The Belle II Experiment: Status and Prospects

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Summary. — The Belle II experiment, a substantial upgrade of the BELLE detector operating at the SuperKEKB energy-asymmetric e^+e^- collider, has recently restarted its data taking with the so called "Phase 3" run at the $\Upsilon(4S)$ resonance. Belle II is designed to operate at a peak luminosity of $8\times10^{35}\text{cm}^{-2}\text{s}^{-1}$ with a target integrated luminosity of 50 ab^{-1}, a factor of 50 more than the BELLE experiment. This will allow studies of B meson decays, along with charm, and many other physics topics, with unprecedent precision in the clean e^+e^- collider environment. In this paper the Belle II experiment is described, with its planned physics program and prospects.

1. – Introduction

Heavy Flavour physics plays an essential role in the understanding of the Standard Model (SM) and its mechanism. Previous experiments at the B factories [1] (BaBar at PEP II-SLAC, Stanford-USA and BELLE at KEKB, Tsukuba-Japan) deeply investigated this sector, but several SM predictions have still to be verified and the investigation of New Physics (NP) processes is crucial. For this purpose, a second generation B-factory, characterised by low-background environment and large data samples of B, D, and τ, will give exclusive advantages to its experiment w.r.t. hadronic machines. The Belle II experiment [2] is the successor of the previous generation asymmetric B factory experiments, intended to extend the reach within the domain of precision flavour measurements by collecting a data sample 50 times larger than the integrated luminosity of these previous experiments. BelleII is a collaboration of over 800 physicists from 26 countries world wide. The Belle II detector has been installed in the interaction region of the SuperKEKB e^+e^- collider [3] at the KEK laboratory, which is designed to operate at instantaneous luminosities of up to $8\times10^{35}\text{cm}^{-2}\text{s}^{-1}$, at approximately 10.5 GeV center-of-mass (CM) energy, in the proximity of the $\Upsilon(4S)$ resonance, see Fig.1. Asymmetric beam energies of 7 and 4 GeV for the e^- and e^+ beams, respectively, result in a CM system which is boosted along the beam (z) axis, with a factor $\beta\gamma = 0.28$, in order to facilitate the separation of B meson decay vertices produced in $\Upsilon(4S) \to B\bar{B}$ interactions, enabling time dependent CP violation studies. The "Phase 1" was successfully completed in 2016, with the commissioning of the SuperKEKB accelerator, then first collisions were recorded by

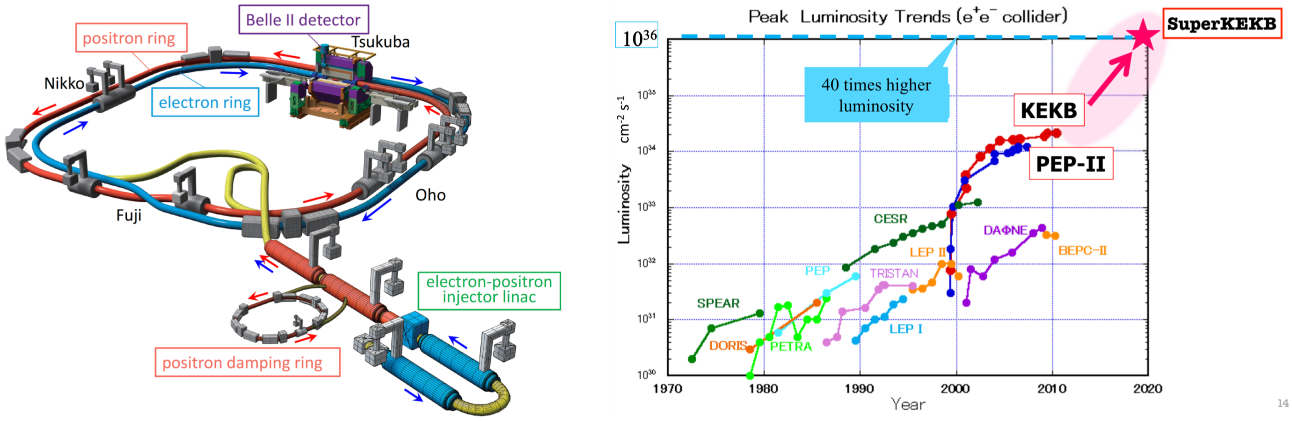

Fig. 1. – Schematic view of SuperKEKB collider (left). Luminosity profile of SuperKEKB compared with previous colliders (right).

