The Belle II experiment at SuperKEKB: input to the European Particle Physics Strategy (update 2018-2020)

European Institutions within Belle II Collaboration*
Endorsed by Belle II Collaboration
Prepared by the Belle II ESPP preparatory group†

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1 Scientific Context

Belle II is a next generation flavour factory, which began recording e^+e^- collision data in April 2018 at the SuperKEKB collider in Tsukuba, Japan. The goal of the experiment with a substantial European contribution (see App. A), is to search for signals of New Physics (NP), i.e. physics beyond the Standard Model (SM), performing measurements of unprecedented precision as well as searches in the low energy regime, exploiting the advantages of an electron positron collision environment. In the present document we wish to underline the necessity of continuation and, in the near term future intensification of the experimental efforts in indirect searches for NP, specifically in electron-positron collisions at an intermediate energy regime. In doing so we outline some reflections which we believe should be taken into account in decisions on the next mid-term particle physics strategy: 1) the need for complementary approach among various frontiers in searches and interpretations of NP; 2) an experimental initiative in the aforementioned efforts, especially after the Higgs boson discovery at the LHC; 3) the specific advantages of e^+e^- over hadron colliders; 4) the complementarity within the existing experiments at the intensity frontier.

1) Despite the tremendous success of SM as an effective theory in description of the processes at the so-far experimentally achieved energies and precision, there are well known shortcomings of the theory (origin of fermion families, neutrino masses, baryon asymmetry, ...), and questions of a more general nature (dark matter, composition of the Higgs sector, ...) pointing to the existence of particles and processes beyond the SM (NP). Searches for those have so far been negative. While the SM of particle physics is a fairly accurate portrait of visible matter in the universe, it does not account for dark matter, which must be explained by physics beyond the SM. In order to find evidences of NP, and even more to interpret such evidence, it will be mandatory to exploit various approaches (energy frontier, intensity frontier, cosmic frontier), and to maximally exploit complementarity among them. As detailed in Sects. 2 and 3, the Belle II experiment will address questions related to both groups of problems mentioned above, with measurements that are complementary to those of other existing and planned experiments. Last but not least, one should bear in mind that any important result (especially related to physics beyond the SM) would probably need to be confirmed by an independent (complementary) experiment, which adds to the necessity of a long-term strategy incorporating a variety of experimental and theoretical approaches.

2) The combination of indirect measurements and direct searches at the energy frontier has proven to be well synchronized and complementary in the past. Recent examples include the indirect searches and ultimately the direct experimental observations of the top quark and Higgs boson [1]. Since the discovery of the Higgs boson by the LHC experiments at a mass that excludes a large part of parameter space of the minimal SUSY models, experimental searches for beyond SM phenomena have become the focus of the field in these efforts. Examples underlining this are the numerous indications of possible NP at LHC (some now shown to be statistical fluctuations, some yet unconfirmed, e.g. [2] and [3]), and various hints of deviations from the SM predictions in flavour physics (e.g.

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[*] The list with principal investigators is presented in App. A.

[†] A. Bozek, Z. Dolezal, S.I. Eidelman, F. Forti, B. Golob (corr. author, bostjan.golob@ijs.si), C. Schwanda, C. Sfientti, K. Trabelsi, P. Urquijo

experimental hints regarding possible lepton universality violation [4]). All these experimental results were followed by a substantial number of theoretical attempts to interpret them. Clearly, indirect searches will continue to rely on accurate theoretical predictions to identify any possible deviations from the SM.

