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## Dark Sector Physics with Belle II

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# Dark Sector Physics with Belle II

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**Abstract.** The Belle II experiment at the SuperKEKB energy-asymmetric  $e^+e^-$  collider is a substantial upgrade of the KEKB facility at the Japanese KEK laboratory. The design luminosity of the machine is  $8 \cdot 10^{35} \text{ cm}^{-2}\text{s}^{-1}$  and the Belle II experiment aims to record  $50 \text{ ab}^{-1}$  of data, a factor of 50 more than its predecessor. From February to July 2018, the machine has completed a commissioning run, where about  $0.5 \text{ fb}^{-1}$  of data have been collected. Regular operation of SuperKEKB has started in March 2019: the machine has achieved a peak luminosity of  $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ , and Belle II has recorded a data sample of about  $6.5 \text{ fb}^{-1}$ . Already this early data set with specifically designed triggers offers the possibility to search for a large variety of dark sector particles in the GeV mass range complementary to searches at LHC and dedicated low energy experiments. The Belle II dark matter analyses will benefit from more data in the process of being accumulated. This talk will review the state of the dark sector searches at Belle II with a focus on the discovery potential of the early data, and show the first results.

## 1. The Belle II experiment

The Belle II experiment operates at the asymmetric collider SuperKEKB, located at the KEK laboratory in Tsukuba, Japan. It is a major upgrade of the Belle experiment. The SuperKEKB facility is a second generation  $B$ -factory designed to collide electron and positron at the energy in the center-of-mass frame corresponding to the  $\Upsilon$  resonances. The collider is designed to operate with asymmetric beam energies to provide a boost to the center-of-mass system and thereby allow for time-dependent  $CP$  violation measurements. Most of data are collected at the  $\Upsilon(4S)$  resonance, i.e.  $\sqrt{s} = 10.58 \text{ GeV}$ , which is just above the threshold of  $B\bar{B}$  pair production and at which the branching ratio ( $BR$ ) for  $B$  meson pair production is  $BR(\Upsilon(4S) \rightarrow B\bar{B}) \sim 96\%$ . SuperKEKB is designed to reach the highest world instantaneous luminosity of  $8 \cdot 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ , about 40 times higher than the luminosity reached by KEKB, thanks to the nano-beam scheme that allows to achieve high luminosity with only a moderate increase of beam currents. The basic idea of the nano-beam scheme is to reduce the beam size at the interaction point (IP) in order to improve the interaction probability and therefore the luminosity [1].

The Belle II detector [1] is a magnetic spectrometer with an angular coverage which exceeds the 90% of  $4\pi$  and it is composed of several subdetectors installed around the IP, which allow to detect and reconstruct all the products of the  $e^+e^-$  interaction.

Thanks to the very high luminosity and the performances of the detector, the Belle II experiment has a very rich physics program that includes the precise measurement of the CKM matrix

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parameters, the study of  $CP$ -violation in  $B$  meson decays, the study of charm and tau physics and of suppressed or forbidden processes in the Standard Model (SM), and search for new physics as dark sector.

In 2016 there was the Phase 1 of the experiment, dedicated to the commissioning of SuperKEKB without the Belle II detector installed. The first data taking period, known as Phase 2, was from April to July 2018 and it was dedicated to the commissioning of the machine and the detector. During this period about  $0.5 \text{ fb}^{-1}$  of data with an incomplete vertex detector (VXD) have been collected. The next data taking period, known as Phase 3, has started on March 25<sup>th</sup> 2019. Up to now  $6.5 \text{ fb}^{-1}$  of data have been collected with full detector, and the goal is to collect  $50 \text{ ab}^{-1}$  by 2027.

## 2. Searches for Dark Photon

Many astrophysical observations are consistent with the existence of dark matter that interacts mostly gravitationally with SM particles. However, several theoretical scenarios introduce the existence of light dark matter weakly coupled with SM matter through a light dark sector mediator. The portal of interaction between dark matter and SM depends on the parity and the spin of the mediator. In the minimal model [2] [3], the dark photon  $A'$  is a vector boson introduced extending the SM with a dark  $U'(1)$  gauge symmetry, and it is the mediator of the vector portal  $\mathcal{L} \supset \kappa/2 B_{\mu\nu} X^{\mu\nu}$ , where  $B_{\mu\nu}$  is the hypercharge tensor field and  $X_{\mu\nu}$  is the tensor field associated to the additional dark  $U'(1)$ . After the spontaneous breaking symmetry, the dark photon acquires mass and it mixes with the SM photon through the kinetic mixing mechanism with strength  $\kappa$ . The interaction term between the dark photon and the electromagnetic current  $\mathcal{L}_{int} \supset \epsilon A'_\mu J_{SM}^\mu$  arises spontaneously in the theory, where  $\epsilon = e\kappa/\cos\theta_W$  [3].

