Recent results on dark sector searches at Belle and Belle II

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Summary. — The Belle and Belle II experiments provide a unique sensitivity to a broad class of models that postulate the existence of new particles with masses in the range between a few MeV/c^2 and GeV/c^2, capable of mediating interactions between dark matter and visible matter. This paper reports the latest world-leading physics results from Belle and Belle II on the search for non-Standard Model resonances produced in B meson decays; on inelastic dark matter produced in association with a dark Higgs boson; as well as short-term prospects for future searches in the dark sector.

1. – Introduction

A variety of astrophysical and cosmological evidence points to the existence of dark matter (DM)—an unknown form of matter that interacts primarily through gravity and not via strong or electroweak forces, rendering it effectively "dark". The dark sector (DS), a promising extension of the Standard Model (SM), offers a potential explanation for the nature of DM and introduces new, undiscovered quantum fields that mediate feeble interactions between visible and dark matter. These interactions could address unresolved phenomena, such as the baryon asymmetry of the Universe and the anomalous magnetic moment of the muon $(g-2)_\mu$, which remain challenging to account for within the SM [1]. They can arise through various "portals," defined by the mediator's spin and parity [2]. The main dark sector portals include the vector portal, mediated by dark photons; the scalar portal, involving a mediator like the Higgs boson or a new scalar particle; the neutrino portal, which employs fermionic mediators such as heavy sterile neutrinos; and the pseudoscalar portal, which includes axions or axion-like particles. High-precision intensity frontier experiments like Belle and Belle II are well equipped to probe these scenarios and identify new physics signatures. This paper provides an overview of the dark sector searches conducted at the Belle and Belle II experiments, based on datasets of 711 fb^{-1} and 365 fb^{-1}, respectively.

1˙1. *The Belle and Belle II experiments.* – B-factories are asymmetric-energy e^+e^- colliders primarily designed to produce B mesons. They provide ideal conditions to study flavor physics alongside D mesons, τ leptons, and potential dark sector phenomena. These experiments operate at the energies of the $Y(nS)$ resonances, with a particular focus on the $Y(4S)$ resonance, where collisions occur at a center-of-mass (CM) energy $\sqrt{s} = 10.58$ GeV, just above the production threshold of B meson pairs. Following the Belle (1999–2010) and BaBar (1999–2008) experiments, Belle II is a second-generation B-factory and represents a major upgrade from the original Belle experiment [3]. It operates at the SuperKEKB accelerator, an advanced facility located at KEK, Japan [4]. To date, Belle II has collected an integrated luminosity of 575 fb^{-1} [5], with a long-term goal of accumulating 50 ab^{-1}, fifty times the dataset of the original Belle experiment.

1˙2. *Dark sector searches.* – Dark matter particles could, in principle, be produced abundantly in electron-positron collisions. While Belle and Belle II primarily focus on studying the properties and rare decays of B mesons, they also offer significant potential for discovering dark matter. These experiments are uniquely sensitive to light dark sector mediators in the mass range from MeV/c^2 to GeV/c^2. Taking advantage of the unique features of B-factories—such as hermetic detector coverage, well-defined initial conditions, and a clean experimental environment with low background levels—Belle and Belle II achieve excellent particle identification and high-precision measurements. Furthermore, Belle II employs dedicated triggers, including single photon, single track, and single muon triggers. These features enable the reconstruction of missing energy events and the search for invisible signatures, both essential for dark matter and dark sector investigation.

2. – Recent results

Dark sector signatures can be explored by searching for dark sector particles that are either directly produced through e^+e^- collisions or occur as a result of the decay of mesons (like B, D) and fermions (such as τ). Different scenarios can arise—featuring visible, invisible, or long-lived particle decays—depending on the nature of the dark sector mediator and the mass of the dark matter candidate. Belle and Belle II investigate these signatures in their search for dark matter candidates, including the dark photon, axion-like particles, or Z' bosons. They may also investigate rare or exotic decay processes of known particles into dark sector states, aiming to discover physics beyond the SM. A summary of the latest findings from the Belle and Belle II dark sector searches is provided below.

