Recent results from Belle and Belle II*

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The Belle II detector started taking data in 2019, with the goal of extending the physics reach of its predecessor, Belle, which collected about 1 ab^{-1} of integrated luminosity of e^+e^- collisions at a center of mass energy corresponding (or near) to the mass of the $\Upsilon(4S)$ resonance. In this contribution, we present results based on (part of) the Run1 data set of Belle II, corresponding to 424 fb^{-1}, in some cases combined with the full Belle data set. The results include measurements related to quantities of the CKM Unitarity Triangle, searches for the rare decay $B^+ \to K^+\nu\bar{\nu}$, for Lepton Flavor Universality violating phenomena, and for Dark Sector particles.

1. Introduction

The B-Factory experiments BaBar and Belle operated for about a decade at the beginning of the 21$^{\text{st}}$ century, with the main goal of discovering CP violation phenomena in the decays of the B mesons and confirming the CKM paradigm, in which all CP violating phenomena arise from the nontrivial complex phase contained in the CKM quark-mixing matrix. The status of the CKM Unitarity Triangle fit [1], [2] at the end of the operation of the B Factories testifies the accomplishments of their physics program and the vast increase in the precision with which many fundamental parameters are known.

Despite the continuing success of the LHCb experiment which took the lead in many areas of flavor physics, there are still strong motivations for pursuing the path opened by the B factories: final states containing neutral particles (π^0's, $\eta^{(\prime)}$'s, K^0_L's, ...) or neutrinos, or affected by *difficult* backgrounds are better studied in the cleaner environment of e^+e^- collisions, where the knowledge of the kinematics of the initial state can be decisive

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in separating an elusive signal from the backgrounds. Moreover, several anomalies, potentially pointing towards physics beyond the standard model (SM) that have been brought to the attention in the past decade, require independent confirmation. Finally, the first generation of B factories has given important (and perhaps unexpected) contributions in the discovery of exotic particles and in the understanding of their properties; in this area, an e^+e^- collider can have unique sensitivity, especially for low multiplicity final states.

All these reasons motivated the upgrade of the Belle detector to Belle II, and of the KEKB collider to SuperKEKB.

2. Belle (II) and (Super)KEKB

The asymmetric energy e^+e^- collider KEKB, which reached a record peak instantaneous luminosity of 2.1×10^{34} cm^{-2} s^{-1}, has been upgraded with the goal of collecting an integrated luminosity of 50 ab^{-1}. To do this, the Lorentz boost has been decreased to $\beta\gamma \sim 0.28$ (4.0 GeV positrons colliding against 7.0 GeV electrons) and more importantly the so-called *nanobeam scheme* [3], which strongly reduces the transverse size of the colliding bunches, has been implemented. This guarantees an increase in the instantaneous luminosity of a factor 20 which, combined with a moderate increase in the beam currents, will bring the design luminosity to 6×10^{35} cm^{-2} s^{-1}.

The Belle detector has been extensively upgraded in most of its components. Of the predecessor, Belle II [4] utilizes only the steel structure, the superconducting solenoid, the crystals of the electromagnetic calorimeter, and part of the resistive plate chambers in the barrel section of the return yoke of the magnetic field. All the other subsystems have been completely redesigned in order to cope with the higher luminosity and more severe background conditions and to improve the performance. The improvements mostly concern the vertexing resolution and K^0_S reconstruction efficiency, the charged K/π separation capabilities, and the development of trigger strategies specifically targeting low multiplicity final states that are relevant for Dark Sector searches (for which Belle had only limited sensitivity).

The Run1 of physics data taking began in the Spring of 2019 and was concluded in June 2022, after which operations stopped for a program of maintenance and upgrade of both detector and accelerator, with the plan of resuming physics data taking in February 2024. During Run1, SuperKEKB achieved the record instantaneous luminosity of 4.7×10^{34} cm^{-2} s^{-1} and Belle II recorded an integrated luminosity of 424 fb^{-1}, of which 362 fb^{-1} were taken at an energy corresponding to the mass of the $\Upsilon(4S)$, 42 fb^{-1} were taken at an energy 60 MeV lower (to study the so called *continuum* background in which the collisions produce pairs of quarks lighter than the b), and 19 fb^{-1} were recorded to study the spectroscopy around the 10.75 GeV region.

