

The Belle II Experiment

Steven H. Robertson

Associate Professor and IPP Research Scientist, Department of Physics, McGill University,
3600 University St., Montreal, Quebec H3A2T8, Canada

E-mail: steven.robertson@mcgill.ca

Abstract. The Belle II experiment has recently completed its “Phase 2” commissioning operations run, during which first collisions at the $\Upsilon(4S)$ resonances were recorded. Belle II is the successor of the *BABAR* and Belle *B* Factory experiments, and is designed to operate at a peak luminosity of $8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ with a target data set of 50 ab^{-1} . This large and inclusive data set will permit studies of *B* meson decays, along with charm, τ and many other physics topics, with unprecedented precision in the clean e^+e^- collider environment. In this presentation I describe the Belle II experiment, its planned physics program and prospects as we head toward the first “physics” run beginning in 2019.

1. Introduction

The Belle II experiment [1] is the successor experiment to the previous generation of asymmetric B factory experiments, *BABAR* and Belle [2], intended to extend the reach of these experiments within the domain of precision flavour measurements by collecting a data sample equivalent to more than 30 times the combined integrated luminosity of these previous experiments. Belle II is a collaboration of over 900 physicists from 26 countries and regions world wide, including more than 260 graduate students. The Belle II detector has been installed in the interaction region of the SuperKEKB e^+e^- collider [3] at the KEK laboratory in Tsukuba, Japan, which is designed to operate at instantaneous luminosities of up to $8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ at, and in the vicinity of, the $\Upsilon(4S)$ resonance, at approximately 10.5 GeV centre of mass (CM) energy. 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, in order to facilitate separation of *B* meson decay vertices produced in $\Upsilon(4S) \rightarrow B\bar{B}$ interactions. First collisions were recorded by Belle II during the “Phase 2” accelerator commissioning run in early 2018, and “factory mode” physics data taking begins in early 2019. In this presentation, I give an overview of the SuperKEKB accelerator and the Belle II detector, and describe some of the unique features of this experimental environment. I then discuss the Belle II physics program, with a focus on prospects for studies of recent flavour “anomalies.” Finally, I briefly present some initial results from the Phase 2 commissioning run and discuss prospects for the 2019 run and beyond.

2. SuperKEKB and the Belle II experiment

The Belle II experiment detector [4] is based on the original Belle detector, with substantial upgrades to all detector subsystems, as illustrated in Figure 1, in order to address the experimental challenges presented by the extremely high luminosity environment provided by SuperKEKB. In particular, the entire inner detector region which provides the tracking system

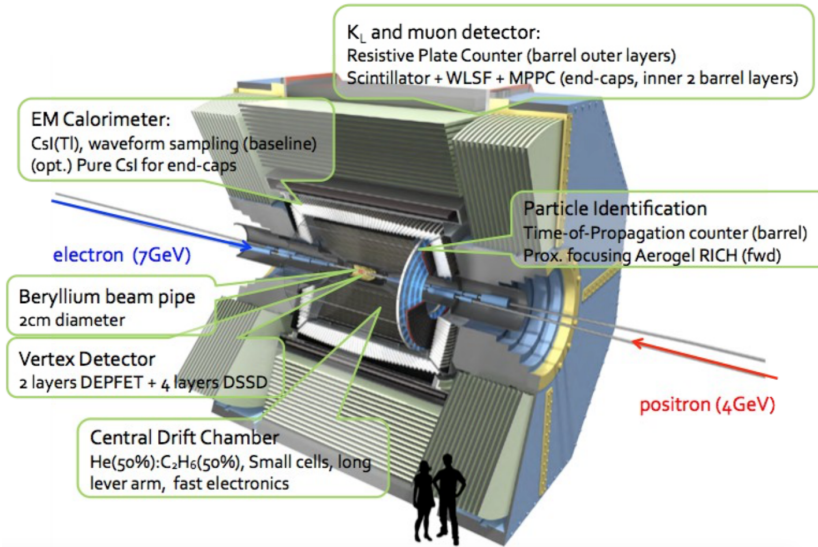


Figure 1. The Belle II detector.

