Belle II

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1 Introduction

The Belle II experiment is running at the SuperKEKB e^+e^- collider at KEK (Tsukuba, Japan), operated at a center-of-mass energy around the $\Upsilon(4S)$ resonance.

SuperKEKB is the first collider to employ the nano-beam scheme and to achieve a sub-millimeter β^*_y focusing parameter; this required major upgrades to KEKB, including a new low-energy ring beam pipe, a new and complex system of superconducting final-focusing magnets, a positron damping ring, and an advanced injector. A significant improvement was the introduction of crab-waist technology, which stabilises beam-beam blow-up using carefully tuned sextupole magnets located symmetrically on either side of the interaction point (IP). This scheme was first proposed at the LNF and successfully tested at DAΦNE.

This second-generation B Factory will allow to complement the exploration of new physics beyond the Standard Model currently being carried out at the energy frontier by the experiments at the Large Hadron Collider (LHC). The LHC experiments provide a direct probe of the TeV mass scale; Belle II will use high-precision measurements of rare decays and CP violation to search for new physics at even higher mass scales, through the effects of new particles in higher order processes. Belle II's direct competitor particularly in $b\bar{b}$ and $c\bar{c}$ precision physics is LHCb, which is currently dominating the scene in flavour sector measurements.

The aim of Belle II is to collect $50\,\mathrm{ab}^{-1}$ of data, about 40 times the luminosity recorded jointly by *BaBar* and Belle up to 2010. With such a dataset Belle II will perform, in the next few years, a wide range of precision measurements in the B meson, charm, and τ sector, and reach an unprecedented accuracy in the determination of the CKM (Cabibbo-Kobayashi-Maskawa) matrix elements, specifically $|V_{ub}|$ and $|V_{cb}|$ and the angles of the Unitarity Triangle. *BaBar* and Belle have also demonstrated that a B factory provides the opportunity to study a wide range of additional topics, such as exotic quarkonia, dark matter and axion searches.

2 Belle II running

First collisions were recorded in Spring 2018, while data taking with the full Belle II detector and significant luminosity started one year later. Between 2019 and 2022 SuperKEKB showed a steady increase of performances, establishing in June 2022 a new record peak luminosity of $4.7 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The first Belle II data-taking run (Run 1) ended in July 2022. After a pause for a scheduled long shutdown of the accelerator complex, data taking resumed in 2024 with Run 2, which allowed to reach the total combined 2019-2025 integrated luminosity of $599.5\,\mathrm{fb}^{-1}$. As the evolution over time of Belle II's daily and total integrated luminosity given in Figure 1 shows, during Run 2 higher priority was given to machine studies to address the background problems found in previous run periods, which were limiting the increase in the performances of SuperKEKB. These studies allowed good progress and led to the achievement of a new world's record peak luminosity for a particle collider of $5.1 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

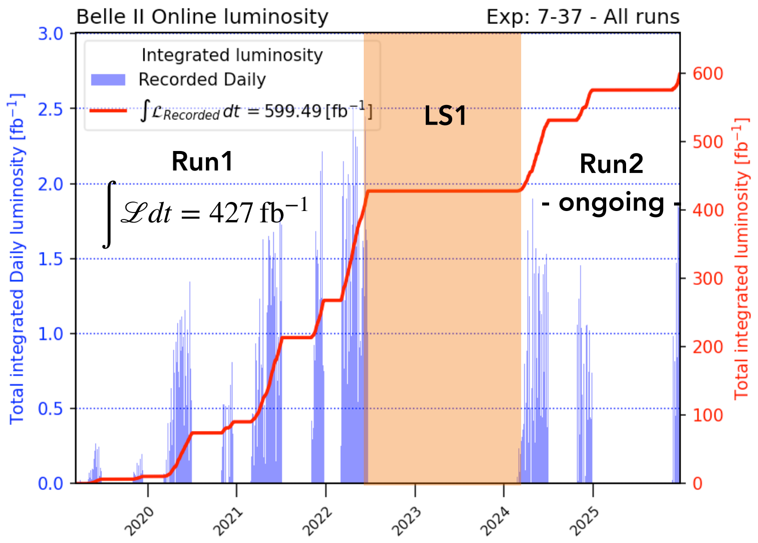

Figure 1: Belle II luminosity history in Run1 and Run2.