3. Time-dependent CP violation in B mesons

Measurements of time-dependent CP violation in B-meson decays were one of the strongest motivations for the construction of the first generation of B Factories and are still very relevant today, as they allow to access fundamental parameters of the SM and they are limited by the statistical uncertainty. The quantity $\sin(2\phi_1)$ (or $\sin(2\beta)$ using an alternative convention) can be accessed from the interference between $B\bar{B}$ mixing and decay in a number of B-meson decays to CP eigenstates.

The golden modes $B^0 \to (c\bar{c})K^0$ are dominated by tree diagram amplitudes and are thus mostly unaffected by new physics contributions. Belle II utilizes the full Run1 data set to measure the time-dependent ($S \simeq \sin(2\phi_1)$) and time-integrated (C) CP asymmetries on $B^0 \to J/\psi K^0_S$ decays [5]. Compared to previous Belle II measurements in this field, the most significant improvement consists in the use of a novel flavor tagger, which is the analysis tool that determines the most likely flavor (B^0 or $\overline{B}^0$) of the unreconstructed B meson in the event. The new algorithm is based on a *graph convolutional neural network* that exploits 25 variables for each of the charged tracks that are not originating from the B decaying to the fully reconstructed CP eigenstate. This new approach guarantees an impressive 18% relative $((37.4 \pm 0.4 \pm 0.3)\%$ vs $(31.7 \pm 0.5 \pm 0.4\%))$ increase in the effective tagging efficiency (which is equivalent to having 18% more luminosity) compared to the previous *category based* flavor tagger. The CP asymmetries measured in $B^0 \to J/\psi K^0_S$ are

$$\begin{aligned} S &= 0.724 \pm 0.035 \pm 0.014\ , \\ C &= -0.035 \pm 0.026 \pm 0.013\ . \end{aligned}$$

Also the time-dependent asymmetry in $B^0 \to \eta' K^0$ measures $\sin(2\phi_1)$ with very little hadronic uncertainty but, proceeding dominantly through loop amplitudes, the result could be significantly perturbed by competing amplitudes from physics beyond the SM. We analyze the full Run1 Belle II data set to measure the time-dependent and time-integrated CP asymmetries in $B^0 \to \eta' K^0_S$ [6], reconstructing the η' decays into the two subchannels $\eta' \to \eta(\to \gamma\gamma)\pi^+\pi^-$ and $\eta' \to \rho^0\gamma$. The discrimination between signal and backgrounds relies on the variables ΔE (difference between the reconstructed and expected energies of the candidate B meson), M_{bc} (invariant mass of the B candidate, assuming that its energy in the center of mass system corresponds to half of the collision energy) and the output of a multivariate discriminator that distinguishes $B\overline{B}$ and continuum events based on their event topologies. The time-dependent fit gives

$$\begin{aligned} S &= 0.67 \pm 0.10 \pm 0.04 \, , \\ C &= -0.19 \pm 0.08 \pm 0.03 \, . \end{aligned}$$

Figure 1 displays the results of the time-dependent fit for the two analyses presented in this section.

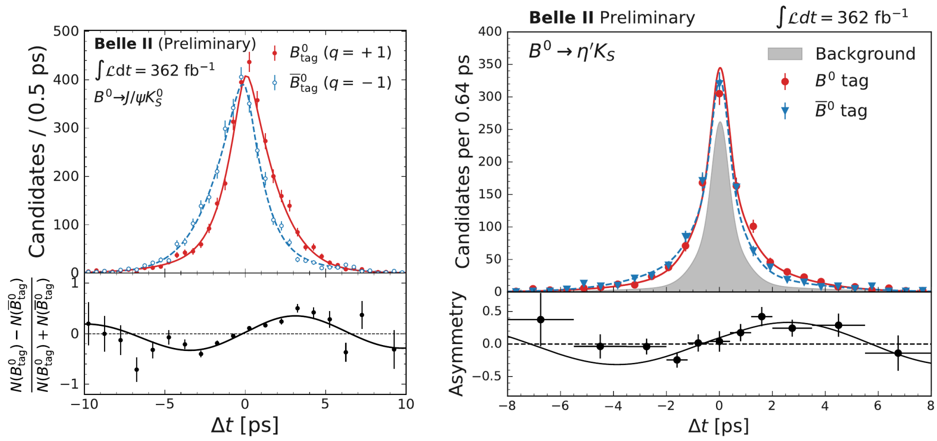

Fig. 1. Distributions of the proper decay time difference of the two B mesons Δt, separately for B^0 tagged (red points) and $\overline{B}^0$ tagged (blue) events for the time-dependent analysis of $B^0 \to J/\psi K_S^0$ (left plot) and $B^0 \to \eta' K_S^0$ (right).