3) In very general terms the searches for NP at B meson factories can be grouped into those studying the structure of the flavour sector and possible deviations from the SM, and searches and measurements not directly related to the flavour structure of the SM and beyond. This classification is detailed in Sect. 2. Perhaps as importantly, the physics aims can be classified in terms of experimental methods, emphasizing those for which experiments in e^+e^- environments provide a necessary and unique complementarity to the experimental efforts at the hadron machines. The former include measurements of processes with missing energy (neutrinos, dark matter,...), (semi)inclusive processes (in many cases allowing for more accurate theoretical predictions), and processes with (several) neutral particles in the final state. Tests of our understanding of QCD are possible through studies of quarkonium states, conventional or exotic ones. These can be produced either directly in e^+e^- collisions, through initial state radiation, or in B mesons decays. All the mentioned methods are examples of advantages of e^+e^- collisions when compared to - typically much more energetic - hadron collider environment. More details of this approach is given in Sect. 3.

4) At present, indirect searches of NP are pursued by several running and planned experiments. They cover a wide range of physics topics; a non-exhaustive list includes neutrino physics (NOνA, T2K, reactor exp's,...), muon physics (COMET, MEG II, Muon g-2, Mu2e, ...), kaon physics (KLOE-2, KOTO, NA62,...), beauty, charm quarks and τ physics (Belle II, BESIII, LHCb, ...), top quark and Higgs boson physics (ATLAS, CMS). Effects of NP are expected to be related among the processes under study. Correlations among various observables are the source of complementarity of the measurements, and increase the potential of these kinds of experiments for searches as well as an eventual interpretation for NP.

In the following we focus on the physics program of Belle II, its potentials and complementarity to other experiments, and last but not least the challenges needing to be dealt with (Sect. 4).

2 Objectives

Belle II succeeded the Belle experiment, which played a key role in constraining and confirming the Cabibbo-Kobayashi-Maskawa (CKM) mechanism of quark flavour mixing. Belle observed CP violation in B meson decays and measured the angles and sides of the CKM triangle, thus establishing the unitarity of the CKM matrix. Belle II will be able to measure the array of CKM observables, the matrix elements and their phases, with an unprecedented precision. However, the objectives of the experiment go beyond the CKM studies, and reach even beyond flavour physics with B and charmed mesons, and τ lepton decays. Expected precisions [5] for selected processes are given in Tab. 1.

In the following we have tried to describe the key objectives of Belle II in terms of fundamental, open questions of the SM:

- *Are there new CP-violating phases in the quark sector?*

  The amount of CP violation in the SM quark sector is orders of magnitude too small to explain the baryon-antibaryon asymmetry of the universe. Belle II can search for new CP violating phases beyond the SM via measurements of the time-dependent CP violation in penguin transitions of $b \to s$ and $b \to d$ quarks, such as $B \to \phi K^0$ and $B \to \eta\prime K^0$ (see Tab. 1; sensitivity with 50 ab^{-1} will reach the SM expectations). The search for CP violation in charm mixing, which is negligible in the SM, will also provide information on new phenomena in the up-type quark sector. Another key area will be to understand the mechanisms that produce large amounts of CP violation in the time-integrated rates of charmless hadronic B decays, such as $B \to K\pi$ and $B \to K\pi\pi$, observed by the B-factories and LHCb.

- *Is lepton flavour universality conserved?*

  Leptonic and semileptonic B meson decays, in particular those involving a heavy τ lepton, are an excellent laboratory for testing lepton flavour universality (LFU), which is conserved in the SM. New heavy mediators or sterile neutrinos could contribute to the decay amplitudes and lead to LFU breaking effects. For instance, the charged Higgs boson in the two-Higgs-doublet model (2HDM) of type II or the minimal supersymmetric standard model (MSSM) has a coupling proportional to the charged lepton mass, m_τ or m_ℓ. In addition, leptoquark models can modify SM couplings in a flavour dependent way. Using advanced tagging methods,