Belle II during the "Phase 2" accelerator commissioning run in early 2018 without the Silicon Vertex Detector, and finally "Phase 3" physics data taking started in March 2019. In this paper an overview will be given of the SuperKEKB accelerator and the Belle II detector, followed by a description of some of the unique features of this experimental environment. The Belle II physics program, with a focus on prospects for studies on recent flavour anomalies will be presented. Finally, some initial results from the "Phase 3" physics run and future prospects will be described.

2. – The Belle II experiment at the SuperKEKB accelerator

The SuperKEKB accelerator is an upgraded version of the KEKB collider with design luminosity of $8\times10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, representing a 40-fold increase compared with its predecessor. This luminosity is achieved via a novel low-emittance nanobeam scheme, combined with a new positron damping ring and positron beam vacuum chamber used to increase the statistics collected by the experiment. The nanobeam scheme allows one to squeeze the beams at the interaction point up to 50 nm in the y direction and 5 μm along the x, as shown in Fig.2. At full luminosity, each beam will host 2500 bunches, with bunch crossings approximately every 4 ns. Given the cross sections for $e^+e^- \to f\bar{f}$ (where f represents any fermion), a rate of order 1 kHz of B$\bar{B}$ recorded events is expected, accompanied by several kHz of charm ($c\bar{c}$), light quark q$\bar{q}$ and $\tau^+\tau^-$ events. In addition, we expect approximately 30 kHz of Bhabha ($e^+e^- \to e^+e^-$) events within the detector acceptance. This last contribution needs to be rejected in real time by the first-level event trigger, while the other components are recorded and made available for data analysis via an inclusive trigger strategy. Consequently, the target integrated luminosity of Belle II of 50 ab^{-1} implies a data sample containing about 50 billion B$\bar{B}$ pairs and a similar size samples of τ and charm events. The Belle II detector [4] is based on the original BELLE detector, with substantial upgrades to all detector subsystems, as illustrated in Fig.3, in order to cope with the experimental challenges presented by the extremely high luminosity environment provided by SuperKEKB and the consequent higher machine background and pile-up. The entire inner detector region, which is provided by the

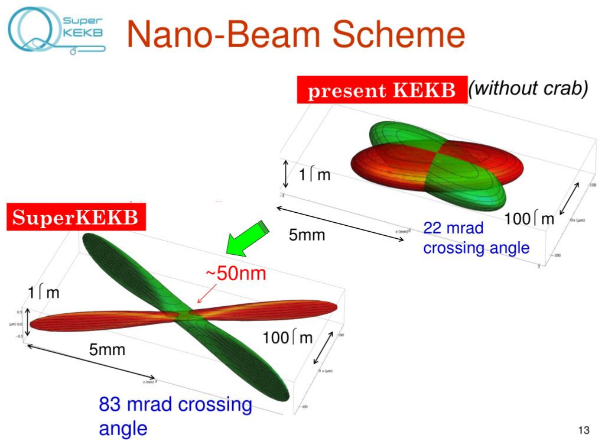

Fig. 2. – Schematic view of the nano beam scheme, comparison with the old scheme of interactions at BELLE.

tracking system, has been entirely replaced. The interaction point (IP) is surrounded by a low-mass beryllium beam pipe with a 2 cm diameter. The small diameter allows to host two completely new layers of DEPFET silicon pixel detectors placed in close proximity to the IP for precision decay vertex reconstruction. These detectors are then surrounded by an additional four layers of double-sided silicon strip detectors, with strips running perpendicular on the two sides, to provide additional xy space points for track and vertex reconstruction. They are designed to have extremely low material content, to minimize the degradation of tracking resolution due to multiple scattering. Additional tracking is provided by a large-volume cylindrical drift chamber based on a 50:50 mixture of helium and ethane. A total of 56 layers of tracking cells are radially arranged to nine groups of superlayers, in which the innermost superlayer has a reduced cell size to cope with the

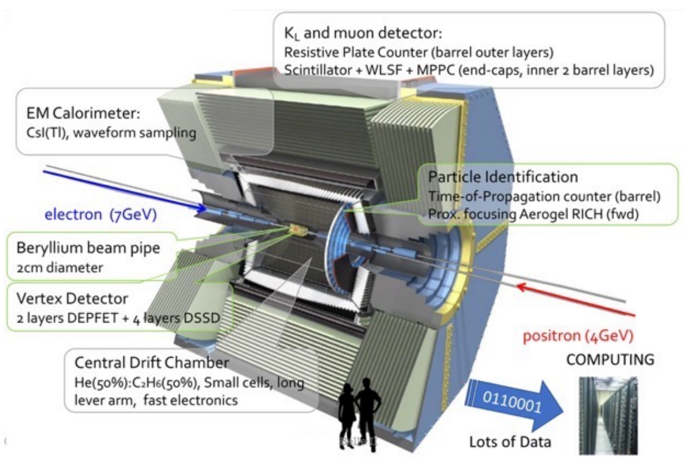

Fig. 3. – The Belle II detector.