Depending on its mass, the dark photon can decay to SM particles,  $A' \rightarrow l^+l^-, h^+h^-$  ( $l$  =lepton,  $h$  =hadrons), or in dark matter particles  $\chi$  if kinematically accessible. Belle II searches for a dark photon which decays in an invisible final state studying the process  $e^+e^- \rightarrow \gamma_{ISR}A'(A' \rightarrow \chi\bar{\chi})$ , where the SM photon is emitted as initial state radiation, and the dark photon decays invisibly in a dark matter  $\chi$  pair, as shown in Figure 1 (left).

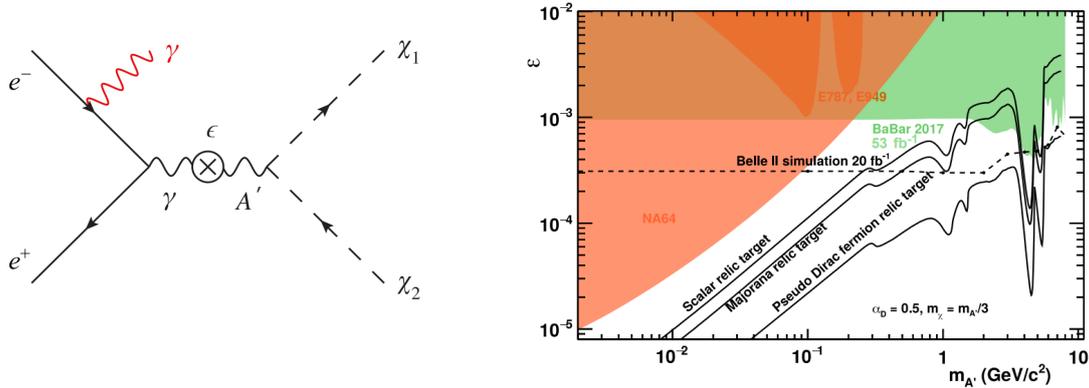
The dark matter particle  $\chi$  does not interact with the detector, for this reason the experimental signature is a single monochromatic photon  $\gamma_{ISR}$  in the final state plus missing energy. The energy of the photon depends on the dark photon mass  $m_{A'}$  as  $E_\gamma = \frac{s-m_{A'}^2}{2\sqrt{s}}$ . Belle II is provided of a first level (L1) single photon trigger sensitive to single photon final states that was not available at Belle and was available only for  $\sim 10\%$  of data at *BABAR*. For further details on the single photon trigger logic see Ref. [4].

The analysis is dominated by the QED background process  $e^+e^- \rightarrow \gamma\gamma(\gamma)$  where two photons are not detected, mainly because of some small but not negligible electromagnetic calorimeter photon detection inefficiency regions.

In order to evaluate the sensitivity of Belle II to the invisible dark photon, a full detector simulation, including all the relevant QED background processes, was performed. The Belle II sensitivity to the kinetic mixing parameter  $\epsilon$  with an integrated luminosity of  $20 \text{ fb}^{-1}$  is shown in Figure 1 (right), where the measurement done by the *BABAR* experiment in 2017 with  $53 \text{ fb}^{-1}$  is reported in green. The expected sensitivity of Belle II is quite better than the one done by *BABAR*, mainly because of the better performances of the Belle II electromagnetic calorimeter [1, 4].