At the end of the 2024 run period, the machine was shut down for an extended period of time to allow the implementation of further improvements to the SuperKEKB accelerator complex, as well as to the Belle II detector. The most important activities carried out on the accelerator included the stabilization of the beam currents, by reducing residual particles in the beam pipe and adding new beam monitors, as well as the replacement of the electron Radio Frequency gun to increase the currents. The Belle II Data Acquisition procedure was optimized by including automatic recovering and restart of the run after errors. The operation on the detector concerned mainly the Drift Chamber, in which better gas flow and mixture were designed to reduce aging, and the cooling of the Ring Imaging Cherenkov Detector.

An intense analysis effort is ongoing using the available dataset: studies covered a wide range of physics, with a shift from re-performing previous measurements to producing new, competitive results. Thanks to the improved detector and more sophisticated analysis tools, several interesting new results were obtained and the number of conference presentation and published papers increased in 2025 with respect to the previous year. A list of published journal papers is given in a following section.

3 Frascati Group Activities

The group joined Belle II in 2013 and has since participated to various programs related to software, physics analysis, R&D for future upgrades, as well as detector construction and commissioning. In this section we present a short summary of the Frascati group main activities in 2025.

3.1 Detector construction, Maintenance and R&D work

After contributing for three years to the R&D program for the electromagnetic calorimeter, in 2016 the group joined the KL and muon detector (KLM) detector group. The KLM is the hadronic calorimeter of the experiment, composed mostly by RPCs in the barrel region. The first two layers of the barrel, as well as the endcaps, feature instead plastic scintillators strips. The active layers are interspersed by iron plates, which also act as return yoke of the magnet, as absorber material. The Frascati group, together with the INFN Roma3 group, took on the responsibility of the construction, installation and commissioning of the readout electronics of the RPC barrel detectors [5]. The KLM detector has performed well during the data taking runs of 2025, after routine maintenance activities of the front end electronics and single channel efficiency optimization led by our group.

3.2 Physics Analysis

Our group pioneered in Belle II the analysis of the $B^0 \to J/\psi\, K^0_L$ decay, a tree-level dominated decay mode important as a Standard Model reference for *CP* violation studies. This was the first analysis in Belle II featuring K^0_L mesons identification, implemented by our group using a Fast BDT MVA.

Our group then undertook the measurement of *CP* violation in the $B^0 \to \eta' K^0_L$ decay. This process is mediated at the lower level by a loop diagram, and is therefore sensitive to possible New Physics effects. Key challenge in this analysis is rejection and treatment of the background from continuum and fake K^0_L candidates. This analysis is part of a wide program to measure the effective sin2β and direct CP violation in $B^0 \to \eta' K^0$ decays. A first iteration of this study was published by the Belle II collaboration in 2023 using Run 1 data and focusing only on $B^0 \to \eta' K^0_S$ decays, with $K_S \to \pi^+\pi^-$ and using only two of the possible sub-decays of the η' meson: ($\eta' \to \eta(\to \gamma\gamma)\pi^+\pi^-$ and $\eta' \to \rho^0(\to \pi^+\pi^-)\gamma$).

The addition of the $B^0 \to \eta' K_L$ channels, along with another η' decay ($\eta' \to \eta(\to \pi^+\pi^-\pi^0)\pi^+\pi^-$), the Run 2 dataset and the improved selections and flavor tagger, enhances the statistical precision of the measurement, while also reducing systematic uncertainties due to the study of both final CP eigenstates. It has to be noted that the BaBar and Belle measurements of $\eta' K^0_L$ [1] could not use the $B^0 \to \eta'(\rho\gamma) K^0_L$ decay due to its high background contamination. The good Belle II performance and our use of advanced analysis techniques allow for the first time to include this decay process.

At the time of writing the present report the analysis is not public yet, and we cannot show any results. However, robust estimates indicate that the combined $B^0 \to \eta' K^0$ dataset yields a precision of the Time-Dependent CP parameters competitive with the world average value. Moreover, the $\eta' K^0_L$ decay alone contribute significantly to the precision of the measurement, improving it by 30% with respect to the $\eta' K^0_S$ decays.

3.3 KLM and ECL Performance Study

The Frascati group is also involved in the study of the performances of the KLM and ECL detectors as K^0_L identifiers. This is now a central issue in Belle II, not only in the measurement of time-dependent processes, but also for a precise determination of the missing energy in the events, crucial in the search for rare B decays or dark matter signals.

This work is based on the use of data from the ISR production of ϕ mesons. Exploiting the two-body decay of the ϕ to a $K^0_L K^0_S$ pair, we obtain an unbiased tag for K^0_L mesons inside the apparatus by reconstructing the momentum of the recoiling ISR photon-K^0_S system, assuming the intermediate ϕ state. This method allows to study the behaviour of neutral hadrons in our detector directly from data and thus obtain a detailed comparison of the Monte Carlo simulation of neutral clusters in the with real data. Two internal notes ([2, 3]) have been published on these studies, and the writing of a third, more comprehensive document, is ongoing. The main results are included in a paper on the Belle II detector performance soon to be published on NIMA.