4. Measurements of the $\phi_3(\gamma)$ CKM angle

The angle ϕ_3 (γ) is one of the most important inputs of the CKM Unitarity Triangle fit, as it can be measured from tree level processes. The current precision is $\sim 3.5°$ and most of the sensitivity comes from measurements of the interference between $B^+ \to D^0 K^+$ and $B^+ \to \overline{D}^0 K^+$ processes. The LHCb experiment, which can perform also time-dependent measurements of B_s decays is currently dominating the world average [7].

Belle II produced several results by combining its data set with that already recorded by the Belle experiment, since all measurements will remain limited by the statistics for the foreseeable future. In particular, we performed an analysis [8] of $B^+ \to Dh^+$, with $D \to K_S^0 h^+ h^-$, $D = D^0, \overline{D}^0$, and $h = \pi, K$ utilizing the so-called BPGGSZ method [9], which exploits the richness of information of the Dalitz plot analysis of the three-body D decay. This is complemented with an analysis [10] in which the neutral D meson decays to the final state $K^0_S K^\pm \pi^\mp$ and the weak phase is extracted using the GLS method [11], and a further one utilizing the GLW method [12] on the final states $D \to K^+K^-, K^0_S\pi^0$ [13]. The combination of these results (see Fig. 2) yields

$$\phi_3 = (78.6 \pm 7.3)^\circ \ . \tag{1}$$

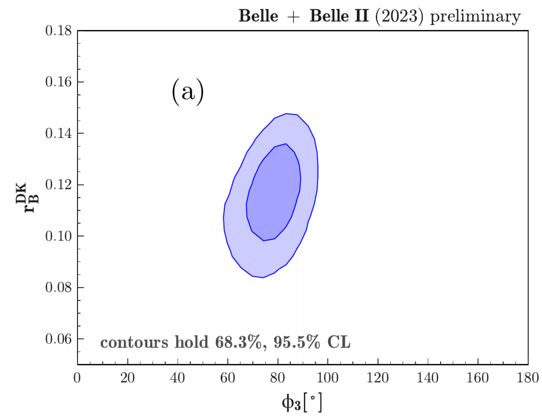

Fig. 2. Two-dimensional confidence regions for the ϕ_3 combination. The parameter r_B^{DK} represents the ratio between the suppressed and favored amplitudes entering the analysis (and thus drives its sensitivity).

5. First evidence for the $B^+ \to K^+\nu\bar{\nu}$ decay

The $B^+ \to K^+\nu\bar{\nu}$ decay proceeds only through box or loop diagrams and its branching ratio can be predicted with accuracy better than 10% by the theory [14]. This process has never been observed before and might be linked to some of the deviations that have been observed in $b \to s\ell\ell$ transitions, while the difficulty of this measurement arises from the presence of two neutrinos in the final state.

At Belle II we utilize two distinct analysis approaches to search for the $B^+ \to K^+\nu\bar{\nu}$ [15]: the first, denoted as Hadronic Tag Analysis (HTA) follows a well established method in which one of the two B's is fully reconstructed into a hadronic final state (so that the only undetected particles are the two neutrinos from the signal B decay), while in the second, called Inclusive Tag Analysis (ITA), the other B meson in the event is not reconstructed and the separation between the signal and backgrounds relies on multivariate discriminators exploiting variables sensitive to the event shape. The HTA (ITA) achieves a tighter (looser) control of the backgrounds, while the signal reconstruction efficiency is lower (higher); overall the ITA analysis achieves the better sensitivity. Despite using the same data set, the two analyses are almost completely statistically independent. We verify that the ITA correctly discriminates signal and background events by using $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$ in which the muons are subtracted from the event (in order to mimic the neutrinos) and the K^+ momentum is scaled to match the expected kinematics of a three-body decay. We find very good agreement between data and simulation in this control channel. The dominant backgrounds come from semileptonic B decays and events in which one or more K^0_L's escape detection. We validate the K^0_L reconstruction efficiency using $e^+e^- \to \phi(\to K^0_S K^0_L)\gamma_{\rm ISR}$ events. Control samples in which the particle identification requirements on the signal K track are modified in order to select pion-enriched or lepton-enriched samples are used to correct and validate the assumptions made on specific backgrounds (e.g. $D \to K^0_L X$).