higher occupancy arising from the high luminosity environment. Superlayers alternate between axial and stereo wires, in order to provide z-coordinate position information. The tracking detectors also provide particle identification (PID) capability via ionization energy deposition (dE/dx), and momentum measurement of charged particles as a result of a 1.5 T axial magnetic field provided by a solenoid positioned outside of the calorimeter. Additional PID, and in particular Kπ separation, in the central barrel region of the detector is provided by a time-of-propagation (TOP) detector, based on a novel configuration of a ring-imaging Cherenkov device, which exploits the total internal reflection of Cherenkov photons in synthetic quartz bars. This is complemented, in the forward endcap region, by a aerogel-based proximity focusing ring imaging Cherenkov system. Electrons and photons are reconstructed using energy measurements from a CsI(Tl) crystal calorimeter, reusing crystals and photodetectors from the original BELLE detector. At the same time, new front-end electronics and a new waveform fitting algorithm provides a faster and more precise energy determination in the high-luminosity environment of Belle II. The magnetic flux return of the solenoid is instrumented with a combination of RPC's and scintillators, read out by MPPC's via wavelength-shifting fibres, in order to provide identification of muons and neutral hadrons (K_L) which penetrate the calorimeter.

3. – The Belle II Physics Program

The previous generation of B factory experiments, Belle and BaBar, operated for approximately a decade and collected an integrated luminosity of the order of 1 ab^{-1} of data at the $\Upsilon(4S)$ resonance; in addition, data was collected at higher and lower mass Υ resonances and also off-peak. These experiments were designed to confirm the Kobayashi-Maskawa mechanism for CP violation within the Standard Model (SM). Therefore the target integrated luminosities for these experiments were driven by the need to validate or falsify the CKM description of CP violation. After the final experimental validation of this description, next generation flavour physics experiments have now substantially different physics goals. The Belle II experiment is designed to look for deviations from SM expectations, which could potentially reveal new physics contributions in a large variety observables in flavor physics. Therefore, its scientific program requires a higher degree of precision than previous B factory experiments, resulting in stringent requirements on data sample sizes. Relevant flavor physics observables include, in addition to CP violation measurements, also branching fractions, kinematic distributions, angular distributions and asymmetries in beauty and charm mesons, and τ lepton decays. In order to claim any observation of new physics, one would be required to measure one or possibly more significant deviations between measured observables and their theoretical predictions within the SM. More in detail, one is expected to either obtain precise measurements of specific flavour observables which deviate from precise theoretical predictions, or to observe rare or forbidden processes for which the SM predictions are well below experimental sensitivity. Examples of these two ways to discovery are CP violation studies, as illustrated by the unitarity triangle representations [5], and studies of electroweak flavour-changing-neutral-current (FCNC) B decays, respectively. In both cases the relevant decay processes can occur via loop-level processes, which can be largely modified by high-mass non-SM particles. Consequently, these measurements can potentially lead to the discovery of new physics coming from mass scales which are not accessible at the LHC. In addition, the study of the observed deviations could shed light on the nature of this high-mass new physics phenomena. Even though Belle II

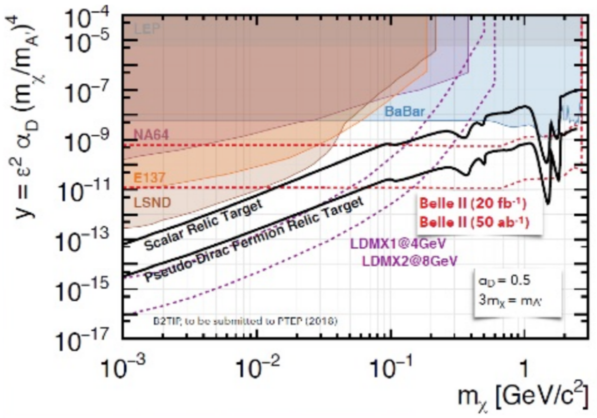

Fig. 4. – Limits on the coupling versus the mass of the dark candidate.

