Belle II

Alessandro Calcaterra (staff), Riccardo de Sangro (staff), Giuseppe Finocchiaro (staff, resp.), Ida Peruzzi (ass), Marcello Piccolo (ass), Alessandro Russo (tec).

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 DA Φ NE.

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 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 $4.7 \cdot 10^{34} \text{ cm}^{-2} \text{s}^{-1}$. After a pause during 2023, for a scheduled long shutdown of the accelerator complex, in 2024 data taking resumed with Run 2, which allowed to reach the total combined 2019-2024 integrated luminosity of 575.7 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 were successful and led to the achievement of a new world's record peak luminosity for a particle collider of $5.1 \cdot 10^{34} \text{ cm}^{-2} \text{s}^{-1}$.



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 improvement to the SuperKEKB accelerator complex, as well as to the Belle II 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 2024 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 2024.

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. [4]. The KLM detector has performed well during the data taking runs of 2024, after routine maintenance activities of the front end electronics and single channel efficiency optimization led by our group.

3.2 Shift Management

Since Summer 2023, the organization of Belle II shifts was managed by Alessandro Calcaterra. In 2018 the Frascati group provided the Belle II Collaboration with a shift system developed by Antonio De Santis for KLOE, and also in use by the PADME experiment. The shift tool provided control of 10 to 20 parallel streams of shifts, both for control room roles as well as surveillance of 8 types of subdetector, Data Acquisition, Data Production etc. This system allowed over 1,000 collaborators to orderly and timely occupy all time slots in each shift stream. Due to an ever increasing number of requirements by the Belle II groups, the original PHP-based system and the lack of documentation for the web application which was designed for much simpler applications, needed replacement. A new version of the serving web system based on Django, was thus written entirely in python from scratch by A. Calcaterra. As the new system retained most of the existing underlying DB structures, the integrity of the past shift history has been guaranteed. The new

system has been completely documented and put online during Summer 2024 and used successfully in the last run.

3.3 Physics Analysis

Our group pioneered in Belle II the analysis of the $B^0 \to J/\psi K_L^0$ decay, a tree-level dominated decay mode important as a Standard Model reference for CP violation studies. This was the firs analysis in Belle II featuring K_L^0 mesons identification implemented by our group using a Fast BDT MVA. In 2023 it was decided to pause the analysis awaiting for new data, and give priority to other measurements. Our group undertook the measurement of CP violation in the $B^0 \to \eta' K_L^0$ 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_L^0 candidates. Figure 2 shows a preliminary result for discriminating variable ΔE in a limited statistics sample (approximately ten times smaller than the data collected to date by Belle II) sample of selected $B^0 \to \eta' K_L^0$ simulated events. The fit models the signal component (blue) and the combinatorial background, mainly originating from continuum events.



Figure 2: ΔE in selected $B^0 \rightarrow \eta' K_L^0$ simulated events.

3.4 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_L^0 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 $K_L^0 K_S^0$ pair, we obtain an unbiased tag for K_L^0 mesons inside the apparatus by reconstructing the momentum of the recoiling ISR photon- K_S^0 system, assuming the intermediate ϕ state.



Figure 3: K_L^0 detection efficiency in the KLM as a function of K_L^0 momentum.

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. The measured K_L^0 detection efficiency in the Belle II KLM is presented in Figure 3. Two comprehensive internal notes ([1,2]) have been published on these studies. Some of the results are included in a paper on the Belle II detector soon to be published on NIMA.

3.5 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 [3] 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 Roma3 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 particular at LNF we set up a cosmic-ray stand to characterise the RPC operation as a function of different gas mixtures, HV settings, and FEE electronics parameters. Preliminary results are foreseen in year 2025.

4 Institutional Responsiblities

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, and Alessandro Calcaterra was the Belle II Shift Manager between 2023 and 2024.

