Dark Sector Searches at Belle II

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Abstract

The Belle II experiment at the SuperKEKB asymmetric energy e^+e^- collider is a substantial upgrade of the B factory facility at the Japanese KEK laboratory. The design luminosity of the machine is 8×10^{35} cm^{-2}s^{-1} and the Belle II experiment aims to record 50 ab^{-1} of data, a factor of 50 more than its predecessor. During 2018, the machine has completed a commissioning run, recording a data sample corresponding to an integrated luminosity of about 0.5 fb^{-1}. Main operations started in March 2019 with the complete Belle II detector; an integrated luminosity of 60 fb^{-1} has been collected so far. These early data sets, with specifically designed low multiplicity triggers, offer already the possibility to search for a large variety of dark-sector particles in the GeV mass range, complementary to the sensitivities of the LHC and to dedicated low-energy experiments. These proceedings review the status of the dark-sector searches at Belle II, with a focus on the discovery potential with early data, and show the first results.

1 Belle II and SuperKEKB

SuperKEKB is an asymmetric energy e^+e^-collider located in Tsukuba, Japan. The beam energies are chosen such that the resulting centre-of-mass energy is equal to 10.58 GeV, which is the mass of the $\Upsilon(4S)$. As this $b\bar{b}$ resonance decays mostly into a pair of B mesons, SuperKEKB is called a *B factory.* Higher beam currents combined with a smaller beam spot will allow SuperKEKB to reach an instantaneous luminosity of 8×10^{35} cm^{-2}s^{-1}, which is 40 times higher than what its predecessor KEKB achieved.

The Belle II experiment is located at the interaction region of the electron and positron beams of SuperKEKB. It consists of different layers of subdetectors arranged concentrically with the vertex detectors being closest to the beam pipe. These are surrounded by a central drift chamber, followed by an electromagnetic calorimeter and the outermost detector responsible for K_L and muon reconstruction.

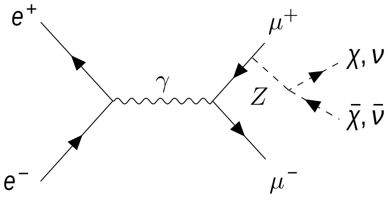

Figure 1: Feynman diagram for Z' production at Belle II and decay into invisible final state.

In 2018, the first collisions were recorded at Belle II while collecting a small dataset of $0.5\,\mathrm{fb}^{-1}$ during a commissioning run. Regular operations started in March of 2019. The plan is to collect 50 times more data than the precursor Belle did, $50\,\mathrm{ab}^{-1}$. Belle II has a rich physics program including B and D physics, quarkonium, τ and low mass dark sector [1]. A more detailed description of both SuperKEKB and Belle II is given in [1].

2 Invisible Z'

One possible way of extending the Standard Model (SM) is by adding a $U(1)'$ gauge group. Along with one of these extensions comes a new massive gauge boson Z' which belongs to an Abelian symmetry indicated as $L_\mu - L_\tau$ and which is charged under the additional $U(1)'$ group. Such a boson may serve as a mediator between the SM and the dark sector (DS), explain the $(g-2)_\mu$ anomaly and address anomalies in $b \to s\mu^+\mu^-$ ([2],[3]). In this scenario, the Z' would only couple to leptons of the 2^{nd} and 3^{rd} generation via a new coupling indicated with g'. In the environment of the Belle II experiment, the Z' could be produced in processes such as $e^+e^- \to \mu^+\mu^- Z'$, while being radiated off one of the muons and then further decaying either into a muon or tau pair, or invisibly to neutrinos or dark matter. The associated Feynman diagram is shown in Figure 1.

A search for a visible decay of the Z' into muons was already performed by the BaBar experiment [4]. In the study at Belle II the invisible-decay channel of the Z' was explored for the first time leading to a final state consisting of two muons plus missing energy. Given the experimental signature, one reconstructs the recoiling mass against the two muons and then looks for a peak at the Z' candidate mass in the resulting distribution. This search was performed using the data collected during the 2018 commissioning run. Due to the configuration of the trigger system for low-multiplicity final states, only $276\,\mathrm{pb}^{-1}$ were available for the analysis. The main contributing backgrounds arise from QED processes with two muons in the final state such as $e^+e^- \to \mu^+\mu^-(\gamma)$, $e^+e^- \to \tau^+\tau^-(\gamma)$ (where both tau decays into muons) and $e^+e^- \to e^+e^-\mu^+\mu^-$. Upper limits on

