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First results and prospects for dark sector searches at Belle II

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Summary. — The Belle II experiment operating at the SuperKEKB energy-asymmetric e^+e^- collider has the capability to search for a large variety of dark sector particles with masses below $10\,\mathrm{GeV}/c^2$, being therefore complementary to LHC and direct-detection experiments. Here, we will review the state of the art of the Belle II experiment in the field of light dark matter searches, with a focus on the first results obtained and the discovery potential of the data collected so far.

1. – Introduction

Understanding the nature of Dark Matter (DM) is one of the most exciting challenges in fundamental physics nowadays, requiring the synergy of different search techniques, as well as several theoretical inputs. In the last decades, much effort has been made to look for heavy DM candidates, as WIMPs for example. However, the lack of experimental evidence, as well as independent theoretical motivation, suggested great interest into light DM candidates neutral under SM and associated with new interactions. Such candidates with their interactions are often referred to as *Dark Sector*. An interesting opportunity for the investigation of light DM is the one offered by the B-factories. The Belle II experiment [1] at the SuperKEKB energy-asymmetric e^+e^- collider is a substantial upgrade of the B-factory facility at the Japanese KEK laboratory. With a machine design luminosity of $6 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, Belle II aims to record 50 ab^{-1} of data (a factor 50 higher than its predecessor) mostly at the nominal collision energy $\sqrt{s} = 10.58$ GeV. Thanks to this large data sample and by using dedicated triggers, Belle II is expected to explore dark sector candidates with unprecedented sensitivity in a mass range up to $\sim 10\,\mathrm{GeV}/c^2$. During 2018, the experiment has completed a commissioning run, recording a data sample corresponding to an integrated luminosity of $\sim 0.5\ \mathrm{fb}^{-1}$ [2], while main operations started on March 2019 with an almost complete detector. An integrated

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luminosity of $\sim 90\,\text{fb}^{-1}$ has been collected so far. These early data-sets already offer the possibility to search for a large variety of dark sector candidates. This paper reviews the status of the dark sector searches at Belle II, with a focus on the first results obtained and the discovery potential with the data-set available in the short term.

2. – Search for a Z' invisible decay

One possibility of extending SM involves a low-mass Z' boson belonging to the Abelian symmetry indicated as $L_\mu - L_\tau$. Under this model, the Z' boson would couple only to the 2nd and 3rd generation of leptons with a new coupling constant g' [3,4]. Such a model is of particular interest, being it able to explain various phenomena not accounted in SM, *i.e.*, dark matter abundance, the $(g-2)_\mu$ anomaly and anomalies in the $b \to s\mu^+\mu^-$ decays reported by the LHCb experiment.

In the Belle II environment, the Z' could be produced in the $e^+e^- \to \mu^+\mu^- Z'$ process, being it radiated by one of the two muons. It can following decay either visibly, in μ or τ pairs, or invisibly, in SM neutrinos or DM if kinematically accessible. A search for a visible decay of the Z' boson to muons was performed by the BaBar experiment [5], while the invisible one has been performed for the first time at the Belle II experiment [6]. The final state consists of only two oppositely charged muons plus missing energy. Given the experimental signature, the search proceeds by reconstructing the recoil mass M_{rec} against the two muons and then looking for a peak at the Z' candidate mass. The main expected background sources are all the SM processes which give rise to final states with two tracks identified as muons plus missing energy. The relevant ones are $e^+e^- \to \mu^+\mu^-\gamma$, $e^+e^- \to \tau^+\tau^-$ and $e^+e^- \to e^+e^-\mu^+\mu^-$. This search has been performed by Belle II using the data collected during the 2018 pilot run. Due to the low-multiplicity trigger configuration usable for this search, only 0.276 fb^{-1} were available. No anomalies have been observed in data, with all results below 3σ local significance. The 90% credibility level (CL) upper limits on the cross-section have been computed using a Bayesian procedure, and results have been translated into 90% CL upper limits on the coupling constant g'. This latter is shown in fig. 1.

