the background is expeted to be significantly higher. Therefore the detector systems will be upgraded. The modified Belle II detector includes several renovated subsystems (Figure 3).

The new vertex detector (VXD) consists of two sub-detectors: a Pixel Vertex Detector (PXD) including two layers of pixalated sensors based on DEpleted P-channel Field Ect Transistor (DEPFET) technology and a double-sided Silicon strip Vertex Detector (SVD) with four layers of silicon strip sensors. A factor 2 on the vertex resolution compared with the Belle vertex detector is obtained with this strategy. 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

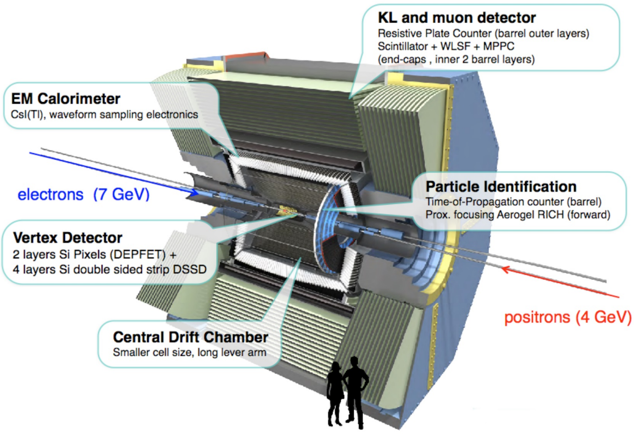

Figure 3. Overview of the Belle II detector.

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 and the position of Cherenkov photons are 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 [3].

4 Belle II schedule

The Belle II schedule consists of 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 Exsorcism 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, an intrabunch scattering, beam gas scattering 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, with only one octant of the PXD and SVD detector, was rolled to the beam line. The main aim of Phase 2 is the SuperKEKB commissioning and BEAST II background studies. All of outer detector systems (CDC, ECL, TOP, ARICH and KLM) were included in Phase 2. An intense debugging phase started and Belle II successfully recorded the first beam collision events on 26 April 2018. Many known resonances have been rediscovered. We processed 500 pb-1 and show the invariant mass distribution of J/ψ left and D^+ in Figure 4. The full vertex system detector will be installed in summer 2018 and the Belle II detector will be ready for physics commissioning stage.

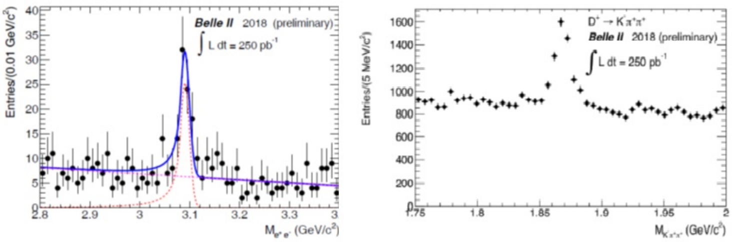

Figure 4. Invariant mass plot for J/ψ and D^+ candidates

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) [4] is organised to study the potential physics topics for Belle II. In this contribution, I cover only a few of them.

5.1 Dark photon searches

A new vector particle A^μ can couple to the Standard Model (SM) electromagnetic current $J^\mu{}_{SM}$ via the so-called vector portal. At Belle II the Dark Photon can be searched for in process $e^+e^- \to \gamma_{ISR}$ $A^{'}$, whose cross section is proportional to $\epsilon^2\alpha/s$ where ϵ is the $A^{'}$ coupling constant with the γ, α is the electromagnetic coupling constant and s the center of mass energy. The Dark Photon can decay to SM final states or to Dark Matter (DM) final states if $A^{'}$ is not the DM lightest particle. Since the DM particles do not interact with the detector, the experimental signature of this decay is a monochromatic photon (γ_{ISR}), having energy E_γ=(s-$m^2_{A^{'}}$)/2 $\sqrt{s}$, plus missing energy. A full detector simulation, including all the relevant QED backgrounds, was performed in order to evaluate the sensitivity of Belle II (also during the Phase II running condition) to $A^{'}$ decaying into an invisible final state [5]. The main sources of background for this search have been found to be radiative Bhabba and $\gamma\gamma$ events where all but one photon are not detected by Belle II, mainly because of small but not-neglibile photon detection inefficiencies in the ECL. The expected Belle II sensitivity for an integrated luminosity of 20 fb^{-1} is shown in Figure 5. The better expected sensitivity compared to BaBar is due to the more homogeneous electromagnetic calorimeter of Belle II, whose barrel part has no projective gaps to the interaction point. The expected sensitivity with the full dataset of 50 ab^{-1} is also shown.