## 3. Searches for Axion-like Particles

Axion-like Particles (ALPs) are hypothetical pseudo-scalar particles with a coupling with the SM bosons through the so-called pseudo-scalar portal. ALPs are a generalized form of the axion, which was originally introduced to explain the strong  $CP$  problem, that do not need to



**Figure 1.** Left. Diagram of the process  $e^+e^- \rightarrow \gamma_{ISR} A' (A' \rightarrow \chi\bar{\chi})$ . Right. Dashed black line: expected Belle II sensitivity to the kinetic mixing parameter  $\epsilon$  for the process  $e^+e^- \rightarrow A' (A' \rightarrow inv.)$  with an integrated luminosity of  $20 \text{ fb}^{-1}$ .

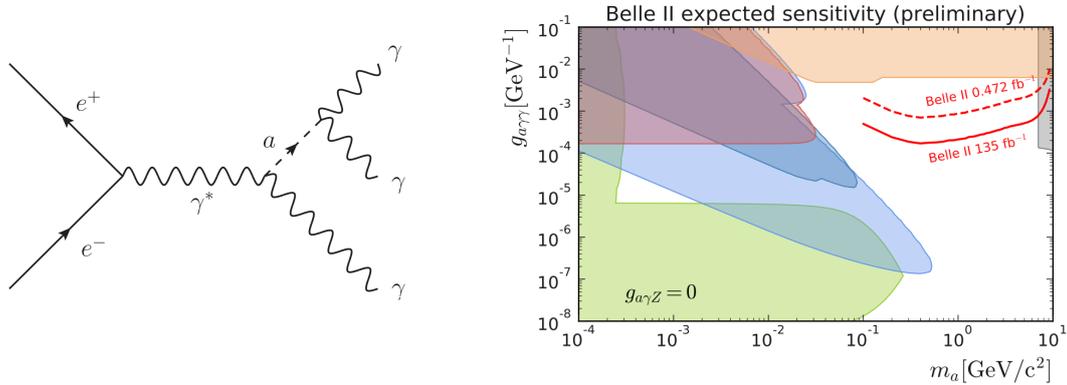
preserve any of the QCD properties that the originally proposed axion has. ALPs can be good dark matter candidates but also good dark sector mediators of a new interaction between dark matter and SM. Belle II currently focuses on the coupling between the ALP  $a$  and the photon, which can be described by the Lagrangian term  $\mathcal{L} \supset \frac{-g_{a\gamma\gamma}}{4} F_{\mu\nu} \tilde{F}^{\mu\nu}$ , where  $\tilde{F}^{\mu\nu} = \frac{1}{2} \epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma}$  and  $g_{a\gamma\gamma}$  is the coupling constant of ALPs with photons.

In particular, the process under study is the production of  $a$  through the ALP-strahlung mechanism where  $a$  decays in two photons:  $e^+e^- \rightarrow \gamma a (a \rightarrow \gamma\gamma)$ . The diagram of the process is shown in Figure 2 (left). The decay width of  $a \rightarrow \gamma\gamma$  is  $\Gamma_a = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$ , then the parameters of the model, the  $a$  mass  $m_a$  and the coupling  $g_{a\gamma\gamma}$ , determine the displacement and the angle ( $\theta$ ) between the two photons produced in the  $a$  decay: if  $m_a \sim \mathcal{O}(\text{GeV})$ ,  $a$  decays promptly and  $\theta$  is large enough that both photons coming from the  $a$  decay can be resolved in the Belle II detector. The invariant mass of the two photons coming from the  $a$  decay is expected to peak at the value of  $m_a$ . The main background component for this search is the QED process  $e^+e^- \rightarrow \gamma\gamma\gamma$ . Another possible background source is the QED process  $e^+e^- \rightarrow \gamma\gamma\gamma$  plus a third photon coming from the beam background; however, the impact of this component is expected to be smaller because of the good electromagnetic calorimeter resolution [5]. The expected Belle II sensitivity with Phase 2 data and the projected sensitivity with an integrated luminosity of  $135 \text{ fb}^{-1}$  is shown in Figure 2 (right). This is a preliminary result: no systematic uncertainty are included and the beam background is assumed to be negligible.

From simulation studies on  $a \rightarrow \gamma\gamma$ , the expected sensitivity of Belle II to  $g_{a\gamma\gamma}$ , assuming the full data sample of  $50 \text{ ab}^{-1}$ , is  $g_{a\gamma\gamma} \sim 10^{-5} - 10^{-4} \text{ GeV}^{-1}$  at 90% of confidence level for  $m_a \sim \mathcal{O}(\text{MeV}) - \mathcal{O}(\text{GeV})$  [5].