Process	Observable	Expected precision	Comment
$B \to \eta' K_s$	$\sigma(S_{\mathrm{CP}})$	0.03 (0.015)	
$B \to K^{(*)}\nu\nu$	$\sigma(Br)/Br$	25% (10%)	Similar precision for each, K and K^* final state
$B \to X_{s+d}\gamma$	$\sigma(A_{\mathrm{CP}})$	0.015 (0.005)	
$B \to X_d\gamma$	$\sigma(A_{\mathrm{CP}})$	0.14 (0.05)	
$B \to K^{*0}\gamma$	$\sigma(S_{\mathrm{CP}})$	0.09(0.03)	
$B \to \rho\gamma$	$\sigma(S_{\mathrm{CP}})$	0.19(0.06)	
$B \to X_s\ell^+\ell^-$	$\sigma(R_{X_s})/R_{X_s}$	9%-12% (3%-4%)	Quoted precision is for an individual q^2 bin
$B \to X_s\gamma$	$\sigma(Br)/Br$	4% (3%)	
$B \to D^{(*)}\tau\nu$	$\sigma(R_{D(*)})/R_{D(*)}$	3%-6% (2%-3%)	Similar precision for each, D and D^* final state
$\tau \to \mu\gamma$	limit on Br	10^{-9} (50 ab^{-1})	
$\tau \to \mu\rho^0$	limit on Br	$2 \cdot 10^{-10}$ (50 ab^{-1})	
$A' \to$ *invisible*	limit on ϵ (γ/A' mixing)	$3 \cdot 10^{-4}$ (20 fb^{-1})	

Table 1: Expected precision for Belle II measurements of selected observables [5]. Unless stated otherwise the precision is given for integrated luminosity of 5 ab^{-1} (50 ab^{-1}).

Belle II has a unique capability to study charged current transitions involving the heavy τ lepton, such as $B \to \tau\nu$ and $B \to D^{(*)}\tau\nu$ (see Tab. 1). Deviations from the SM have been observed in the latter modes with significance greater than three standard deviations (the current world average relative accuracies on $R(D)$ and $R(D^*)$ are 11% and 5%, respectively).

- *Does nature have a left-right symmetry, and are there flavour-changing neutral currents beyond the SM?*

  Belle II can access $b \to s\nu\bar{\nu}$ transitions such as $B \to K^{(*)}\nu\bar{\nu}$ (see Tab. 1; the SM expectations for the branching fractions are around $\mathcal{O}(10^{-5})$) and other decays with large missing energy to probe the SM picture of flavour-changing neutral current (FCNC) decays. It is also important to improve FCNC measurements of $b \to d$ and $c \to u$ transitions, which could all separately receive NP contributions. To further probe the SM description, it is crucial to measure differential distributions (*e.g.*, the forward-backward asymmetry as a function of q^2) in inclusive $b \to s\ell^+\ell^-$ decays. Other relevant observables are the time-dependent CP violation in $B \to K^{*0}(\to K^0_S\pi^0)\gamma$ (see Tab. 1; the SM expectation is $\mathcal{O}(10^{-2})$), the triple-product CP violation asymmetries in $B \to VV$ decays, and semileptonic decays $B \to V\ell\nu$, $V = D^*, \rho$.

- *Are there sources of lepton flavour violation (LFV) beyond the SM?*

  Are there flavour changing processes such as $\tau \to \mu\gamma$ visible at the 10^{-8} level? LFV in charged lepton decays at such rates is a key prediction in many neutrino mass generation mechanisms and other models of physics beyond the SM. The expected sensitivities (see Tab. 1) to τ decays will be unrivalled due to correlated production with minimal collision background. Beyond LFV, Belle II can search for CP violation in τ decays and measure the electric dipole moment and $(g-2)$ of the τ lepton.

- *Is there a dark sector of particle physics at the same mass scale as ordinary matter?*

  Despite the impressive sensitivity reached so far by direct detection experiments there is no evidence yet for weakly interacting massive particles (WIMPs). Beyond the WIMP paradigm, low-mass messenger particles of a hypothetical dark sector have been suggested. One such particle mediator is the dark photon: it has a mathematical structure that is similar to the SM photon with which it mixes.