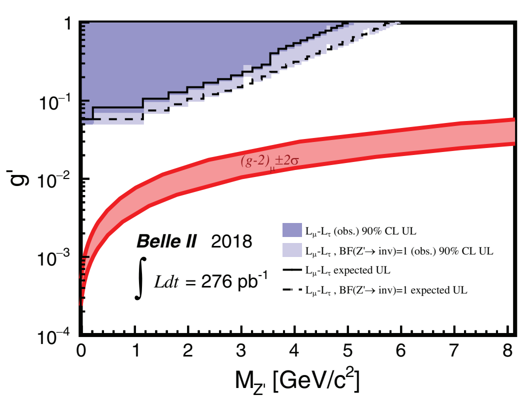

Fig. 1. – 90% CL upper limits to the g' coupling constant and the space parameter region that could explain the $(g-2)_\mu$ anomaly. The solid line assumes the L_μ–L_τ model expected branching fraction, while the dashed line assumes $BF[Z' \to \text{invisible}] = 1$. From [6].

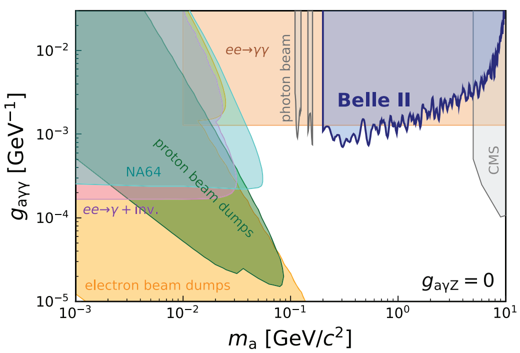

Fig. 2. – 95% CL upper limit on the ALP–photon coupling constant $g_{a\gamma\gamma}$ from the Belle II analysis [8] and previous constraints.

3. – Search for an axion-like particle visible decay

Axion-like particles (ALPs) are hypothetical pseudo-scalar ($J^P = 0^-$) particles able to couple to SM gauge bosons, and often referred to as a possible extension of SM. At low-energy e^+e^- colliders, the simplest approach to search for ALPs is via the two-photon coupling. Two production mechanisms are possible: ALP strahlung ($e^+e^- \to \gamma^* \to \gamma\, a$) and photon-photon fusion ($e^+e^- \to e^+e^-a$). Here, we concentrated on the ALP-strahlung production, with the following ALP decay into two photons. Depending on the properties of the ALPs model, namely its mass m_a and the coupling constant $g_{a\gamma\gamma}$ to SM photons, more experimental signatures are expected within the Belle II detector [7]: the three final-state photons being either resolved, two of them overlapping (*i.e.*, not resolved in the electromagnetic calorimeter) or the ALP decaying outside of the detector leading to only one detectable photon in the final state. Belle II searched first for the resolved three-photon case [8], being it a unique final state, with lower backgrounds. The main background component is represented by the QED process $e^+e^- \to \gamma\gamma$ plus an additional radiated photon or beam background photon. The entire data-set collected during 2018 was used for this analysis. No significant excess of events consistent with an ALP signal has been observed in data, thus the 95% confidence level upper limits on the cross-section as a function of m_a have been computed and then converted in terms of $g_{a\gamma\gamma}$ coupling (fig. 2). Even with these first data collected, the Belle II limits are more restrictive than the previous experiments constrains in the range $0.2 < m_a < 1$ GeV/c^2. In a future update of the analysis with an increased luminosity, Belle II is expected to improve the sensitivity to $g_{a\gamma\gamma}$ by more than one order of magnitude [7].

4. – Search for a dark higgsstrahlung process

A widely used theoretical framework able to account for DM is the one which introduces a new gauge mediator A' called *dark photon*, coupling to SM photons through a kinetic mixing mechanism with strength ϵ. Since the dark photon needs to be massive, one can implement, in close analogy with the SM, a spontaneous breaking mechanism of the additional gauge group, introducing a Higgs-like particle h', called *dark Higgs*. Thus, the process $e^+e^- \to A'^* \to A'\,h'$ (called *dark Higgsstrahlung*) with the A' decaying into lepton or hadron pairs, is an interesting reaction to be studied at an e^+e^- collider.