5.2 Searches for Axion-Like Particles

Axion-like Particles (ALPs) are hypothetical pseudo-scalar that can couple to the SM gauge boson via the so-called axion portal. Axions were originally motivated by the strong CP problem and have a fixed relation between coupling strengh and mass. While the Axion and its parameters are related to QCD, the coupling and mass of ALPs are taken to be independent and can appear in a variety of extensions to the SM. The simplest search for ALPs is via its coupling to photons. There are two different production processes of interest at Belle II: ALP-stralung ($e^+e^- \to \gamma\ a$) and photon fusion ($e^+e^- \to e^+e^-\ a$). Even if ALP production via photon fusion tipically dominates over ALP-stralung (unless m_a is close to $\sqrt{s}$), the final state in photon fusion production features only two soft photons

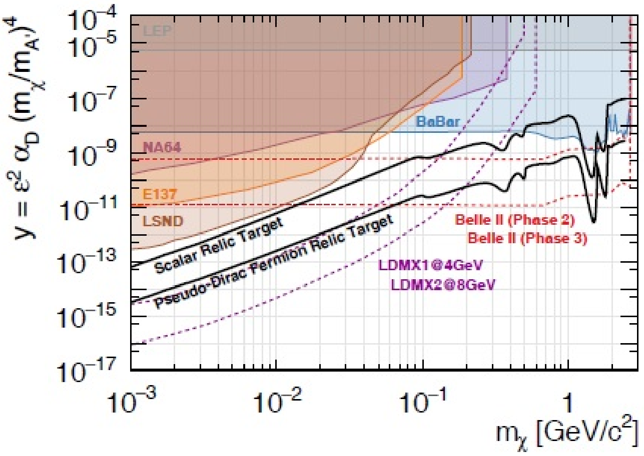

Figure 5. Expected upper limit (90 % CL on $y = \epsilon^2 \alpha_D$ for the process where the A' decays in DM for a 20 fb^{-1} dataset and for a 50 ab^{-1} dataset. In this plot α_D=0.5 and $m_D = m_{A'}/3$.

(from $a \rightarrow \gamma\,\gamma$) and missing momentum which will lead to very high QED background. The most promising search is therefore from ALP-stratung producton Figure 6. Depending on the ALP mass

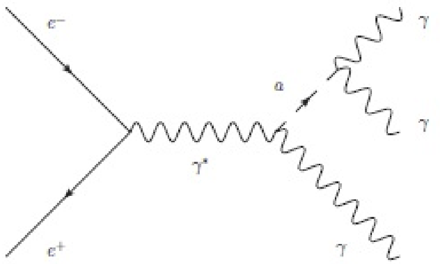

Figure 6. Feynman diagram for the process $e^+e^- \rightarrow \gamma\, a$, with $a \rightarrow \gamma\, \gamma$

its decay lenght can escape from the detector fiducial volume on not. If the ALP escape the fiducial volume its signature will be the same as the one of an invisibly decayng dark photon. On the contrary if its mass is high it'll be produced with a small boost, and the opening angle of the decay photons will be large thus giving three resolved and detectable photons in the final state. The main background is the three QED photon final state though also a two QED photon final state with an additional photon coming from machine background contributes. The expected Belle II sensitivity for the process $e^+e^- \rightarrow \gamma\, a$ in given in Figure 7 considering 20 fb^{-1} (Phase 2) and 50 ab^{-1} (full Belle II dataset).