5 "2024 Belle II journal publications"

References

- 1. R. de Sangro, G. Finocchiaro, C. Martellini, A. Passeri, M. Piccolo, "Event selection for the $e^+e^- \rightarrow \phi \gamma_{\rm ISR}$ reaction in Belle II", BELLE2-NOTE-TE-2018-007, Sep. 2023 (unpublished).
- 2. R. de Sangro, G. Finocchiaro, C. Martellini, A. Passeri, M. Piccolo, R. Volpe, "Study of K_L^0 reconstruction efficiency at Belle II using the ISR reaction $e^+e^- \rightarrow \phi \gamma_{\text{ISR}}$ " BELLE2-NOTE-TE/2024-016 Aug. 2024 (unpublished).
- H. Aihara *et al.*, "The Belle II Detector Upgrades Framework Conceptual Design Report" doi: 10.48550/arXiv.2406.19421

- 4. C. Ketter *et al.* "Design and Commissioning of Readout Electronics for a K_L^0 and muon Detector at the Belle II Experiment" doi: 10.48550/arXiv.2502.02724 [submitted to NIMA]
- 5. I. Adachi *et al.* [Belle-II], "Observation of the decay $B^0 \rightarrow J/\psi \omega$ at Belle II," Phys. Rev. D **111** (2025) no.3, 032012
- 6. I. Adachi *et al.* [Belle and Belle-II], "Observations of the singly Cabibbosuppressed decays $\Xi_c^+ \to pK_S^0$, $\Xi_c^+ \to \Lambda \pi^+$, and $\Xi_c^+ \to \Sigma^0 \pi^+$ at Belle and Belle II," JHEP **03** (2025), 061
- 7. I. Adachi *et al.* [Belle and Belle-II], "Measurement of the time-integrated CP asymmetry in $D^0 \to K_s^0 K_s^0$ decays using Belle and Belle II data," Phys. Rev. D **111** (2025) no.1, 012015
- 8. I. Adachi *et al.* [Belle-II], "Observation of time-dependent CP violation and measurement of the branching fraction of $B^0 \rightarrow J/\psi \pi^0$ decays," Phys. Rev. D **111** (2025) no.1, 012011
- 9. I. Adachi *et al.* [Belle-II], "Measurement of CP Asymmetries in $B^0 \to K_s^0 \pi^0 \gamma$ Decays at Belle II," Phys. Rev. Lett. **134** (2025) no.1, 011802
- 10. I. Adachi *et al.* [Belle-II], "Search for the baryon number and lepton number violating decays $\tau^- \to \Lambda \pi^-$ and $\tau^- \to \overline{\Lambda} \pi^-$ at Belle II," Phys. Rev. D **110** (2024) no.11, 112003
- I. Adachi *et al.* [Belle-II], "Measurement of the integrated luminosity of data samples collected during 2019-2022 by the Belle II experiment", Chin. Phys. C 49 (2025) no.1, 013001
- 12. I. Adachi *et al.* [Belle-II], "Measurement of the branching fractions of $\overline{B} \rightarrow D^{(*)}K^-K^{(*)0}_{(S)}$ and $\overline{B} \rightarrow D^{(*)}D^-_s$ decays at Belle II," JHEP **08** (2024), 206
- 13. I. Adachi *et al.* [Belle and Belle-II], "Measurements of the branching fractions of $\Xi_c^0 \to \Xi^0 \pi^0$, $\Xi_c^0 \to \Xi^0 \eta$, and $\Xi_c^0 \to \Xi^0 \eta'$ and asymmetry parameter of $\Xi_c^0 \to \Xi^0 \pi^0$," JHEP **10** (2024), 045
- 14. I. Adachi *et al.* [Belle and Belle-II], "Search for the decay $B^0 \rightarrow \gamma \gamma$ using Belle and Belle II data," Phys. Rev. D **110** (2024) no.3, L031106
- 15. I. Adachi *et al.* [Belle-II], "Measurement of the energy dependence of the $e^+e^- \rightarrow B\overline{B}, B\overline{B}^*$, and $B^*\overline{B}^*$ cross sections at Belle II," JHEP **10** (2024), 114
- 16. I. Adachi *et al.* [Belle-II], "Test of light-lepton universality in τ decays with the Belle II experiment," JHEP **08** (2024), 205

