# Probes of the dark sector from the Belle II experiment

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The possibility of dark sectors weakly coupling to Standard Model particles through new light mediators is explored at the Belle II experiment. As few interactions are allowed by SM symmetries, new vector and scalar bosons, as well as pseudo-scalar particles with masses in the MeV-GeV range can be searched at Belle II with a unique or world-leading reach. The first results on 2018 and 2019 data are here presented, along with the prospects for further analyses on the larger data set.

## 1 Introduction

The dark matter (DM) existence has been established by several astrophysics and cosmological observations, despite its origins and nature are still unknown. Disclosing new particles that might explain dark matter properties is one of the most compelling reasons for new physics beyond the standard model (SM). A light dark sector scenario has raised a lot of attraction in recent years [6], especially after the null results from direct searches for heavier DM candidates. Usually, for secluding light dark sectors, new sub-GeV scale mediators are needed to explain the observed DM relic abundance in our Universe. According to the spin and parity of the mediators, three main renormalizable portals can be defined: a vector portal, as the dark photons ($A'$ and other $Z'$ bosons); a scalar portal, as for example a dark higgs $h'$; a neutrino portal $N$, and, additionally, as non-renormalizable portals with coupling constants, the axion-like particles (ALPs).

Belle II has a world-leading potential to address all these cases. We report about searches for ALPs, $Z'$ bosons and dark Higgsstrahlung processes using the data collected by the Belle II detector [1], which is built around the interaction region of the SuperKEKB [10] asymmetric energy collider, mainly running at a centre-of-mass energy of 10.58 GeV. SuperKEKB adopts a nano-beam scheme that squeezes the vertical beam size at the interaction point and almost double the beam currents with the final goal to achieve an instantaneous luminosity of order $\sim 6 \times 10^{35}\text{cm}^{-2}/\text{s}$ and to deliver a final data set of 50 $\text{ab}^{-1}$.

## 2 Belle II experiment

The Belle II detector is a multi-purpose spectrometer surrounding the interaction point and ensuring hermetic coverage on more than 90% of the solid angle. It consists of a tracking system composed by a vertex detector, with two layers of pixels (PXD) and four layers of double-sided silicon strips sensors (SVD), and a small-cells helium-based Central Drift Chamber (CDC); a particle identification system and an electromagnetic calorimeter (ECL) for electron and photons reconstruction are also inside the the 1.5 T superconducting magnet. The outermost sub-system consists of a dedicated muon and $K_L^0$ detector (KLM). The details of the Belle II detector can be found elsewhere [1]. Belle II ensures a very high reconstruction efficiency for neutral particles and excellent resolutions despite the harsher beam background environment, which are crucial when dealing with recoiling system and missing-energy final states.

## 3 Signature-driven analyses

According to the relationship between the mediator mass ($m_{A'}$) and the masses of the dark matter candidates ($m_{DM}$), different regimes can be probed as shown in Figure 1, resulting in three main kinds of signatures to look for:

1. for $m_{A'} > 2m_{DM}$, decays to dark matter candidates are usually favored with respect to SM decays, assuming 100% branching fraction for the dark mediator to decay into $\chi\bar{\chi}$ and therefore as *invisible* final states;
2. below the $2m_{DM}$ threshold, if the mediator is heavier than two electron masses, it can decay to SM *visible* final states;
3. otherwise, for mediator also lighter than two electron masses, SM decays are highly suppressed and the new particle is long-lived, either escaping detection or giving origin to displaced signatures.