The yields are exctracted from a fit to the output of the multivariate discriminator that separates signal from backgrounds; in the ITA the q^2, equal to the square of the invariant mass of the two neutrinos, is also considered as second fit variable. Both ITA and HTA observe an excess over the expected backgrounds: the signal strength μ (ratio of measured branching ratio over the SM expectation) is 2.2 for HTA and 5.4 for ITA (see Fig. 3, left). Combining the two analyses (Fig. 3, right), we obtain

$$\mu = 4.6 \pm 1.0(\text{stat}) \pm 0.9(\text{syst}) \,, \tag{2}$$

$$\text{BR}(B^+ \to K^+\nu\bar{\nu}) = [2.4 \pm 0.5(\text{stat})^{+0.5}_{-0.4}(\text{syst})] \times 10^{-5} \,. \tag{3}$$

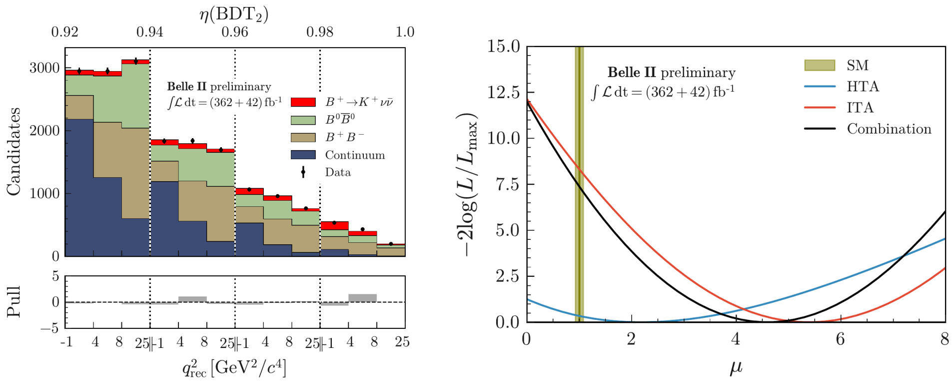

Fig. 3. Left figure: distribution of the output of the multivariate classifier utilized for signal discrimination in the ITA analysis (the signal component is in red). Right: results of the combination of the HTA and ITA analyses.

The significance is 3.5 (2.7) standard deviations above the background-only (SM) hypothesis and this result constitutes the first evidence of the $B^+ \to K^+\nu\bar{\nu}$ decay.

6. Measurement of $R(D^*)$

One of the most interesting hints for possible Lepton Flavor Universality violation comes from the measurement of the quantities

$$R(D^{(*)}) = \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)} \qquad \ell = e, \mu \; , \tag{4}$$

whose averages [16] have been for several years above the very precise SM predictions. At Belle II we utilize about half of the Run1 data set to measure $R(D^*)$ [17] for both charged and neutral B mesons, exploiting only leptonic τ decays (which implies that there are three neutrinos in the final state). The analysis is performed on the recoil of B mesons fully reconstructed in hadronic final states. The different components ($B \to D^*\tau\nu$, $B \to D^*\ell\nu$, and the backgrounds) are extracted through a 2-dimensional fit. The first variable is $M^2_{\mathrm{miss}} = (p_{e^+e^-} - p_{B_{\mathrm{tag}}} - p_{D^*} - p_\ell)^2$, which peaks at 0 for $B \to D^*\ell\nu$ while it exhibits a broader distribution for $B \to D^*\tau\nu$ and the backgrounds. The second variable is $E^{\mathrm{extra}}_{\mathrm{ECL}}$ (see Fig. 4), which is the sum of the energy of the clusters in the calorimeter that are not associated to the particles explicitly reconstructed in the decay chains; this peaks at 0 for the correctly reconstructed semileptonic B decays. Several control samples are utilized to constrain the backgrounds including D^{**} resonances or incorrectly reconstructed D^* decays. We obtain the result

$$R(D*) = 0.262^{+0.041}_{-0.039}(\mathrm{stat})^{+0.035}_{-0.032}(\mathrm{syst}) \; , \tag{5}$$

which is in agreement with both the world average and the SM expectation. Despite the fact that this result does not surpass the precision reached by Belle, we stress that the statistical error obtained with Belle II with equivalent luminosity is 40% better.

Also the inclusive analysis [18] of

$$R(X) = \frac{\mathrm{BR}(B \to X\tau\nu)}{\mathrm{BR}(B \to X\ell\nu)} \tag{6}$$

yields results that are compatible with the SM predictions.