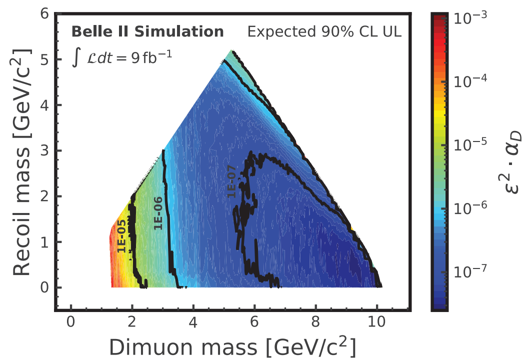

Fig. 3. – Belle II expected upper limits (90% CL) to the coupling constants $\epsilon^2 \cdot \alpha_D$ for the process $e^+e^- \to A'h'$, $A' \to \mu^+\mu^-$, $h' \to$ invisible, with an integrated luminosity of $9\,\mathrm{fb}^{-1}$.

The production cross-section of this process is proportional to the product $\epsilon^2 \cdot \alpha_D$, where α_D is the unknown dark coupling constant [9]. Previous results are from Belle and BaBar experiments [10,11] for the case of a dark Higgs decaying into a dark photon pair. Belle II is finalizing the search for the invisible dark Higgs case ($m_{h'} < m_{A'}$) via the $e^+e^- \to A'h'$, $A' \to \mu^+\mu^-$, $h' \to$ invisible process, by using data collected during 2019 (corresponding to an integrated luminosity of $\sim 9\,\mathrm{fb}^{-1}$). The final state is given by a pair of opposite charge muons plus missing energy. For signal events, the presence of simultaneous peaks both in the distribution of the dimuon invariant mass $M_{\mu\mu}$ and in the distribution of the invariant mass M_{rec} of the system recoiling against the two muons is expected. The interesting phase space region has a triangular shape, being limited on the left by the required condition $\mathrm{m}_{h'} < \mathrm{m}_{A'}$ (thus $M_{rec} < M_{\mu\mu}$) and on the right by energy conservation: $M_{rec} + M_{\mu\mu} < \sqrt{s}$. Figure 3 shows the expected 90% CL upper limits to the coupling constant product $\epsilon^2 \cdot \alpha_D$. Belle II is expected to constrain $\epsilon^2 \cdot \alpha_D$ down to $\mathcal{O}(10^{-6}$–$10^{-7})$ in most of the phase space. The sensitivity in the low-mass region is limited by the low trigger efficiency for low opening angle tracks. In that region, a noticeable improvement is expected with the use of more inclusive triggers available from 2020 on.

REFERENCES

[1] Belle-II Collaboration (Kou E. *et al.*), *Prog. Theor. Exp. Phys.*, **2019** (2019) 123C01.
[2] Belle-II Collaboration (Abudinén E. *et al.*), *Chin. Phys. C*, **44** (2020) 021001.
[3] Shuve B. and Yavin I., *Phys. Rev. D*, **89** (2014) 113004.
[4] Altmannshofer W. *et al.*, *JHEP*, **12** (2016) 106.
[5] BaBar Collaboration (Lees J. P. *et al.*), *Phys. Rev. D*, **94** (2016) 011102.
[6] Belle-II Collaboration (Adachi I. *et al.*), *Phys. Rev. Lett.*, **124** (2020) 141801.
[7] Dolan M. *et al.*, *JHEP*, **12** (2017) 094.
[8] Belle-II Collaboration (Abudinén E. *et al.*), *Phys. Rev. Lett.*, **125** (2020) 161806.
[9] Batell B. *et al.*, *Phys. Rev. D*, **79** (2009) 115008.
[10] Belle Collaboration (Jaegle I. *et al.*), *Phys. Rev. Lett.*, **114** (2015) 211801.
[11] BaBar Collaboration (Lees J. P. *et al.*), *Phys. Rev. Lett.*, **108** (2012) 211801.