#### 4. Searches for $Z'$ ( $L_\mu - L_\tau$ model)

It is possible to consider another extension of the SM that introduces a dark vector boson  $Z'$  with mass of  $\mathcal{O}(\text{MeV}) - \mathcal{O}(\text{GeV})$  and thereby that can be copiously produced in  $e^+e^-$  colliders. The  $Z'$  boson could be a mediator of a new kind of interaction between the SM and the dark sector particles. In particular, the Belle II experiment is searching for a  $Z'$  introduced by a very well theoretically motivated model called  $L_\mu - L_\tau$  [6]. In this model the  $Z'$  has a coupling only to the second and third generation of leptons through the lagrangian term  $\mathcal{L} = \sum_l \theta g' \bar{l} \gamma^\mu Z'_\mu l$ , where  $\theta = +1$  if  $l = \mu, \nu_\mu$ ,  $\theta = -1$  if  $l = \tau, \nu_\tau$  and  $g' \sim 10^{-6} - 10^{-2}$ . Such a  $Z'$  does not couple with  $e$  and  $\nu_e$ . It is possible to search for the visible decays  $Z' \rightarrow \mu^+\mu^-$ ,  $Z' \rightarrow \mu^+\mu^-$  and for



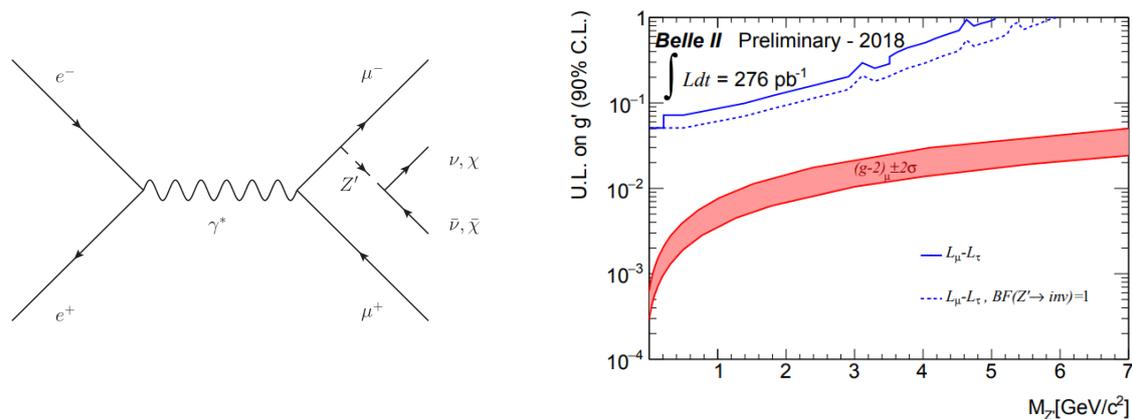
**Figure 2.** Left. Diagram of the ALP-strahlung process:  $e^+e^- \rightarrow \gamma a (a \rightarrow \gamma\gamma)$ . Right. Dashed red line: Belle II sensitivity on the process  $e^+e^- \rightarrow \gamma a (a \rightarrow \gamma\gamma)$  with well resolved photons coming from the  $a$  decay, with the Phase 2 data. Continuous red line: Belle II sensitivity on the same process with an integrated luminosity of  $135 \text{ fb}^{-1}$ . This is a preliminary result. The coloured regions are the current existing limit set by other experiments [5].

the invisible decay  $Z' \rightarrow \nu\bar{\nu}$ . The search for the visible decay to muons was already performed by the BaBar experiment [7], while the search for the  $Z'$  invisible decay has been performed for the first time by the Belle II experiment. The branching ratio of  $Z' \rightarrow inv.$  depends on the  $Z'$  mass  $m_{Z'}$  and it can be calculated from the model: if  $m_{Z'} < 2m_\mu$ , the only possibility is the invisible decay to neutrinos and  $BR(Z' \rightarrow inv.) = 1$  while, if  $m_{Z'} > 2m_\tau$ , both visible decays in muons and tauons and the invisible decay are allowed so  $BR(Z' \rightarrow inv.) \approx 1/3$ . However, if a kinematically accessible dark matter particle  $\chi$  exists it is invisible to the detector and  $Z' \rightarrow \chi\bar{\chi}$  is the favored decay, so the branching ratio of the invisible decay is enhanced to 1. For this reason, the invisible decay can be an indication of the existence of a new invisible particle, as a light dark matter particle.