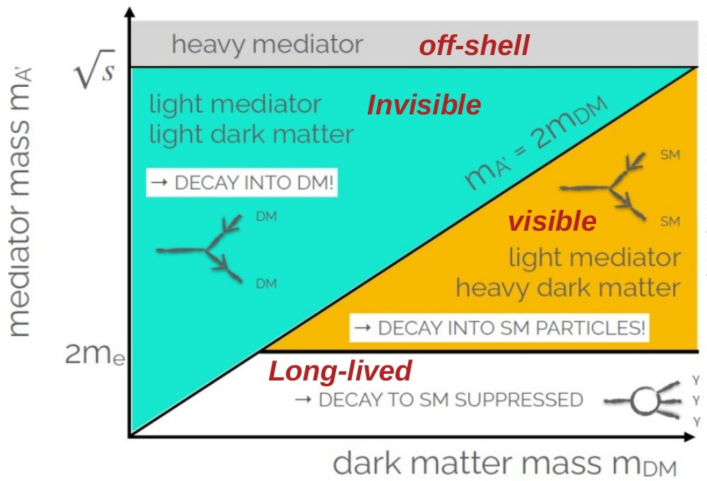


Figure 1 – Different accessible regimes depending on the relationship between the dark mediator mass ($m_{A'}$, on the vertical axis) and the dark matter candidates mass displayed on the horizontal axis. In these regions, different signatures are searched for depending on the resulting final states.

When dealing with missing energy final state and undetectable particles, it is crucial to know precisely the initial state to close the kinematics of an event. Belle II can profit of the clean environment and the known initial state of $e^+e^-$ collisions. It can directly access the mass range that is favored by the light dark sectors models and thanks to its hermetic, $4\pi$ coverage detector, it has a unique capability to probe invisible final states dealing with missing energy, recoiling systems and long-lived particles escaping detection.

## 4 Belle II benchmark on early data

In order to look for the above mentioned signatures, dedicated trigger lines have to been devised. The new hardware (Level 1) trigger menu at Belle II for dark sector searches represents one of the main advantages with respect to previous and competitor experiments. The main challenge for the trigger selection is to suppress high-cross section QED processes characterized by few tracks and missing energy signatures, without killing the signal itself. Moreover, to effectively devise vetoes against known SM background processes, a deep understanding of the detector performance and inefficiencies is fundamental.

### *4.1 Searches for axion-like particles to two photons*

A proof of concept of the Belle II world-leading reach in probing dark sectors is the result for the Axion-Like Particles (ALPs) search performed on the 2018 data [2], on an integrated luminosity of 445 $pb^{-1}$. ALPs are pseudo-scalars coupling mainly to bosons, with non-renormalizable coupling constants. Differently from the axion case, there is no relation between their mass and the couplings. A promising process to look for in $e^+e^-$ data for probing the photon coupling $g_{a\gamma\gamma}$ is the ALP-strahlung reaction, where one ALP candidate is produced radiatively and promptly decays into two photons. At the $\Upsilon(4S)$ centre-of-mass energy, the photon-fusion process as ALPs production mechanism would even have higher cross-section, but it's mostly dominated by the irreducible background coming from the QED interaction like $e^+e^- \to \gamma\gamma(\gamma)$ processes, where one photon escape detection or goes into the calorimeter gaps. The Feynman diagrams of the two production mechanisms are reported in Figure 2.

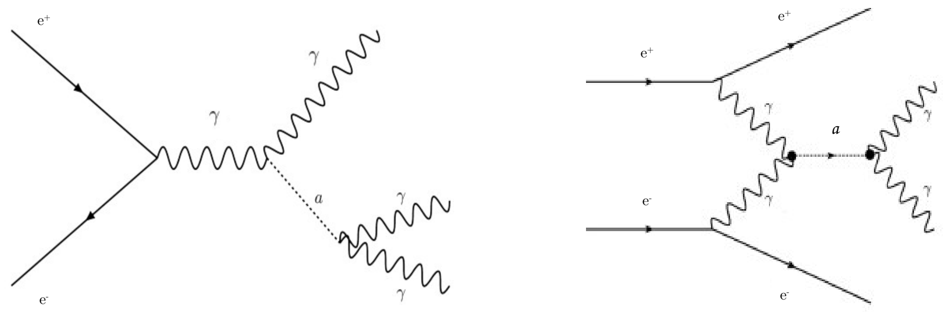


Figure 2 – Feynman diagram of two possible production mechanism for ALPs candidate in $e^+e^-$ collisions: ALPs-strahlung process on the right (a) and the photon fusion production on the left (b).