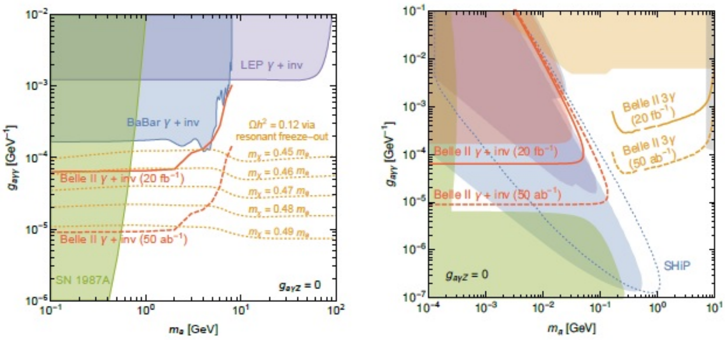

Figure 7. Expected upper limits (90 % CL) on the $g_{a\gamma\gamma}$ coupling constant for a 20 fb^{-1} dataset (Phase 2) and for a 50 ab^{-1} (Phase 3, full Belle II dataset)

5.3 Lepton flavour violation in τ decays

LFV τ decays are forbidden in the SM, but enhanced in NP models, with BRs up to the order of 10^{-8}. Belle II will have access to final states containing neutral particles (such as π^0, η, $\eta^{'}$). In these searches, the control of the beam backgrounds will be crucial and will be precisely assessed only during data taking. If we project the current upper limits to the expected Belle II integrated luminosity we can foresee an improvement of 1-2 orders of magnitude as summarized in Figure 8.

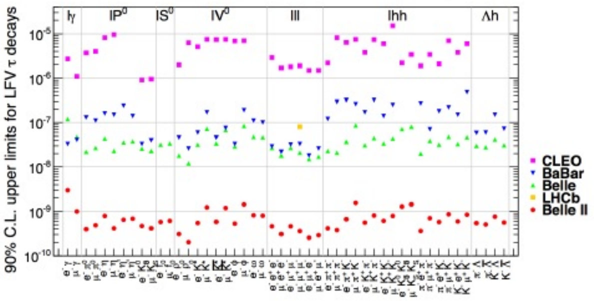

Figure 8. Upper limits on LFV τ decays 90% CL for 50 ab^{-1}

5.4 $B \rightarrow D^{(*)}\ \tau\ \nu_\tau$

This class of B decays are described in the SM by the tree-level diagram with a virtual W boson exchange. The Lepton Flavour Universality (LFU) ratio

$$R_{D^*} = \left(\frac{Br(B \rightarrow D^* \tau \nu_\tau)}{Br(B \rightarrow D^* l \nu_\tau)} \right)$$

together with:

$$R_D = \left(\frac{Br(B \rightarrow D \tau \nu_\tau)}{Br(B \rightarrow D^l \nu_\tau)} \right)$$

are two useful quantities to search for NP contributions as theoretical uncertainties in transistions form factors $B \to D(*)$ as well as V_{cb} CKM element cancel out. As shown in Figure 9 at the moment there is tension between Belle, BaBar, LHCb and the SM prediction. A 4 σ level effect is present. At Belle II the current precision can be significantly extended as shown in Figure 9.

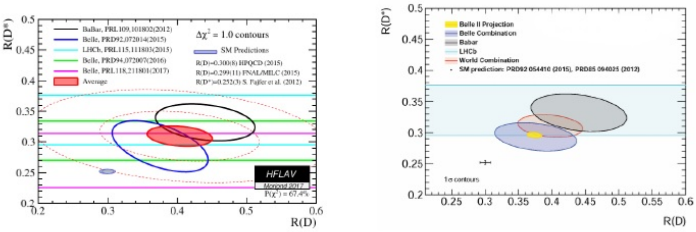

Figure 9. Measurement on R_D and R_{D^*}. the left side is the current average from [6]. The right side shows the Belle II sensitivity with the full data set.

6 Conclusions

The Belle II experiment has started the first data taking period on April 2018. Thanks to a hermetic and upgraded detector, Belle II will immediately have world leading sensitivity on the Dark Sector searches even with a small dataset if compared with previous generation B-factories. In addition to the Dark Sector program Belle II has a wide physics program spanning from Lepton Favour Violating searches to B meson rare decays.

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