7. Searches for Dark Sector particles

Direct searches for particles beyond the SM are not focusing only on the high energy frontier but also on the so-called Dark Sector. Many new physics theories postulate the existence of particles that interact with the SM particles only through weekly coupling mediators whose mass could be in the [0.1; 10] GeV/c^2 range. Several scenarios have been probed experimentally at Belle II, with the mediator being a spin-0 or spin-1 particle,

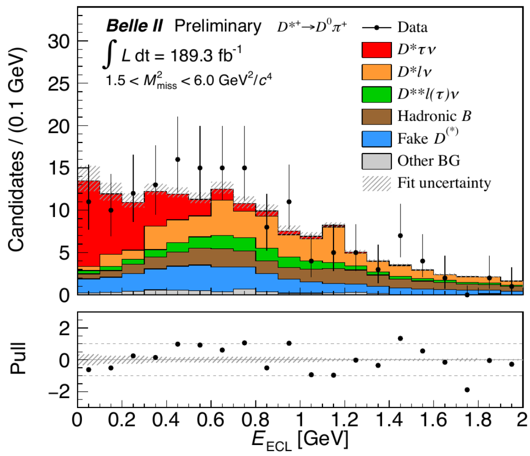

Fig. 4. Distributions of $E_{\rm ECL}^{\rm extra}$ for events with $1.5 < M_{\rm miss}^2 < 5.0$ GeV$^2/c^4$ (this selection enhances the $B \to D^*\tau\nu$ component).

long- or short-lived, and with different hypotheses on the coupling strengths to the ordinary particles.

We utilized a fraction of the Run1 data set to search for $e^+e^- \to \mu^+\mu^- Z'$ events, with the vector particle Z' decaying to invisible particles [19]. We do not find any peaking structure in the recoil mass of the $\mu^+\mu^-$ system and thus we proceed to set limits in the coupling constants of the Z' with the SM particles (see Fig. 5, left). The search is complemented by another Belle II analysis, focusing on the $Z' \to \mu^+\mu^-$ process [20]. Also in this case no significant signal is found and we exclude some areas of the phase space that had not yet been probed by previous experiments.

We also search for the production of a long-lived scalar particle S in $B \to K^{(*)}S$ decays, with $S \to x^+x^-$ and $x = e, \mu, \pi, K$ [22]. The decay vertex of S can be displaced from the interaction region by as much as 100 cm and we veto $K_S^0 \to \pi^+\pi^-$ candidates. No signal is detected and exclusion limits are provided in a model-independent way and also on the parameter space of a model in which the axionlike mediator mixes with the SM Higgs boson. Finally, we search for resonances decaying to pairs of τ leptons in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$ [21]. The search for peaking structure in the mass recoiling against the $\mu^+\mu^-$ system does not yield any significant signal, so limits are set in different models, taking into consideration both spin-0 and spin-1 particles.

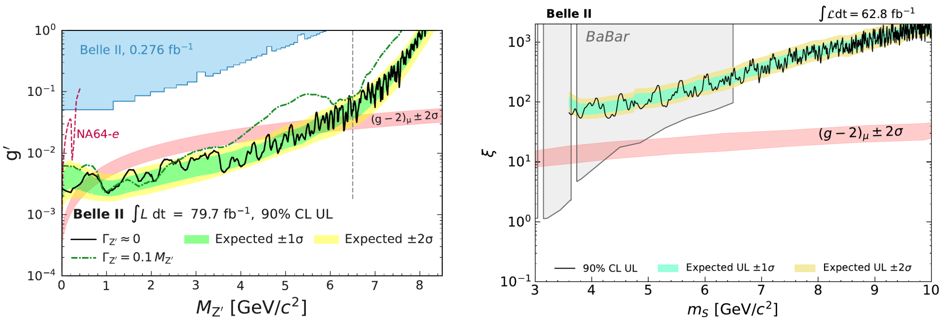

Fig. 5. Left figure: exclusion limits on the coupling strength g' of the $L_\mu - L_\tau$ model as a function of the Z' mass for the $Z' \to$ invisible search [19]. Right: exclusion limits for the leptophilic scalar coupling ξ as a function of the mass of the resonance S in the $S \to \tau^+\tau^-$ analysis [21]. In both figures the red band displays the interesting region for a possible explanation of the $(g-2)_\mu$ anomaly.

8. Conclusions

The Belle II experiment successfully concluded its Run1 data taking period. While the integrated luminosity is still a factor 100 smaller than the final goal, these data allowed the collaboration to perform many analyses in the physics of the B and D mesons, of the τ leptons, and of the Dark Sector. In many cases our results are already world leading, in others we show better sensitivity, compared to Belle, on equivalent luminosity. By combining the Belle and Belle II data sets we can obtain the best sensitivity on several flavor physics observables.

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