has been replaced. The interaction point (IP) is surrounded by a low-mass beryllium beam pipe with a 2 cm diameter. The small diameter enables two layers of DEPFET silicon pixel detectors to be placed in close proximity to the IP for precise decay vertex reconstruction. These detectors are surrounded by an additional four layers of double-sided silicon strip detectors, with strips running perpendicular on the two sides, to provide additional $x - y$ space points for track and vertex reconstruction. These detectors are designed to have extremely low material content, to minimize the degradation of tracking resolution due to multiple scattering. Additional tracking at radii between 160 and 1130 mm from the beam axis 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 radially are arranged in nine groups of “superlayers,” in which the innermost superlayer has a reduced cell size to help address occupancy issues arising from the high luminosity environment. Superlayers alternate between axial and “stereo” wires, in which wires are offset between 45 and 74 mrad between the two ends, in order to provide z -coordinate position information. The tracking detectors additionally 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 large-bore solenoid positioned outside of the electromagnetic calorimeter. Additional PID, and in particular $K - \pi$ 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, with Cherenkov photons detected by an array of approximately 60000 channels of hybrid APDs. Electrons and photons are reconstructed using energy measurements from a CsI(Tl) crystal calorimeter, reusing crystals and photodetectors from the original Belle detector. New front-end electronics and upgraded feature extraction capability permit a faster and more precise energy determination in the high-luminosity environment of Belle II. The magnetic flux return for the solenoid is instrumented with a combination of RPCs and scintillators read out by MPPCs via wavelength-shifting fibres in order to provide identification of muons and neutral hadrons (K_L) which penetrate the calorimeter.

The SuperKEKB accelerator is a substantially upgraded version of the KEKB collider

with design luminosity of $8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$, representing a 40-fold increase compared with its predecessor. This luminosity is achieved via a novel low-emittance “nanobeam” scheme exploiting ILC and light-source technologies, combined with a new positron damping ring and positron beam vacuum chamber. At full luminosity, each beam will circulate 2500 bunches, with bunch crossings approximately every 4 ns. Given the cross sections for $e^+e^- \rightarrow f\bar{f}$ (where f represents any fermion) we expect a rate of order 1 kHz of $B\bar{B}$ events recorded, accompanied by several kHz of charm ($c\bar{c}$), light quark $q\bar{q}$ and $\tau^+\tau^-$ events. Additionally, we expect approximately 30 kHz of Bhabha ($e^+e^- \rightarrow e^+e^-$) events within the detector acceptance. This later contribution must 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 the Belle II collaboration of 50 ab^{-1} implies a data sample containing in excess of 50 billion $B\bar{B}$ pairs, with similar size samples of τ and charm events.

3. The Belle II physics program

The previous generation of B Factory experiments, Belle and *BABAR*, operated for approximately a decade beginning in 1999. These experiments collectively integrated data sets in excess of 1 ab^{-1} of data at the $\Upsilon(4S)$ resonance, as well as substantial data samples at higher and lower mass Υ resonances as well as off-peak. The primary objective of these experiments was the confirmation of the Kobayashi-Maskawa mechanism for CP violation within the Standard Model (SM) via the CKM matrix. While many of these measurements remain statistically limited, the target data sets for these experiments were chosen so as to provide sufficient measurement precision to indisputably validate or refute the SM picture of the origin of CP violation within the CKM matrix. With this picture now firmly established experimentally, the scientific objectives of the next generation of flavour physics experiments has evolved: the Belle II experiment is designed to look for deviations from SM expectations indicative of new physics contributions across a very broad class of flavour observables. This scientific program requires a much higher degree of precision, and hence a much larger data sample, than previous B Factory experiments. In addition to CP violation measurements, potential flavour observables include branching fractions, kinematic distributions, and angular distributions and asymmetries in B , charm and τ decays.

Observation of new physics would require one or more measurements to deviate significantly from theoretical predictions within the context of the SM. This can occur in one of two ways: either precise measurements of specific flavour observables can be shown to deviate from (equally precise) theoretical predictions; or very rare or forbidden processes can be observed when SM predictions are well below experimental sensitivity. CP violation studies, as illustrated by the ubiquitous “unitarity triangle” representations [5], are an excellent example of the first of these ways, while studies of electroweak flavour changing neutral current (FCNC) B decay processes exemplify the second. In both cases, however, a key feature is that the relevant decay processes can occur via loop-level processes which can potentially contain high-mass non-SM particles, and the presence of these non-SM contributions can measurably alter various experimental observables. Moreover, the existence of a particular non-SM particle or interaction would be expected to contribute in predictable ways across a variety of related B meson decay modes. Consequently, these measurements have the potential to not only discover new physics phenomena arising from mass scales in excess of those directly accessible at the LHC, but also to elucidate the nature of this high-mass new physics via the pattern of deviations observed across a broad class of measurements.