The analysis strategy is to select fully neutral events consisting of three isolated photons with a total invariant mass consistent with the center-of-mass energy. A calorimeter-based trigger selection is exploited, whose efficiency measured directly on data is found to be almost 100%. Additional selections on the energy deposit of the photon candidates and on the timing of the deposited clusters is used to further suppress the background. The optimization of all selections is performed by maximizing the sensitivity to an ALP candidate. Signal yields are extracted with binned extended maximum likelihood fits to the di-photon invariant mass from 0.2 up to 6.85 GeV/$c^2$ and to the invariant mass of the recoil with respect to the initial state radiation (ISR) photon for ALP mass hypotheses larger than 6.85 GeV/$c^2$. As mass step, half the measured mass resolution is deployed. Masses lighter than 0.2 GeV/$c^2$ are excluded from this search to avoid overlapping photon candidates not well resolved in the calorimeter, due to the small mass of the ALP that results in a boosted topology. The transition between fits to the direct mass to the recoil invariant mass at 6.85 GeV/$c^2$ has been determined as the point of equal sensitivities based on background simulations. No signal excess has been found on the analysed data set, with a highest local significance of $2.8\sigma$. The upper limits at 95% confidence level on the $g_{a\gamma\gamma}$ coupling are finally computed in a frequentist approach from the measured yields as a function of the ALP candidate mass (Figure 3). They are the world best to date below $1\mathrm{GeV/c^2}$.

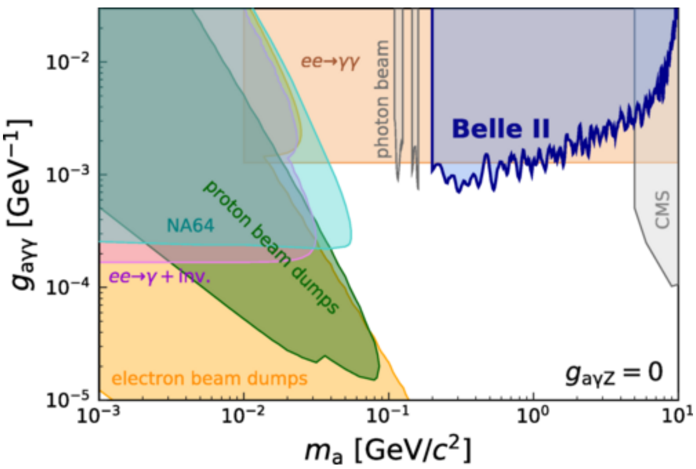


Figure 3 – Upper limit (95% C.L.) on the ALP-photon coupling from this search also compared to previous constraints from electron beam- dump, proton-beam and photon-beam experiments experiments, as well as heavy-ions collisions.

Additionally, it would be possible to exploit flavor changing neutral current processes involving rare meson decays, such as $b \to s\gamma\gamma$ transitions, to investigate the ALP-W boson coupling $g_{aW}$. Sensitivity studies are ongoing for the $B \to Ka$ search, with $a \to \gamma\gamma$ either promptly or long-lived. Previous results from searches at BaBar experiment [12] set constraints down to $10^{-5}$ on the $g_{aW}$ coupling for ALP masses below $4.78\mathrm{GeV/c^2}$. Belle II is expected to extend the searched range for larger lifetimes in the long-lived regime up to $c\tau_a = 40$ cm, being competitive already with a smaller data set.

### *4.2 Search for invisibly decaying $Z'$ bosons*

Among the simplest extensions of the SM to account for DM, a new $U_D(1)$ gauge symmetry with its associated massive vector boson $Z'$ is one of the most favored to explain the feeble interaction between SM and DM particles. The search for an invisibly decaying $Z'$ within the $L_\mu - L_\tau$ symmetry framework belongs to this class of theories. The model could explain the problem of DM abundance and the observed DM relic density [13]; the well-known discrepancy associated with the anomalous magnetic moment of the muon $(g-2)_\mu$, and also the rare decay anomalies [3] observed in the $B \to Kl^+l^-$ analyses. Within the model, the $Z'$ could couple only to the second and third generation of leptons and therefore being searched in $e^+e^- \to \mu^+\mu^- Z'$ processes radiated off one of the final muons. Previous studies at BaBar [11] and Belle [7] have searched already for such a reaction where the $Z'$decays *visibly* into a couple of muons and the signal would then appear as a peak in the reconstructed dilepton invariant mass, in events with four muons in the final state.