  Thanks to a single-photon trigger Belle II will be in a unique position to search for dark photons. A typical example of such a search is the process $e^+e^- \to \gamma A'$, with A' a dark photon (see Table 1). In case of A'

decay into an invisible final state, the photon from the initial state radiation is the only detectable final state particle, and the dark photon can be searched for in the energy spectrum of detected SM photons. Along with the dark photon Belle II will search for dark Higgs bosons. Similar in nature to the SM Higgs boson, this particle would allow for certain mathematical symmetries to break, providing mass to the dark photon or possibly even other axion-like particles. One of possible production mechanisms (Higgsstrahlung) would lead to specific final states with several pairs of oppositely charged leptons or light hadrons.

- *What is the nature of the strong force in binding hadrons?*

  Large mass, non-relativistic dynamics, large energy level spacing and clear experimental signatures are unique characteristics of the bottomonium states that make this sector so rich with a wide range of opportunities for new studies to understand how the spectrum and structure of hadrons emerge from QCD and to find out whether there are new forms of matter.

  Belle II is in a unique position regarding bottomonium physics, being the only experiment with full capability to explore QCD phenomenology and exotica in this sector. The clean environment at Belle II allows for inclusive searches for new states by reconstructing a single resonance and studying the recoil system. Overcoming the statistical limitations of previous experiments, Belle II will be in a unique position to perform for example searches for resonant states via Initial State Radiation (ISR). These samples may be smaller compared to direct production in e^+e^- collisions, however provide a method to reach states with high masses up to 7 GeV not accessible by other experiments. A variety of studies can be conducted using bottomonium annihilation: study of conventional and exotic quarkonium spectroscopy, the search for new physics in rare decays of heavy mesons, the study of the light scalar meson family using dipion transitions among bottomonia, and the study of production and properties of light nuclei and other QCD bound states (dibaryons) with astrophysical implications.

  Belle II will also collect an unprecedented number of exotic hadronic (”XYZ”) states enabling studies of their properties, even through their relatively rare decays.

3 Methodology

The SuperKEKB accelerator [6] is an upgrade of the KEKB B-factory. It is designed to collide electrons and positrons at center-of-mass energies in the region of the Υ resonances. The target luminosity is $8 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and it is higher than that of KEKB by a factor of 40. The beam energies for the High Energy Ring (HER) and the Low Energy Ring (LER) are 7 GeV and 4 GeV, respectively.

Several upgrades were needed to achieve this performance. 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. A new lattice design has been applied to the HER and a totally new ring was built for the LER to reach low emittance. A pair of new superconducting final-focusing magnets was designed and fabricated. In this framework it is essential to squeeze the beams. For this purpose quadrupole magnets, compensation solenoid magnets and correction magnets in the single cryostat have been installed. Moreover, new TiN-coated beam pipes with an antechamber structure were designed and constructed to suppress the photoelectron cloud in the LER. A new damping ring was built in the injection linac section to meet the smaller acceptance requirements of the LER.

Belle II is a hermetic magnetic spectrometer and it is a major upgrade of the Belle experiment. 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 $B\bar{B}$ production 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 to allow for time-dependent CP violation measurements. The modified Belle II detector includes several substantially upgraded or new subsystems.

The new vertex detector (VXD) consists of two subdetectors: a Pixel Vertex Detector (PXD) including two layers of pixelated 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. An improvement by a factor of two 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. In order 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 type of Cherenkov detector and an Aerogel Ring Image CHerenkov (ARICH) detector in the forward region. In the TOP system the time of propagation and the impact positions of Cherenkov photons are measured. In the ARICH detector the number and the positions 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 with layers of scintillator strips with silicon photomultipliers in order to be able to operate with significantly higher neutron fluxes.

Higher event rates also require modifications to the trigger scheme, data acquisition system, software and computing with respect to the precursor experiment. The trigger and DAQ have also been adapted to support a broader low-multiplicity (dark sector) physics analysis program. The Belle II detector is described in [7].