While Belle II shares many of the same physics objectives as the LHCb experiment [6], there exists a high degree of complementarity between these two experiments. As a hadron collider experiment, LHCb benefits from a large $b\bar{b}$ production cross section and highly boosted

topologies, with hadronization into a variety of B_d , B_s mesons and b -baryons. However, the high background environment imposes limitations on the accessibility of some decay modes for analysis, in particular inclusive processes, some decays with neutral particles and decays with missing energy. In contrast, Belle II exploits the extremely clean e^+e^- environment and exclusive $\Upsilon(4S) \rightarrow B_d\bar{B}_d$ production to access a broader range of B_d final states, but this production mechanism has a relatively low cross section and is limited to B_d meson decays (although B_s mesons can be produced through dedicated running at the $\Upsilon(5S)$ resonance). This complementarity is exemplified by the recent measurements of anomalies in $B \rightarrow K^*\ell^+\ell^-$ (where $\ell = e, \mu$) by LHCb [7, 8]. Although these modes have been studied previously at B factory experiments, the large sample of B_d mesons available at LHCb have resulted in significantly improved precision of determinations of the lepton universality ratio, $R_{K^{(*)}}(q^2) \equiv \mathcal{B}(B \rightarrow K^{(*)}\mu^+\mu^-)/\mathcal{B}(B \rightarrow K^{(*)}e^+e^-)$, as a function of q^2 , resulting in a deviation from SM expectations with a combined significance of approximately 4σ . As highly suppressed SM FCNC processes, these modes are excellent places to look for new physics, so such a discrepancy is tantalizing. Belle II will also be able to study these modes, in both charged and neutral B decays. With the much higher luminosity compared to the previous B factory experiments, it is anticipated that Belle II will have comparable precision to the current LHCb measurements with an integrated luminosity of about 5 ab^{-1} , or about 10% of the full dataset. Moreover, this measurement will use a distinct methodology compared to LHCb and hence provide an important validation and crosscheck of the LHCb results. The two experiments will then collect data concurrently following the LHC LS2 shutdown, providing further precision to these measurements over the coming decade.

However, it is likely that any new physics effect which may contribute to $R_{K^{(*)}}(q^2)$ would also result in potentially observable impacts on other related B decay processes which proceed via similar one-loop FCNC decays. In particular, with the excellent $K-\pi$ separation in Belle II, exclusive $b \rightarrow d\ell^+\ell^-$ decays will be accessible, while the inclusive trigger and hermetic detector will permit measurements of the inclusive processes $B \rightarrow X_{s,d}\ell^+\ell^-$ (where $X_{s,d}$ represents a hadronic system containing an s or d quark). The self consistency of these measurements will provide further validation of any evidence of non-SM contributions to these decays. Many new physics scenarios in which lepton universality is violated between the two light charged lepton generations also predict similar effects for the third generation τ leptons. Consequently, $B \rightarrow K\tau^+\tau^-$ is also very much of interest. A recent BABAR measurement [9] has demonstrated the potential for this decay at B factories, and Belle II is expected to be able to extend limits on this process to close to the SM range. Similarly, lepton non-universality in the charged lepton sector could potentially also impact the corresponding neutral-lepton decays $B \rightarrow K^*\nu\bar{\nu}$. In contrast to $B \rightarrow K^*\ell^+\ell^-$, the neutrino modes proceed in the SM only via FCNC processes in which the $\nu\bar{\nu}$ couples to Z^0 bosons rather than photons or W^\pm bosons. Consequently, the presence or absence of a deviation from SM predictions in these modes would help elucidate the nature of any non-SM effect seen in $B \rightarrow K^*\ell^+\ell^-$. Finally, lepton non-universality in new physics models is often accompanied by violations of lepton flavour. As such, it would also be interesting to search for decays of the type $B \rightarrow K^*\ell^\pm\ell'^\mp$, where $\ell' \neq \ell$ could be any of e, μ or τ . While the light-lepton LFV modes $B \rightarrow K^*e^\pm\mu^\mp$ are accessible at LHCb, Belle II possesses a unique capability, discussed below, for studying decays with missing energy such as $B \rightarrow K^*\ell^\pm\tau^\mp$. Clearly, the strength of the Belle II physics program lies in breadth, and the ability to test new physics scenarios with high precision across a large number of decay modes.