and LHCb shares many of the same physics objectives, the two experiments are highly complementary. LHCb profits from the large $b\bar{b}$ production cross section at the hadron machine, from the highly boosted topologies and from the production of a variety of B_d, B_s mesons and b-baryons. On the other hand, some decays are not accessible, due to the high background, in particular inclusive processes, some decays with neutral particles and decays with missing energy. Belle II conversely exploits the clean e^+e^- environment and exclusive $\Upsilon(4S) \to B_d\bar{B}_d$ production, with a broader range of B_d final states, even though with relatively low cross section and limited to B_d meson decays, unless dedicated running at the $\Upsilon(5S)$ resonance can be performed. This complementarity is exemplified by the recent measurements of anomalies in $B \to K^* l^+ l^-$ (where l = e,) by LHCb [6, 7]. Although these modes have been studied previously at B factory experiments, the large sample of B_d mesons available at LHCb lead to an improved precision in the measurement of the lepton universality ratio, $R_{K^{(*)}}(q^2) \equiv \mathcal{B}(B \to K^{(*)}\mu^+\mu^-)/\mathcal{B}(B \to K^{(*)}e^+e^-)$, as a function of q^2. A combined 3σ deviation from SM expectations has been observed. Further investigation of this discrepancy is needed and urgent, being an excellent place to look for new physics, given the SM suppression of FCNC processes. Belle II will play a major role in the study of these modes, in both charged and neutral B decays, thanks to the expected luminosity, much higher than previous B factory experiments. From simulation studies, Belle II is expected to reach comparable precision to the current LHCb measurements with an integrated luminosity of about 5 ab^{-1}, which corresponds to about 10% of the full dataset. In addition, Belle II measurement, using distinct methodology, could provide an important crosscheck and validation of the LHCb results. The two experiments will simoultaneously provide further precision to these measurements over the coming decade. If new physics effects are observed in $R_{K^{(*)}}(q^2)$, they would very likely result in observable deviations also in other B decay processes which proceed via similar one-loop FCNC decays. Last but not least, studies of the dark sector and search for dark matter candidates - i.e. dark photon (Fig.4) - will be particularly important in the beginning of the Phase 3 run, and first results are expected with the initial luminosity. For this purpose, Belle II will use a dedicated single photon trigger, in order to be able to reconstruct hypotetical dark matter decay into an invisible final state, using the presence of a single photon and missing energy as signature. The Belle II physics

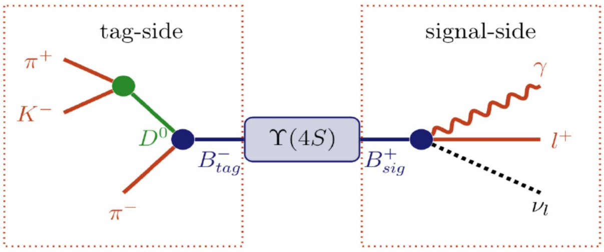

Fig. 5. – Particles reconstruction in the tag- and signal- side respectively.

program strength is then based on the ability to test new physics scenarios with high precision across a large number of decay modes.

3˙1. *B decays with missing energy*. – Belle II has unique capabilities to reconstruct final states with one or more undetected particles, including neutrinos or possible non-interacting new physics particles, thanks to the precisely known e^+e^- initial state and the hermeticity of the detector. Many interesting B meson decay processes fall into this category, including $B \to D^{(*)}\tau\nu$ and the related tree-level leptonic decays $B^+ \to \tau^+\nu$ and $B^+ \to \mu^+\nu$, as well as the flavour-changing-neutral-current decays $B \to K^{(*)}\nu\bar{\nu}$ and others. A common feature of these decays is the presence of multiple neutrinos in the final state, produced either directly in the B decay or via the secondary decays of τ leptons. Since B meson production occurs exclusively via $\Upsilon(4S)$ production, reconstructed particles, and also the missing energy four-vector, can be associated with a signal decay mode by using information on the decay of the other B meson. Belle II takes advantage of a powerful tool called Full Event Interpretation (FEI) [8]. The B-tag side is completely reconstructed and its flavor derived, in both semi-leptonic and hadronic decay, the latter being more precise but less efficient. This allows one to infer the flavour of the B-signal and isolate decay particles, thus obtaining large advantages in analysis with missing energy and missing mass, see Fig.5. The clean background environment and the very good hermeticity of the detector are essential for the full exploitation of the FEI algorithm. A factor of 2 larger efficiency is expected from simulation studies, w.r.t. previous versions of the reconstruction algorithm, yielding a larger effective data sample. In this way, Belle II is able to access many missing-energy modes, otherwise excluded by the lack of a reconstructable signature. A relevant example is the decay $B \to D^{(*)}\tau\nu$, which has shown indications of tension with respect to SM predictions in the ratio $R(D^{(*)}) \equiv \mathcal{B}(B \to D^{(*)}\tau\nu)/\mathcal{B}(B \to D^{(*)}l\nu)$ (l=e, μ) [9]. The expected precision of these measurements with the full Belle II dataset is shown in Fig.6, along with current measurements from other experiments.