2˙1. *Search for inelastic dark matter and a dark Higgs boson at Belle II.* – A non-minimal class of dark sector models introduces inelastic DM (iDM), where DM couples inelastically to SM states. The simplest among them can reproduce the observed relic dark matter density without violating cosmological limits, featuring two dark matter particles, χ_1 and χ_2, and a massive dark photon A' [6]. The A' interacts with the SM photon via a kinetic mixing mechanism at strength ϵ and with DM via the coupling $g_D = \sqrt{4\pi\alpha_D}$, while it decays predominantly via $A' \to \chi_1\chi_2$. A small mass splitting Δm between the two dark matter particles χ_1 and χ_2, with $m_{\chi_2} > m_{\chi_1}$, is induced by a dark Higgs field and a corresponding dark Higgs boson h'. This mass gap makes the heavier state χ_2 long-lived before decaying into a pair of SM particles and the lighter state χ_1, while χ_1 is stable and escapes the detector. The h' may interact with the SM Higgs via a mixing angle θ, rendering it naturally long-lived for small values of θ, and couples to DM via the coupling $k \approx g_D \Delta m / m_{A'}$.

We search for a dark Higgs h' produced in association with iDM through the process $e^+e^- \rightarrow h'(\rightarrow x^+x^-)A'(\rightarrow \chi_1\chi_2(\rightarrow \chi_1 e^+e^-))$ where $x^\pm = \mu^\pm, \pi^\pm, K^\pm$ and $m_{h'} < m_{\chi_1} < m_{A'}$. The analysis aims to identify an excess in the h' invariant mass distribution in four-track events featuring up to two displaced vertices and missing energy. The signal signature consists of two tracks forming a displaced vertex that points back to the interaction point (IP) and two tracks forming a non-pointing displaced vertex, corresponding to h' and χ_2 in signal events respectively. Background levels are expected to be close to zero as the selection criteria exploit the signal signature to minimize them: we require at least one vertex displaced sufficiently from the IP in order to suppress prompt SM contributions, the h' vertex pointing back to the IP, a track opening angle > 0.1 rad to suppress photon conversions, and missing energy > 4 GeV to reject remaining SM backgrounds. Other background sources include the long lived K^0_S and Λ particles as well as the ϕ resonance, whose mass regions are excluded from the search and studied as control data samples.

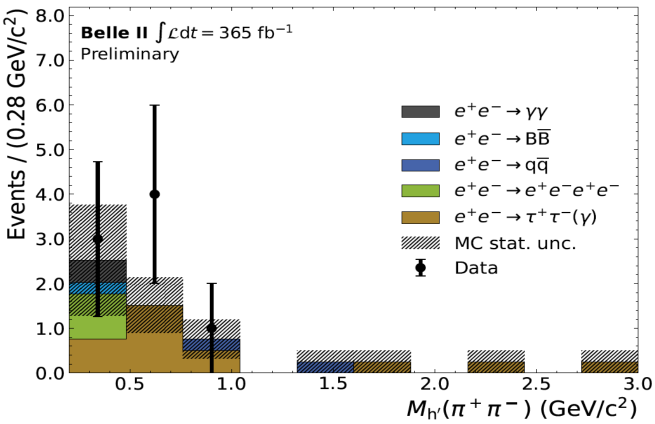
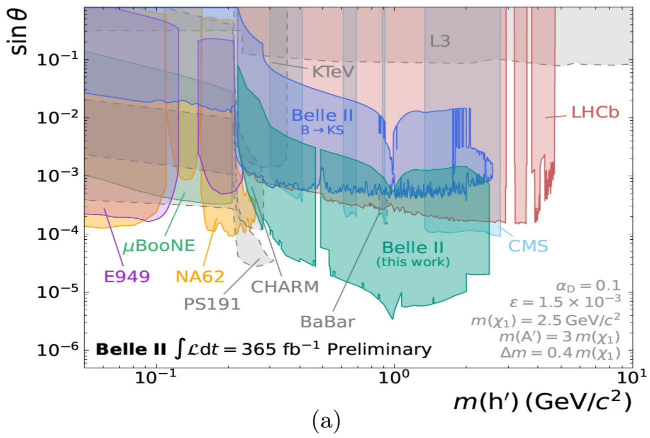
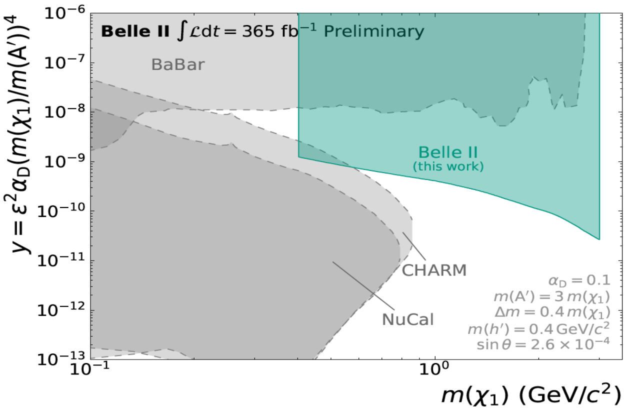


Fig. 1.: Distribution of $M(\pi^+\pi^-)$ together with the stacked contributions from the various simulated SM background samples for $h' \rightarrow (\pi^+\pi^-)$ candidates.