3.1. Processes with missing energy

As a consequence of the precisely known e^+e^- initial state and the hermeticity of the detector, Belle II possesses a unique ability to reconstruct final states with one or more undetected particles, including neutrinos or possible non-interacting new physics particles. Many interesting

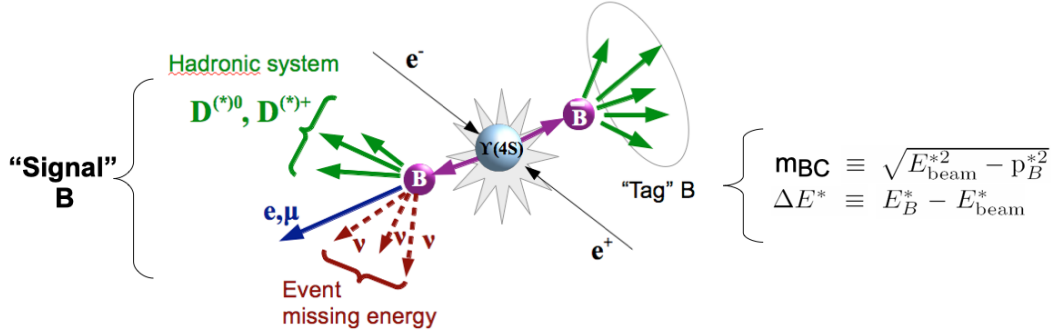


Figure 2. Hadronic B tag reconstruction methodology as applied to a $B \rightarrow D^{(*)}\tau\nu$ signal event produced in $\Upsilon(4S) \rightarrow B\bar{B}$.

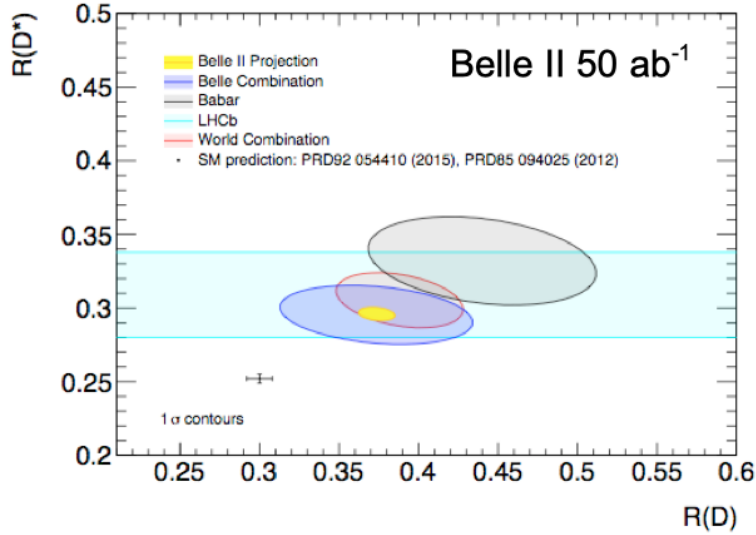


Figure 3. Expected Belle II sensitivity to $R(D^{*})$ with the full 50ab^{-1} data sample.