With the data collected during the pilot run of 2018, corresponding to an integrated luminosity of 276 $\mathrm{pb}^{-1}$, Belle II has looked for the first time at the invisible decay of the $Z'$, that is assumed to have a branching fraction equal to one if DM candidates are kinematically accessible. The analysis strategy is to search for a bumb in the invariant mass distribution of the recoil in the centre-of-mass system against the two final-state leptons, in events where nothing else is detected. Also the possibility of a Lepton Flavor Violating (LFV) $Z'$ is investigated in addition to the *standard* $Z'$ search, simply requiring the particle identification for one of the lepton track candidates to be consistent with the electron hypothesis.

The main background contamination comes from QED processes that could mimic the signal signature of two tracks plus missing energy because of some detector inefficiencies or particles escaping detection outside the detector acceptance. Namely, those processes are radiative di-lepton final states either with muons ($e^+e^- \to \mu^+\mu^-(\gamma)$) and taus ($e^+e^- \to \tau^+\tau^-(\gamma)$) decaying into muons, affecting the recoil mass region below 3 GeV/c$^2$and in the range 3-7 GeV/c$^2$, respectively. Above 7 GeV/c$^2$, the main contribution derives from four-lepton final state processes $e^+e^- {\to} e^+e^-\mu^+\mu^-$, where the electron-positron pair escape along the beam pipe and the two muons plus missing energy are detected as potential signal. Those events are rejected exploiting the reconstructed transverse momentum of the recoil and the kinematic properties of the signal as Final State Radiation (FSR).

From the surviving events counted in the final recoil invariant mass spectrum in the data, we derive an upper limit at 90% credibility level on the $g'$ coupling constant as a function of the searched standard $Z'$ mass.

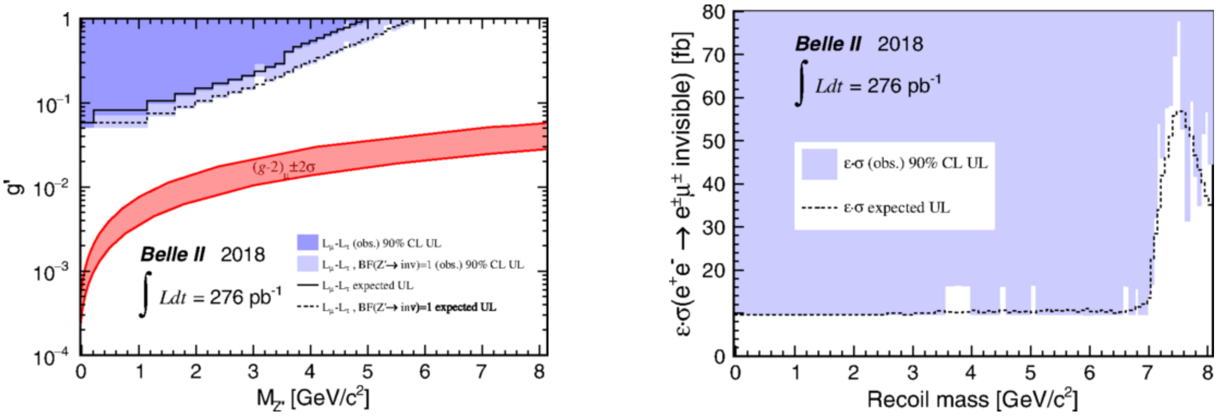


Figure 4 – Upper limits (90% C.L.) on the $g'$ coupling constant as a function of the searched standard $Z'$ mass are shown on the left. The red band indicates the phase space region that could explain the observed $g-2$ muon anomaly. On the right, the upper limits at 90% CL on the product of efficiency times cross section for the LFV $Z'$ study are shown.

These results ( solid blue area in the left plot in Figure 4) probe for the first time the phase space region below the two-muons invariant mass threshold and provide unique constraints already with a minimal data set. For the LFV case, limits are provided on the product of the signal efficiency times the production cross-section for the process $e^+e^-{\to}\ e^\pm\mu^\mp{+}missing\ energy$ and displayed in the right plot of Figure 4.

With an almost 300 times larger statistics, more inclusive hardware trigger lines and improved analysis algorithms relying on multivariate methods for background rejection, the new results for this search on the 2019 data will supersede the current ones. The sensitivity is shown in Figure 5 for different luminosity scenarios: with 50 fb$^{-1}$ Belle II is expected to rule out most of the region favored by the $g-2$ anomaly below 5 GeV/c$^2$ $Z'$ mass.