New experimental challenges (decays with neutrinos in the final state, dark matter searches) require novel approaches to trigger and data analysis. Several new methods have been developed and implemented in the Belle II DAQ, reconstruction and analysis chain:

Full Event Interpretation Measurements of decays including neutrinos, in particular rare decays, suffer from missing kinematic information. The Full Event Interpretation (FEI) algorithm recovers this information partially and infers strong constraints on the signal candidates by automatically reconstructing the rest of the event in thousands of exclusive decay channels. The FEI algorithm is analysis technique unique to B factories and an essential component in a wide range of important analyses, including (but far from exhaustive):

- the measurement of the CKM element $|V_{ub}|$ through the semileptonic decay $b \to u\ell\nu$;
- the search for new physics effects in $B \to D^{(*)}\tau\nu$;
- the precise measurement of the branching fraction of $B \to \tau\nu$, which is sensitive to new physics effects;
- search for rare decay $B \to K^{(*)}\nu\nu$;

This technique reconstructs one of the B mesons and infers strong constraints for the remaining B meson in the event using the precisely known initial state of the $\Upsilon(4S)$. The actual analysis is then performed on the second B meson. The two mesons are called tag-side B_{tag} and signal-side B_{sig}, respectively. In effect, the FEI method allows one to reconstruct the initial $\Upsilon(4S)$ resonance, thereby recovering the kinematic and flavour information of B_{sig}. Furthermore, the background can be drastically reduced by discarding $\Upsilon(4S)$ candidates with remaining tracks or energy clusters in the rest of event.

Previous generation B Factories already employed a similar technique called Full Reconstruction (FR) with great success. As a further development, the FEI is more inclusive, provides more automation and analysis-specific optimisations. Both techniques heavily rely on multivariate classifiers (MVC). The expected performance can be seen from the Tab.2

Table 2: Tag-side efficiency defined as the number of correctly reconstructed tag-side B mesons divided by the total number of $\Upsilon(4S)$ events.

Tag	FEI @ Belle MC	FEI @ Belle II MC
Hadronic B^+	0.49 %	0.61 %
Semileptonic B^+	1.42 %	1.45 %
Hadronic B^0	0.33%	0.34 %
Semileptonic B^0	1.33%	1.25 %

Dark Sector There is a variety of theories that involve a dark sector. Dark matter searches are a significant challenge for the trigger, since they are characterised by the presence of only a single energetic photon in the final state. The single-photon trigger developed for Belle II is a powerful tool to register potential dark sector candidates. Bhabha scattering and $e^+e^- \to \gamma\gamma$ are the dominant background in the endcaps and at high luminosity.

Consequently loose triggers are applied for the photon in the barrel of ECL, and tight conditions are applied in the endcaps. Some trigger lines may need to eventually be prescaled but this will be decided later.

4 Readiness and Expected Challenges

Phase2 machine and detector commissioning The Phase2 commissioning of the accelerator and detector started in February 2018. The accelerator included the complete optics, including the superconducting final focus, although not all foreseen collimators were installed. Belle II included all the subsystems from the CDC outwards, while in the inner volume the VXD was replaced by the BEAST detector, including several sensor technologies to monitor radiation levels and backgrounds. A vertical slice of pixels (PXD) and strip detectors (SVD) was installed in small angular region. The rationale behind this choice was to prevent damage to the final PXD and SVD while performing initial machine commissioning and tuning. First collisions were realized on Apr 25, 2018, and operation continued until July 17, 2018. During this period the accelerator reached the peak luminosity of $0.5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and the experiment was able to integrate a luminosity of about $500\,\mathrm{pb}^{-1}$. The novel nano-beam scheme was verified, reaching the record $\beta_y^* = 3\,\mathrm{mm}$ with high specific luminosity even when $\beta_y^* < \sigma_z$. The detector was operational and collecting data, although the overall efficiency will require improvements. Collimator positions have been optimized and background levels were acceptable, although there are still significant discrepancies with simulation, requiring further detailed studies at the beginning of Phase 3.