4. – Phase 2 performance

First collisions at the SuperKEKB occurred in early 2018 and the accelerator subsequently achieved a peak instantaneous luminosity of $5.5\times10^{33}\text{cm}^{-2}\text{s}^{-1}$ during the so-called "Phase 2" commissioning run. The main purpose of this run was the optimization of accelerator performance, that is because the Belle II experiment was installed without the silicon vertex detector, in order to avoid possible damages. However, in spite of this limitation, the experiment successfully recorded collisions data corresponding to 472

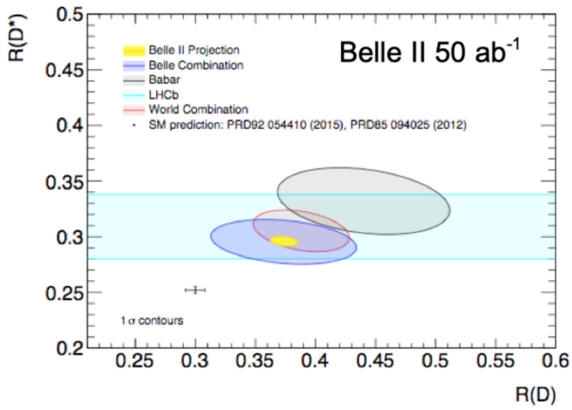

Fig. 6. – Expected Belle II sensitivity to $R(D^{()})$ with the full 50 ab^{1} data sample.

pb^{-1} of integrated luminosity, for a total of about one million B meson decays. These data have been used to optimize detector performance and to validate the reconstruction of physics objects within the detector. Examples of performance during this run are shown in Fig.7, including π° and η reconstruction, and J/Ψ reconstruction in muon and electron decay channels. In addition to detector performance studies, initial physics studies have been performed with the aim of re-discovering known physics processes. In particular, topological differences between $B\bar{B}$ events produced at the $\Upsilon(4S)$ and contin-

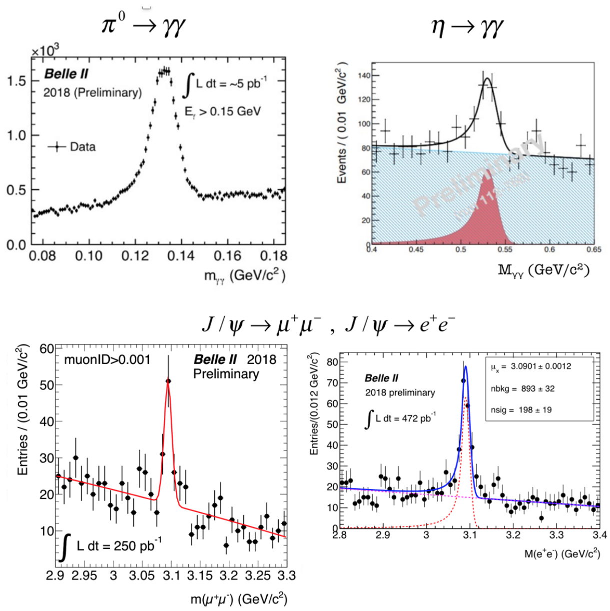

Fig. 7. – Performance of the Belle II detector during the Phase 2 commissioning run: reconstruction of π° and η (top); J/Ψ reconstruction in muon and electron decay channels (bottom).

uum $q\bar{q}$ production have been used to extract the $B\bar{B}$ content and measure the expected rate to be consistent with the SuperKEKB accelerator being operational at the peak of the $\Upsilon(4S)$ resonance.

5. – Future perspectives

In July 2019, Belle II finished the physics run phase 3, started in March 2019, collecting 6.5 fb^{-1} with the full detector installed including the vertex detector. SuperKEKB has reached a peak instantaneous luminosity of $6.1\times10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. 8.5 months of operations are foreseen for the year 2020 with a goal of increasing the luminosity in the following years up to to the design value of $8\times10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, in order to collect a competitive $\Upsilon(4S)$ dataset which will allow one to shed light on the possible presence of New Physics beyond the Standard Model in the flavour sector.

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