B meson decay processes fall into this category, including $B \rightarrow D^{(*)}\tau\nu$ and the related tree-level leptonic decays $B^+ \rightarrow \tau^+\nu$ and $B^+ \rightarrow \mu^+\nu$, as well as the flavour changing neutral current decays $B \rightarrow K^{(*)}\nu\bar{\nu}$, $B \rightarrow K^{(*)}\tau^+\tau^-$ and the lepton flavour violating decays $B \rightarrow K^{(*)}\tau^\pm\ell^\mp$ and $B^0 \rightarrow \tau^\pm\ell^\mp$ ($\ell = e, \mu$). Common features of these decays is that they contain multiple neutrinos in the final state, either produced directly in the B decay or via the secondary decays of τ leptons. Because B meson production occurs exclusively via $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$, reconstructed particles, and also the missing energy 4-vector, can be associated with a signal decay mode by process of elimination; the accompanying “tag B ” is exclusively reconstructed into one of many possible hadronic decay modes (see Figure 2), utilizing kinematic constraints to ensure that all of the tag B daughters are correctly identified. Having done this, all remaining reconstructed particles in the event, as well as any missing energy, can then be attributed to the “signal B ”. In this way, Belle II is able to access many missing-energy modes which would otherwise be intractable due to the lack of a reconstructable signature. An important example is the decay $B \rightarrow D^{(*)}\tau\nu$, which has shown indications of tension with respect to SM predictions in the ratio $R(D^{*}) \equiv \mathcal{B}(B \rightarrow D^{(*)}\tau\nu)/\mathcal{B}(B \rightarrow D^{(*)}\ell\nu)$ ($\ell = e, \mu$) [10]. The expected precision