Phase3 plans Between July 2018 and February 2019, the PXD and SVD subdetectors will be installed in Belle II, completing the detector. The remaining collimators will be installed in SuperKEKB, leading to the beginning of Phase3 physics running in March 2019. The full first layer and 1/6 of the second layer of PXD will be installed at this time due to construction delays; the current plan is to install a complete PXD in a long shutdown in 2020. The initial running will be devoted mainly to luminosity and background optimization, after which luminosity integration will start, with a continuous improvement on peak luminosity. It is foreseen to run for 9 months/year with a 3 months summer shutdown to avoid high electricity costs. It is planned to reach a peak luminosity of $8 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ by 2022 and continue running until 2025 to integrate more than $50\,\mathrm{ab}^{-1}$. The planned integrated luminosity is shown in Fig. 1

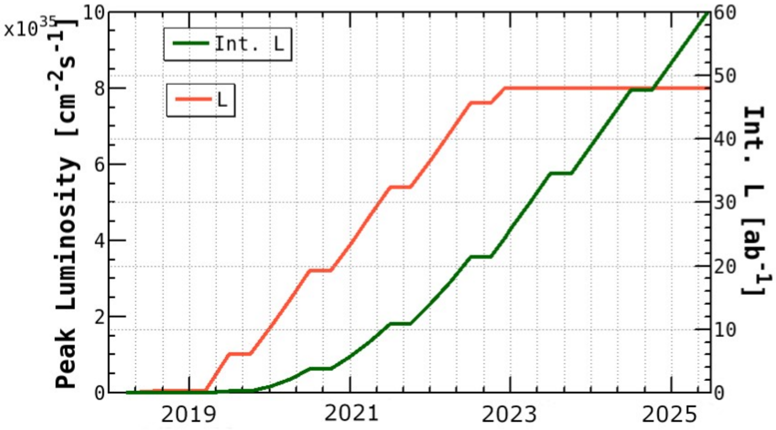


Figure 1: Plan of instantaneous and integrated luminosity increase.

Experiment readiness During Phase 2 pilot run the experiment collected data, which have been analyzed identifying the expected known particles present in the sample, like π^0 s, K's, as well as D and B mesons. Some examples of early performance plots obtained on the Phase 2 data sample of $472\,\mathrm{pb}^{-1}$ are shown in Fig. 2 for the J/ψ, in Fig. 3 for the D^{*0}, and in Fig. 4 for the the B mesons. Physics studies, especially in the dark sector,

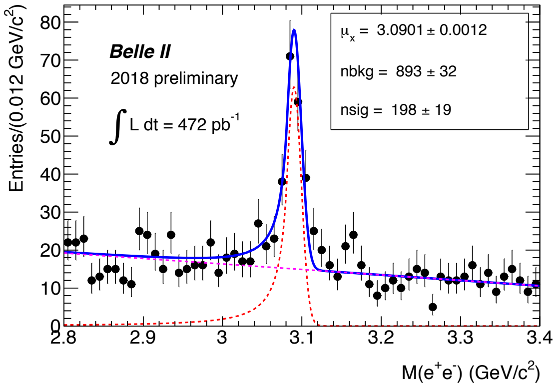


Figure 2: Distribution of the J/ψ mass.