### *4.3 Visible decays of the $Z'$ to leptons*

The analysis of 2019-2020 data to look for visible decays of $Z'$ bosons into a pair of muons is also ongoing. Belle II sensitivity on a 200 fb$^{-1}$data set, corresponding to less than half the statistics deployed by Belle and BaBar searches, is expected to be competitive thanks to the more aggressive background rejection strategy. A factor up to 14 is achieved in suppressing QED events contamination thanks to a neural network selection algorithm.

Moreover, the analysis for a $Z'$ boson decaying into a $\tau$-pair is pursued at Belle II for the first time. The final $\tau$ candidates are reconstructed as single charged tracks plus missing energy due to the neutrinos and a neural network method is deployed to reach better purity. The study is almost model independent since it aims at constraining the product of the production cross

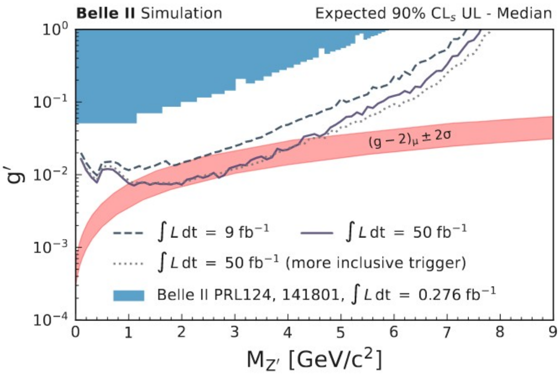


Figure 5 – Expected sensitivity ( dashed and solid blue lines) for the $Z'$ search for different luminosity scenarios compared to the 90% CL upper limits from the 2018 data analysis.

section times the branching fraction for any resonance $X$ decaying into taus. This would allow to interpret the results in a broader class of theoretical models.

### *4.4 Dark-Higgsstrahlung search*

Similarly to the SM, dark boson masses, for example the dark photon mass $m_{A'}$, can be generated via a spontaneous symmetry breaking mechanism [5], by adding a dark Higgs boson ($h'$). The dark Higgsstrahlung process, $e^+e^- \to$A$'^* \to A'h'$ is a promising signature to look for in $e^+e^-$ collision. If the dark higgs candidate is heavier than twice the dark photon mass, it can decay to dark photons and consequently to lepton pairs. This visible decay signature has been already looked for by the previous generation of B-factories. Otherwise, when the $h' \to A'A'$ process is kinematically forbidden, the dark higgs is long-lived and escape detection, resulting in a two tracks plus missing energy final state, with the same signature searched for in the $Z'$ analysis. The latter has been searched before only by KLOE [4].

Belle II already with the 2019 data set of $\sim$ 9 fb$^{-1}$ can provide world leading results by looking for the invisible $h'$ decays accompanied by two muons. This search provides the best upper limits on a mostly unexplored region of the non-trivial parameter space of $\epsilon^2 \times \alpha_D$ versus the dark photon mass $m_{A'}$. The analysis strategy consists in scanning the two-dimensional phase space of the di-muon invariant mass versus the reconstructed recoil mass looking for peaks.

Accepted event are required to pass the CDC-based trigger selection of two track satisfying a certain opening angle in the detector. To mimic the trigger requirements, the reconstructed di-muon mass has to be larger than 1.65 GeV/c$^2$. The background suppression strategy inherits from the $Z'$ search since the two analysis deal with the same final state and show similar background composition. The final yields are extracted by more than 9000 fits performed in sliding elliptical windows in the reconstructed di-muon mass versus the recoil invariant mass plane. No significant excess has been found and after accounting for a challenging look-elsewhere effect, limits at 90% Bayesian credibility are provided on the cross section for the searched process $e^+e^- \to$A$'^* \to A'h'$ and on the effective coupling $\epsilon^2 \times \alpha_D$ as functions of both the $h'$ and the $A'$ searched masses. The latter couplings are displayed in Figure 6.

This analysis leads the world results in the mass range 1.65 $< m_{A'} <$ 10.51 GeV/c$^2$, for $M_{h'} < M_{A'}$ and can be interpreted in a wider class of theoretical models, e.g., long-lived higgs mixing with the SM higgs.