- 17. I. Adachi *et al.* [Belle-II], "Search for lepton-flavor-violating $\tau^- \rightarrow \mu^- \mu^+ \mu^-$ decays at Belle II," JHEP **09** (2024), 062
- 18. I. Adachi *et al.* [Belle and Belle-II], "Determination of the CKM angle ϕ_3 from a combination of Belle and Belle II results," JHEP **10** (2024), 143
- 19. I. Adachi *et al.* [Belle-II], "Measurement of the branching fraction of the decay $B^- \rightarrow D^0 \rho(770)^-$ at Belle II," Phys. Rev. D **109** (2024) no.11, L111103
- 20. I. Adachi *et al.* [Belle and Belle-II], "Search for Rare $b \rightarrow d \ell^+ \ell^-$ Transitions at Belle," Phys. Rev. Lett. **133** (2024) no.10, 101804
- 21. I. Adachi *et al.* [Belle-II], "Measurement of the $e^+e^- \rightarrow \pi^+\pi^-\pi^0$ cross section in the energy range 0.62 3.50 GeV at Belle II," Phys. Rev. D **110** (2024) no.11, 112005
- 22. I. Adachi *et al.* [Belle-II], "Search for a $\mu^+\mu^-$ resonance in four-muon final states at Belle II," Phys. Rev. D **109** (2024) no.11, 112015
- 23. I. Adachi *et al.* [Belle-II], "Measurement of CP asymmetries in $B^0 \to K_s^0 K_s^0 K_s^0$ decays at Belle II," Phys. Rev. D **109** (2024) no.11, 112020
- 24. I. Adachi *et al.* [Belle-II], "New graph-neural-network flavor tagger for Belle II and measurement of $\sin 2\phi_1$ in $B^0 \to J\psi K_s^0$ decays," Phys. Rev. D **110** (2024) no.1, 012001
- 25. I. Adachi *et al.* [Belle-II], "Measurement of CP asymmetries in $B^0 \rightarrow \eta' K_s^0$ decays at Belle II," Phys. Rev. D **110** (2024) no.11, 112002
- 26. I. Adachi *et al.* [Belle-II], "Study of $\Upsilon(10753)$ decays to $\pi^+\pi^-\Upsilon(nS)$ final states at Belle II," JHEP **07** (2024), 116
- 27. I. Adachi *et al.* [Belle-II], "Test of lepton flavor universality with a measurement of $R(D^*)$ using hadronic *B* tagging at the Belle II experiment," Phys. Rev. D **110** (2024) no.7, 072020
- 28. I. Adachi *et al.* [Belle-II], "Search for the $e^+e^- \rightarrow \eta_b(1S)\omega$ and $e^+e^- \rightarrow \chi_{b0}(1P)\omega$ processes at $\sqrt{S} = 10.745 \, GeV$," Phys. Rev. D **109** (2024) no.7, 072013
- 29. I. Adachi et al. [Belle-II], "Evidence for $B^+ \to K^+ \nu \bar{\nu}$ decays" Phys. Rev. D 109 (2024) no.11, 112006
- 30. I. Adachi *et al.* [Belle-II], "First Measurement of $R(X_{\tau/\ell})$ as an Inclusive Test of the $b \to c\tau\nu$ Anomaly," Phys. Rev. Lett. **132** (2024) no.21, 211804

- 31. I. Adachi *et al.* [Belle-II], "Measurement of branching fractions and direct CP asymmetries for $B \to K\pi$ and $B \to \pi^+\pi^-$ decays at Belle II," Phys. Rev. D **109** (2024) no.1, 012001
- 32. I. Adachi *et al.* [Belle and Belle-II], "Measurement of branching-fraction ratios and CP asymmetries in $B^{\pm} \rightarrow D_{CP\pm}K^{\pm}$ decays at Belle and Belle II," JHEP **05** (2024), 212