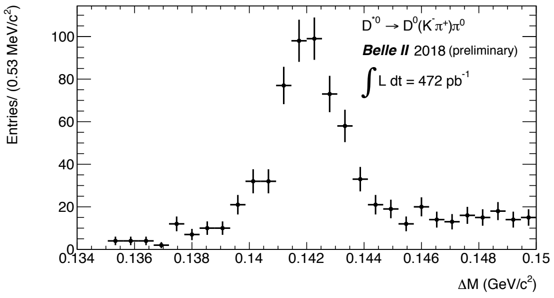
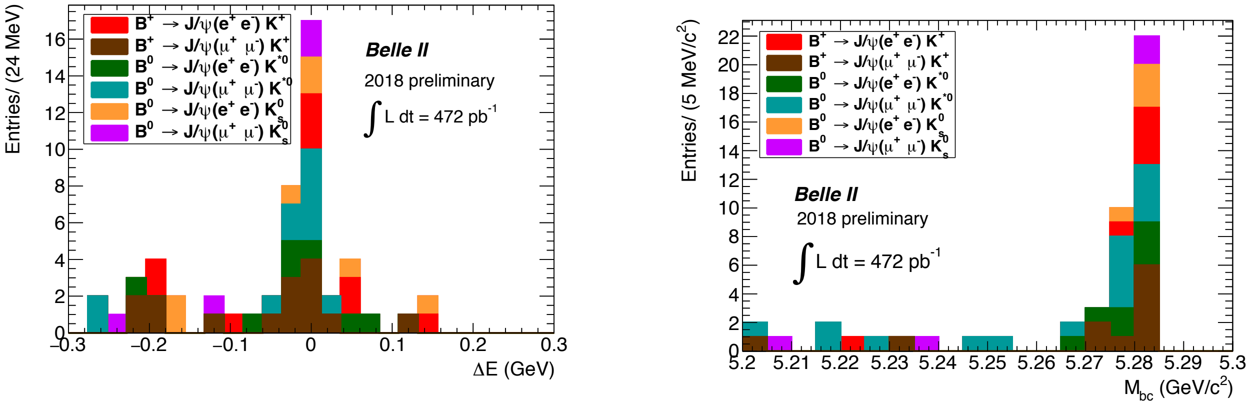


Figure 3: Distribution of the mass difference between D^{*0} and D^0.



(a) Distribution of the energy difference between the B meson and the beam.

(b) Distribution of the B mass, beam constrained.

Figure 4: Measurement of $B \to J/\psi\, K$ process in the Phase 2 data sample.

are ongoing, although the currently small amount of statistics collected makes competitiveness and sensitivities of measurements with this initial sample from the pilot run rather low. Still, the fast turnaround of the rediscoveries is a good indication of the overall experimental readiness for physics data taking. Improvements in several areas are being implemented to be able to run in factory mode.

Challenges for full luminosity running The main challenges for full luminosity run are expected to be related to the level of the background from several relevant sources: beam-gas interactions, Touschek intra-beam scattering, radiative Bhabha events, and low energy electron-positron pairs from two-photon events. The levels measured during the Phase 2 pilot run can be used to extrapolate to the full luminosity, but since the machine configuration and optics will change, it is very difficult to arrive at solid numbers. It is clear, though, that several detector subsystems are rather sensitive to the background levels, and since the readiness of the detector to sustain high background rates could only be partially demonstrated during Phase 2 running, this aspect remains the most critical challenge for the Phase 3 operation.

Future opportunities Now that the physics data taking is starting in earnest, the Belle II and SuperKEKB communities are starting to look at future accelerator and detector improvement opportunities, although detailed studies have not yet been carried out on the technical feasibility or cost implications of these possible upgrades.

Polarization. The possibility of introducing polarization of the electron beam, through the use of a polarized source and spin rotators placed before and after the IP, is being considered. Precision electroweak physics measurements can be greatly improved by the polarization, while lepton flavour violation searches can possibly benefit from the production of polarized τ leptons.

Luminosity. Even though the data sample is increased by a factor of 50 compared to previous B-factories with the foreseen integrated luminosity, many measurements remain statistically limited, and would call for further improvements in the delivered luminosity. The Belle II community has just started to consider implications for the detector performance under the working hypothesis of a factor of five increase in the peak luminosity of the machine, which seems to be a very challenging but not an impossible goal. The increased background rate will most certainly require upgrades of the sensors and the electronics, especially in the innermost layers of the apparatus. In addition, it may be possible to take advantage of technologies that have matured after the Belle II detector design has been decided upon. An upgrade study group is being formed inside Belle II to quantify the limitations and possible upgrade paths for various subdetectors. It is expected that in the course of 2019 a more defined activity plan will be elaborated.

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