In the absence of an additional signal, fewer than 10 events are expected in the combined final states of the dark Higgs, based on SM background simulations corresponding to an integrated luminosity of 365 fb^{-1}. This can be seen in fig. 1. Due to the significantly low levels of background observed, we apply a cut and count technique to extract the signal. We do not find any significant excess compatible with signal events in 365 fb^{-1} of data, thus we set 95% confidence level (CL) upper limits on the product of the cross section $\sigma(e^+e^- \rightarrow h'\chi_1\chi_2)$ and the branching fractions $\mathcal{B}(\chi_2 \rightarrow \chi_1 e^+e^-) \times \mathcal{B}(h' \rightarrow x^+x^-)$ where $x = \mu, \pi, K$ [7]. We translate these results to constrain the parameters of the model and set upper limits on the $(sin\theta - m_{h'})$ parameter space, that is defined by the sine of the mixing angle θ and the h' invariant mass, and $(y - m_{\chi_1})$ plane, where $y = \epsilon^2 \alpha_D (m_{\chi_1}/m_{A'})^4$ is a dimensionless variable and m_{χ_1} is the χ_1 invariant mass. Results on the exclusion regions are shown in fig. 2a and fig. 2b. For a specific configuration of the model parameters, fig. 2a shows that this analysis manages to probe two orders of magnitude more in $sin\theta$ with respect to the existing limits set by other experiments. Additionally, we set upper limits and provide plots for several configurations of the model parameters.



(a)



(b)

Fig. 2.: Exclusion regions at 95% CL in the (a) $(sin\theta - m_{h'})$ plane and in the (b) $(y - m_{\chi_1})$ plane, from this work (teal) together with existing constraints from various experiments.

2·2. *Search for axion-like particles through* $B \to K^{(*)}a$ $(a \to \gamma\gamma)$ *at Belle.* – Axion-like particles (ALPs) are key components in many new physics models and could serve as mediators between the dark sector and the SM via the axion portal, particularly in the few O(GeV) mass scale. In the simplest scenarios, ALPs primarily couple to pairs of SM gauge bosons. Their couplings with photons, leptons, and gluons have been extensively investigated through collider and beam dump experiments. However, the coupling to charged W bosons—denoted as g_{aW}—remains relatively unexplored. This coupling enables ALP production via flavor-changing neutral current (FCNC) decays, which are highly suppressed in the SM and thus offer promising discovery channels.

We search for an ALP via the process $B \to K^{(*)}a$ $(a \to \gamma\gamma)$, using four Kaon modes K^0_S, K^+, K^*, K^{*+} and extending a previous analysis by the BaBar experiment [8]. For ALP masses where $m_a < m_{W^\pm}$, the $a \to \gamma\gamma$ channel dominates, resulting in an almost 100% branching fraction. The search covers the mass range 0.16 to 4.50 GeV/c^2 for K modes and 0.16 to 4.20 GeV/c^2 for the K^* modes. Both prompt and long-lived ALP decays are considered, probing ALP decay lengths $c\tau$ from 10 mm to 500 mm.

The experimental signature is a narrow peak in the two-photon invariant mass distribution $M_{\gamma\gamma}$. Event selection exploits the characteristic kinematics of the signal, notably the absence of missing energy in the final state. Two key variables are used: the beam-constrained mass $M_{bc} = \sqrt{E_{beam}^2 - p_B^2}$ and the energy difference $\Delta E = E_B - E_{beam}$, where p_B and E_B are the momentum and energy of the B candidate in the CM frame, and E_{beam} is the beam energy in the CM frame. We require $M_{bc} > 5.27$ GeV/c^2 and -0.2 $< \Delta E <$ 0.1 GeV. Additionally, a vertex fit is applied to the selected B candidates, constraining the kaon and photon tracks to originate from the IP, and fixing their total invariant mass to the nominal B meson mass. The main background in this search arises from $e^+e^- \to q\bar{q}$ processes, with additional contributions from π^0, η and η' resonances; the latter are excluded from the signal search region and treated as control samples. This can be seen in fig. 3. To further suppress background, a set of fast Boosted Decision Tree (BDT) classifiers is applied following the event selection. Since the input variable distributions vary notably between the low and high mass regions, the BDTs are trained separately in distinct $M_{\gamma\gamma}$ intervals—specifically above and below 1 GeV—to improve classification performance.