3.4 Belle II Upgrade

The Belle II community is planning near and potential longer-term upgrades of the Belle II detector to cope with planned SuperKEKB upgrades aimed at increasing the machine luminosity. These upgrades will allow increasingly sensitive searches for possible new physics beyond the Standard Model in flavor, tau, electroweak and dark sector physics that are both complementary to and competitive with the LHC and other experiments. A comprehensive discussion of the possible roadmap for the upgrades to the Belle II detector has been published in [4] last year. There are two options for the upgrade of the KLM detector, namely either to replace the RPC detector planes in the barrel with scintillators, or to operate the RPCs in *avalanche* mode rather than in *streamer* mode as currently done in Belle II. The motivation of the latter choice is obviously to minimize the accumulated charge and the dead time due to the much increased background level envisioned in the upgraded SuperKEKB, and would be considerably less expensive. Moreover, it would be much simpler to implement since it would not involve dismantling the whole detector to extract the RPC planes but only change the operating conditions (gas mixture, HV) and add some front-end electronics to amplify the signal.

The LNF and Roma Tre groups started in 2024 an R&D program to define a working solution for the avalanche-mode RPC operation, and eventually propose this solution to the Collaboration.

In 2025 we set up a cosmic-ray stand at LNF to characterise the RPC operation as a function of different gas mixtures, HV settings, and FEE electronics parameters. Two 30x30 cm^2 glasss RPC to be used in the LNF setup, identical to those installed in the KLM detector, have been built in Roma Tre. At the same time, the Roma Tre group also designed the front-end amplifier electronics, which is under production and will be available for installation on the test chambers in early 2026. In 2025 we obtained preliminary results by using a single channel prototype of the electronics under production, with which we instrumented one of the chamber's pickup strip. The signals have been recorded with a 20 GS/sec LeCroy digital oscilloscope and analyzed offline.

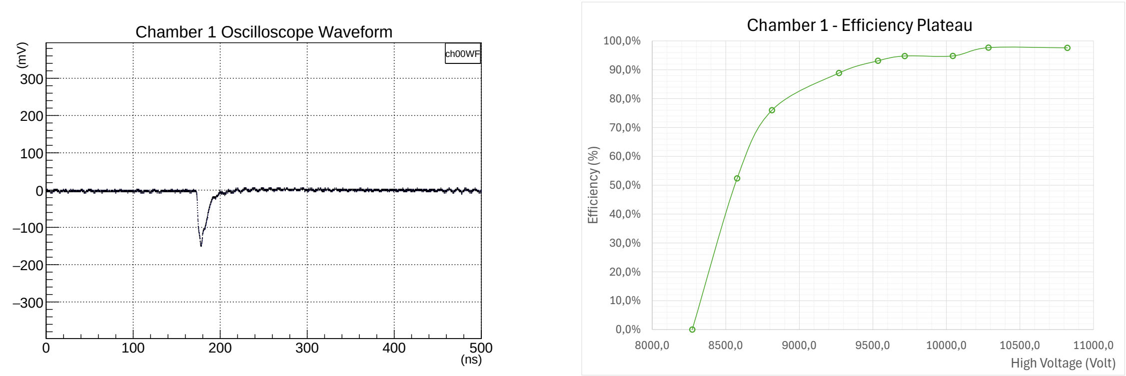

Figure 2: RPC Waveform recorded by the digitsal oscilloscope (left) and efficiency curve as a function of applied high voltage (right).

In Figure 2 we show an example of a recorded waveform (left) and a plot of the efficiency as a function of high voltage setting (right), which is showing a nice plateau as expected.

4 Institutional Responsibilities

In the Belle II organisation chart, Giuseppe Finocchiaro is the chair of the KLM PI group, attending the matters that involve the KLM sub detector management, is responsible for the K_L^0 reconstruction within the KLM group, KLM liason to the neutral particle reconstruction group, and coordinates K_L^0 efficiency and identification activities of the whole collaboration. Riccardo de Sangro is member of the Council of the JENNIFER 3 collaboration

5 Talks

G. Finocchiaro: "Time-dependent *CP* violation in *B* decays". Invited review talk at the 23rd Conference on Flavor Physics and CP Violation (FPCP 2025).

6 "2025 Belle II journal publications"

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