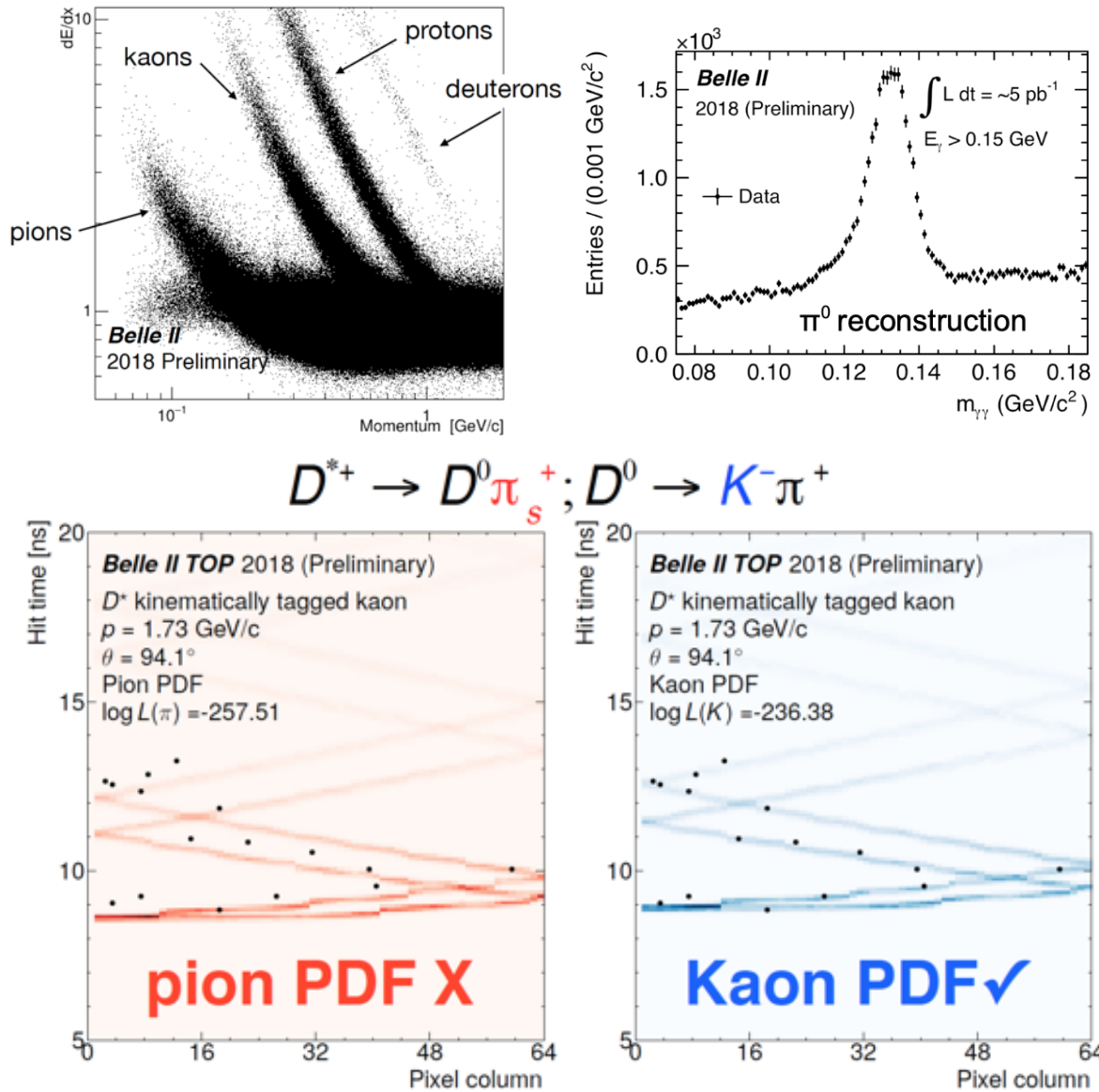


Figure 5. Belle II detector performance during Phase 2 commissioning. See text for description.

hypothesis for Cherenkov photons produced in the TOP by a charged track identified as a kaon via tagging of a soft pion in D^{*+} decays.

In addition to detector performance studies, initial physics studies have been performed on this dataset in order to begin the process of “re-discovering” known physics processes. In particular, topological differences between $B\bar{B}$ events produced at the $\Upsilon(4S)$ and “continuum” $q\bar{q}$ production have been used to demonstrate (see Figure 6, left) that $B\bar{B}$ events are present in the dataset at the expected rate, confirming the the SuperKEKB accelerator was operating at the peak of the $\Upsilon(4S)$ resonance. Exclusive reconstruction of hadronic B decay modes has also shown clear evidence of B mesons (Figure 6, right).

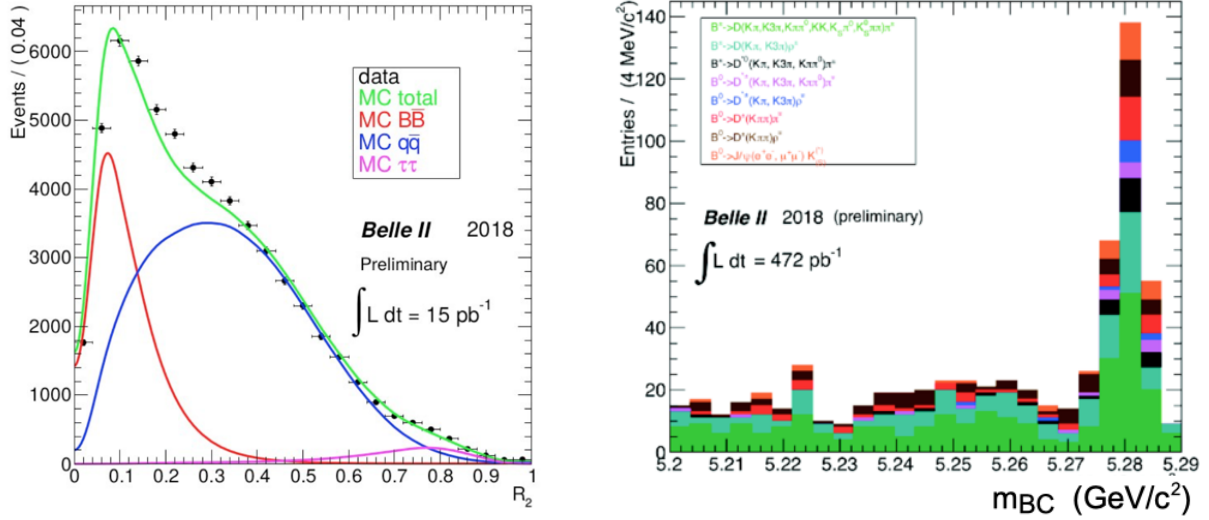


Figure 6. Evidence of $B\bar{B}$ events in Belle II Phase 2 data from event shapes (left) and exclusive hadronic B decays (right).

6. Future prospects

Belle II is currently preparing for “Phase 3” operations, with high-luminosity factory-mode data taking, beginning in March 2019. Beam background studies from Phase 2 have indicated that the vertex detectors can be safely operated, and they have now been installed in the interaction region, completing the Belle II detector. Approximately seven months of operations are foreseen for 2019, with instantaneous luminosity initially comparable to *BABAR* or Belle, but increasing rapidly in the following years to the design value, with a competitive $\Upsilon(4S)$ dataset anticipated by early in the coming decade.

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