Belle II searches for the process  $e^+e^- \rightarrow \mu^+\mu^- Z' (Z' \rightarrow inv.)$ , where the  $Z'$  is radiated by one of the two muons, as shown in Figure 3 (left), then the final state consists of two opposite charged muon tracks coming from the interaction point plus missing energy.

The final state can be reconstructed knowing the energy of the initial  $e^+e^-$  state and the properties of the muon tracks with a high accuracy. It is possible to define the recoil mass against the muon pair  $M_{rec}^2 = s + M_{\mu\mu}^2 - 2\sqrt{s}(E_{\mu^+}^{CMS} + E_{\mu^-}^{CMS})$ , where  $M_{\mu\mu}^2$  is the squared invariant mass of the muon pair and  $E_{\mu^\pm}^{CMS}$  is the energy of the muon in the center-of-mass frame, which is expected to show a peak corresponding to the  $Z'$  mass in case of signal events. The main background source for this search are the QED processes:  $\mu\mu(\gamma)$ , which is expected to dominate at  $M_{rec} < 2 \text{ GeV}/c^2$ ,  $\tau\tau(\gamma)$ , ( $\tau \rightarrow \mu\nu\bar{\nu}$ ) where neutrinos are invisible to the detector, which is expected to dominate at  $2 \text{ GeV}/c^2 < M_{rec} < 7 \text{ GeV}/c^2$ , and  $ee\mu\mu$  where the electron pair is not detected, which is expected to dominate at  $M_{rec} > 7 \text{ GeV}/c^2$ .

The analysis has been done using  $276 \text{ pb}^{-1}$  of Phase 2 data. No evidence for signal was found and upper limits on the coupling constant  $g'$ , as a function of the  $Z'$  mass, were set. After taking into account the trigger, tracking and reconstruction efficiencies, the preliminary sensitivity of Belle II on the coupling  $g'$  at 90% of confidence level are shown in Figure 3 (right), where systematics uncertainties are included [8].



**Figure 3.** Left. Diagram of  $e^+e^- \rightarrow \mu^+\mu^-Z'$  ( $Z' \rightarrow \text{inv}$ ). Right. Belle II sensitivity to the parameter of the  $L_\mu - L_\tau$  model with Phase 2 data. Continuous line: assuming only  $Z' \rightarrow \nu\bar{\nu}$ . Dashed line: assuming the existence of a light dark matter particle  $\chi$  such that  $BR(Z' \rightarrow \text{inv}) = 1$ . The red band is the parameter region that can explain the  $(g-2)_\mu$  anomaly. This is a preliminary plot.

## 5. Conclusions

Although the Belle II experiment is mainly designed to study heavy flavour physics, it has a broad and active program to explore the dark sector physics. In 2018 there was the successful SuperKEKB commissioning with the detector installed, although the VXD was incomplete. The  $0.5 \text{ fb}^{-1}$  of data collected have been used for dark sector searches. In 2019, Phase 3 has started and up to now  $6.5 \text{ fb}^{-1}$  of data with the full detector installed have been collected so far. The results discussed in this contribution can be summarised as follow: from simulation studies on  $A' \rightarrow \text{inv}$ . search, assuming  $20 \text{ fb}^{-1}$ , the sensitivity of Belle II on the mixing parameter  $\epsilon$  is expected to be better than current limits set by *BABAR* with  $53 \text{ fb}^{-1}$ ; from preliminary studies on  $a \rightarrow \gamma\gamma$ , using the Phase 2 data sample, the sensitivity of Belle II on the coupling constant  $g_{a\gamma\gamma}$  is expected to be better than the existing limits; finally, from preliminary studies on  $Z' \rightarrow \text{inv}$ ., using the Phase 2 data, the sensitivity of Belle II on the coupling constant of the  $Z'$  with muons is expected to be  $g' \sim 10^{-2} - 10^{-1}$ , but there will be the possibility to exclude the region of the parameters able to explain the  $(g-2)_\mu$  anomaly with Phase 3 data.

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