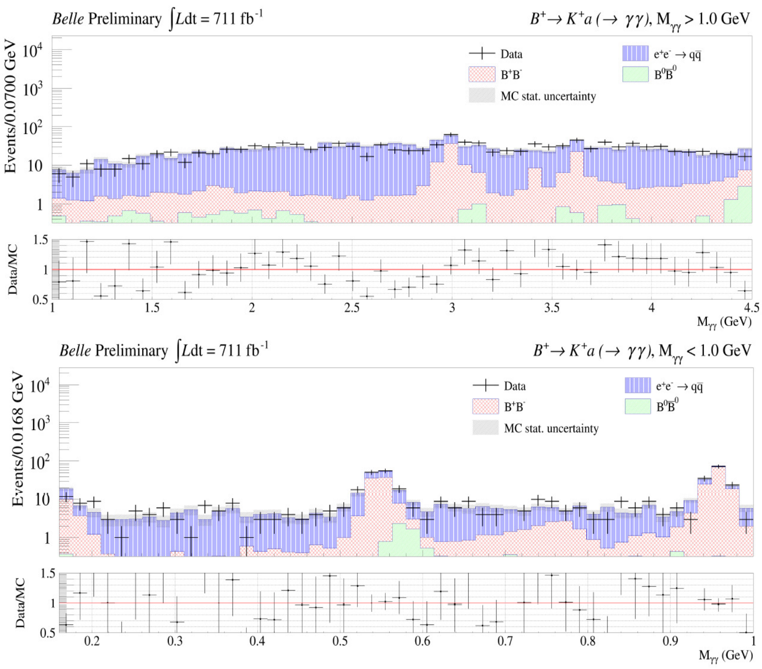


Fig. 3.: Distribution of $M_{\gamma\gamma}$ for ALP candidates in $B^+ \to K^+a$ decays, above and below 1 GeV, overlaid with simulated background contributions.

The signal is extracted by a scan over the $M_{\gamma\gamma}$ distribution and performing a series of unbinned maximum likelihood fits. We observe no significant excess in any of the Kaon modes using 711 fb^{-1} of data and set 90% CL upper limits on the coupling g_{aW} as a function of m_a. Results are subsequently combined for the four kaon modes yielding world-leading constraints on g_{aW} [9]. As shown in fig. 4, the constraints on the ALP coupling g_{aW} to electroweak gauge bosons are improved by a factor of two compared to the most stringent previous experimental results. Additionally, the analysis accounts for the effect of the ALP lifetime, particularly in the low-mass and low-coupling region, where longer lifetimes result in reduced signal efficiency.

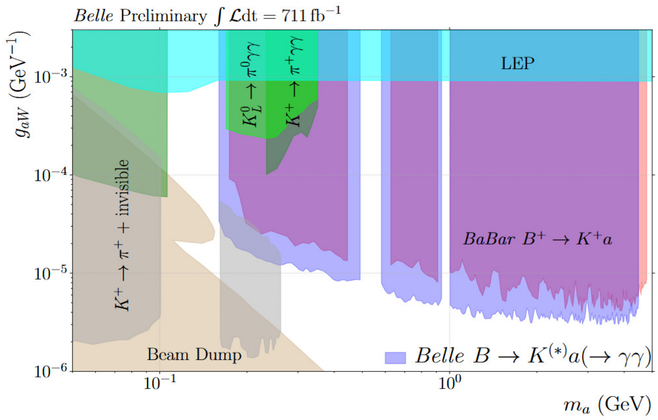


Fig. 4.: Exclusion regions at 90% CL in the $(g_{aW} - m_a)$ plane. Results are shown from a simultaneous fit to the four $B \to K^{(*)}a$ modes, together with existing constraints from various experiments.

3. – Summary and prospects

B-factories have unique sensitivity to explore the dark sector, complementary to that of higher-energy and beam-dump experiments. This paper presented the latest dark sector searches from Belle and Belle II experiments, featuring world-leading results and competitive limits across several dark sector models. As Belle II continues to accumulate data, the sensitivity to such signatures will improve, with increasingly stringent upper limits expected [10]. In the future, continued progress —driven by high luminosity, improved analysis methods, and dedicated triggers for displaced topologies—holds great potential for advancing dark sector searches.

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