Figure 2: 90% CL upper limits on coupling constant g'. Dark blue filled areas show the exclusion regions for g' at 90% CL, assuming the $L_\mu - L_\tau$ predicted branching fraction (BF) for $Z' \to$ invisible; light blue areas are for BF($Z' \to$ invisible)=1. The solid and dashed lines are the expected sensitivities for the two hypotheses. The red band shows the region that could explain the muon anomalous magnetic moment $(g-2)_\mu \pm 2\sigma$ [5].

the coupling g' at the 90% confidence level (CL) as a function of the candidate Z' mass were extracted and are shown in Figure 2 [5]. No evidence for a Z' was seen with a significance greater than 3σ.

3 ALPs

Axion-like particles (ALPs) are pseudoscalar particles that can couple to SM bosons and appear in different extensions to the SM. Unlike axions, which are originally motivated by the strong CP problem [6], the coupling and the mass of ALPs are taken to be independent. At Belle II the simplest approach to search for ALPs is via the two-photon coupling $g_{a\gamma\gamma}$. Two different processes may be considered for this scenario: photon fusion ($e^+e^- \to e^+e^-a$) and ALP-strahlung ($e^+e^- \to \gamma a$). Whereas photon fusion dominates over ALP-strahlung in terms of production cross section (unless m_a approaches $\sqrt{s}$), the latter is still preferred for experimental searches as the final state of photon fusion consists of two soft photons giving rise to large QED backgrounds. The corresponding Feynman diagram for ALP-strahlung is shown in Figure 3.

According to the ALP mass and coupling, there are different topologies that can be observed in the Belle II detector: the three final-state photons being either resolved, two of them overlapping (in terms of cluster shape in

Figure 3: Feynman diagram for ALP-strahlung process.

the electromagnetic calorimeter) or the ALP decaying outside of the detector leading to one single photon in the final state. The general idea of the analysis consists of reconstructing three photon candidates with energies summing up to the beam energy and no charged tracks in the event. The main contributing background processes are $e^+ e$! ( ), $e^+ e$! $e^+ e$ and $e^+ e$! P with P = ^{0}; ; ^{0} and P ! . The expected sensitivity at 90% CL for the ALPs search via the ALP-strahlung process is shown in Figure 4 [7]. The existing limits on the two-photon coupling can already be improved by Belle II with the small dataset of 472 pb ^{1} collected during the commissioning run.

4 Dark Photon

In a minimal extension of the SM the dark photon A^0 may serve as the mediator of a hypothetical dark force. It is charged under a $U(1)^0$ gauge-symmetry-extension and kinetic mixing with the SM is allowed with a strength equal to , leading to interactions between SM and DS particles. At Belle II we consider on-shell A^0 decays and differentiate between a number of experimental signatures according to the mass of the dark photon, m_{A^0}. If A^0 is the lightest DS particle, it will decay into SM particles and we look for a peak in the invariant mass of the decay products. However, if A^0 is not the lightest DS particle, it decays into dark matter and it can be searched for in the process $e^+ e$! $_{ISR}$ A^0, which is shown in Figure 5.

The first search for the A^0 at Belle II will be performed in the invisible decay channel whilst looking for monoenergetic initial-state radiation photon with energy $E = \frac{s \quad m^2_{A^0}}{2^p s}$. This mono-photon final state is mimicked by different QED processes such as $e^+ e$! ( ) and $e^+ e$! $e^+ e$ ( ), where different final-state particles go outside of the detector acceptance except one photon. Special low-multiplicity trigger logic has been developed and implemented into the Belle II trigger system, so that these single-photon signatures may be selected. Preliminary estimates on the sensitivity of the kinetic-mixing strength have been computed and are shown in Figure 6 [1].

Figure 4: Expected sensitivity (90% CL) for the ALPs search at Belle II with early datasets [7].

Figure 5: Feynman diagram for the production of A^0 via kinetic mixing and subsequent invisible decay.

5 Conclusion

In these proceedings, the Belle II experiment as well as its capabilities for performing low-mass DS searches have been presented. Indeed there is a broad and active program of DS physics at Belle II including many different models and mediators such as the Dark Photon, ALPS and Z^0. First results have been published and there is much more to come with Belle II ramping up to its design luminosity and collecting much larger data sets.