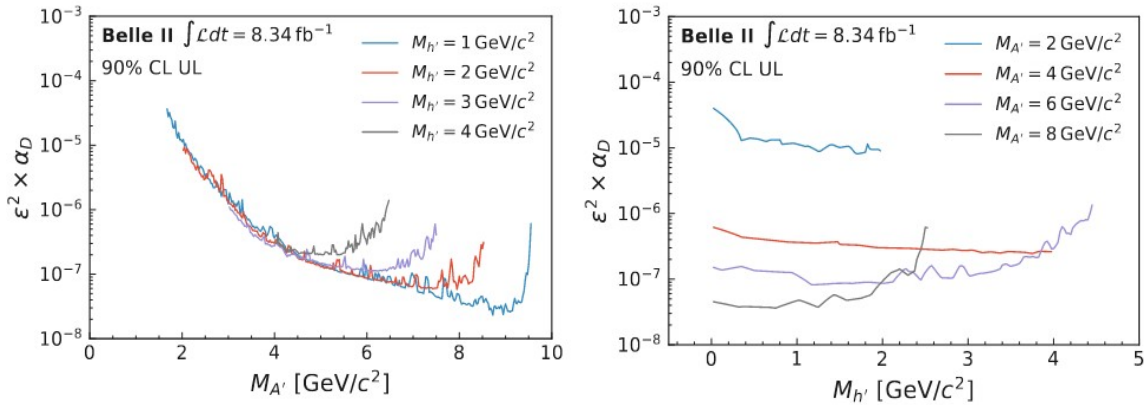


Figure 6 – Observed 90% CL upper limits on $\epsilon^2 \times \alpha_D$ (left) as functions of $m_{A'}$ for four values of $M_{h'}$ and (right) as functions of $M_{h'}$ for four values of $m_{A'}$.

## 5 Prospects on further searches

Many other analysis for dark sector searches are ongoing at Belle II. Among the most striking capabilities, the single photon search for probing the dark photon $A'$ decaying invisibly into DM candidates is a compelling benchmark for the Belle II physics program. Thanks to the ECL configuration, with no projective cracks pointing back to the interaction region, the dedicated single photon trigger lines implemented at hardware level, and the possibility to exploit the KLM detector to veto photons that escape detection through the ECL gaps, Belle II could lead the world's best limits on the kinetic mixing constant $\epsilon$ in the $m_{A'}$ range between few MeV/$c^2$ and 10 GeV/$c^2$. However for this analysis to be competitive it's crucial to devise the KLM veto for photons, which is currently not available yet, but studies are ongoing.

Additionally, the search for long-lived particles (LLP) is of particular interest to probe new physics scenarios involving light scalar mediators with lifetimes much longer than any observed in the SM. Rare $b \to s$ transitions at Belle II offers a unique sensitivity to probe new scalar bosons of few GeV mass with couplings as small as $10^{-5}$ [9]. The experimental signatures to be searched require a precise and efficient tracking to be able to reconstruct displaced vertices, and the application of the powerful constraints of the closed event kinematics. The possibility to consider even more exotic signatures, with non-pointing displaced vertices and missing energy in the final state, would finally allow to extend the models to probe, including the Inelastic Dark Matter (iDM) scenario [8]. Belle II is expected to be able to explore a large portion of the parameter space also in this case, constraining with only 100 fb$^{-1}$ of data the kinetic mixing parameter down to $10^{-4}$ .

## 6 Conclusions

Belle II has a very active and wide-ranging program of searches for dark sectors and it has proved already its capability to produce world leading results even on a minimal data set. The study for a new $Z'$ boson coupling only to the second and third generation of leptons ( within the $L_\mu - L_\tau$ framework) produced in association with a pair of muons and decaying invisibly has been performed on 2018 data collected during the pilot and is being updated on the 300 times larger statistics collected during 2019-2020. Similarly, with the same signature Belle II can look for a new scalar particle emitted in a dark Higgsstrahlung process and enough long-lived to escape detection. Thanks to the excellent tracking capabilities, the hermetic detector and new dedicated trigger selections, Belle II can provide competitive results in searches for displaced vertices and inelastic DM signatures as well. With the increased luminosity, improved performance and optimized analysis techniques more competitive results are to come.

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