Status and prospects for dark sector searches at Belle II

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1 Belle II and SuperKEKB

Belle II is an almost complete upgrade of the original Belle experiment, with better performance and higher rate capabilities [1]. It is located at the SuperKEKB e^+e^- collider at the KEK laboratory in Tsukuba, Japan. In addition to dark sector searches, its physics program includes rare and forbidden B meson decays, lepton flavour and CP asymmetries, and charm and tau physics [5]. Belle II has recorded $428\,\mathrm{fb}^{-1}$ of data since March 2019. It is currently in long shutdown 1 (July 2022 – September 2023) to install a new two-layer pixel vertex detector.

SuperKEKB is the world's highest instantaneous luminosity collider, reaching a peak of $4.7 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. To reach the target of $6 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, accelerator developments will focus on increasing current while reducing injection backgrounds; reducing catastrophic beam loss events; and controlling emittance blowup and beam instability. An international task force is providing input, including on a possible upgrade of the final focus or other hardware upgrades for long shutdown 2 in 2028.

2 Z' and leptophilic dark scalars

$L_\mu - L_\tau$ models seek to explain possible Standard Model anomalies in muon $(g-2)$ and in B decays to leptons. These models include a vector gauge boson Z' that couples to only the second and third generations leptons of the Standard Model, thereby evading strong limits from processes involving electron production or decay. Existing limits from BaBar [17], CMS [18], and Belle [9] strongly the constrain the parameter space relevant for $(g-2)_\mu$ for Z' masses above $2m_\mu$ through searches for resonances in four muon final states.

If, however, the anomaly is related to a scalar that couples only to muons, the existing constraints do not cover the relevant parameter space. A Belle II search in the four muon final state will provide powerful constraints with a few ab^{-1} of data [12].

Search for the invisible decay of the Z': Below the $2m_\mu$ threshold, the $L_\mu - L_\tau$ Z' would decay exclusively to ν_μ or ν_τ. It is also possible that the Z' is the mediator between dark matter (χ) and the Standard Model. In this case, the decay $Z' \to \chi\chi$—which also produces no particles detectable by Belle II—would be dominant even above $2m_\mu$ threshold.

Limits on these invisible Z' decays have been set by an early Belle II analysis searching for $e^+e^- \to \mu^+\mu^- Z'$, where the mass of the Z' is deduced from the missing mass recoiling against the muon pair [3]. Belle II has recently updated this analysis, with a dramatic increase in sensitivity [4]. This is due in part to a $300\times$ increase in integrated luminosity. The new analysis also significantly improves the suppression of Standard Model backgrounds, which are primarily muon pairs accompanied by one or more undetected photons, tau pairs decaying to muons, and two-photon-fusion production of muon pairs. This is accomplished by a boosted decision tree that exploits the kinematics resulting from the Z' being produced in final-state radiation. The resulting limits, under the assumption that $\mathcal{B}(Z') \to \text{invisible} = 1$, exclude the parameter space that would explain $(g-2)_\mu$ for $0.8 < m_{Z'} < 5.0\,\mathrm{GeV/c^2}$ (Fig. 1).

Under the hypothesis that the Z' decays only to Standard Model particles, the new paper improves the existing Belle II limits below the $2m_\mu$ threshold by more than an order of magnitude. Current sensitivity for these masses does not reach the $(g-2)_\mu$ parameter space, but future luminosity increases and planned analysis improvements will provide significant improvements.

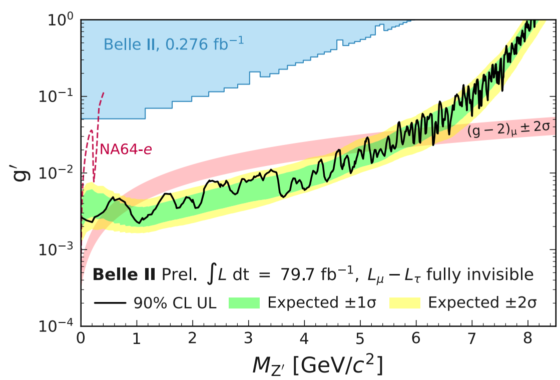

Figure 1: Belle II limits on the coupling g' between the Z' and the muon as a function of Z' mass, under the hypothesis that the Z' decays only invisibly [4]. Also shown are limits from NA-64 [7].

Search for a $\tau^+\tau^-$ resonance in $e^+e^- \to \tau^+\tau^-$: A $L_\mu - L_\tau$ Z' boson produced via final-state radiation from a muon pair could also decay to a tau pair, if it is massive enough. Due to the neutrinos produced by the tau decays, the sensitivity is poor compared to the muon pair final state. However, if the new particle is a leptophilic scalar with mass-dependent couplings, the loss of kinematic constraints is more than compensated by the increased branching fraction. The signature is four tracks including at least two muons, with missing energy, consistent with a particle produced as final state radiation recoiling against a muon pair. A preliminary Belle II result sets the first leptophilic scalar results above $6.5\,\mathrm{GeV/c^2}$.

3 Dark photons

Dark photons are produced via initial state radiation, and then decay either invisibly or to a pair of leptons or other standard model particles. Partially visible decays are also possible in slightly more complicated cases, such as indirect dark matter [10], or dark showers [8]. Both of these involve displaced vertices, which significantly reduces Standard Model backgrounds. Analyses have so far focused on the case where the dark photon mass is less than the center of mass energy, resulting in on-shell production.

Invisible dark photon decays: The visible final state in this case is a single photon. Although its decay products are not reconstructed, the mass of the dark photon $m_{A'}$ is directly related to the center-of-mass energy of the photon under the assumption that there are no additional initial-state radiation photons in the event. Backgrounds include $e^+e^- \to \gamma\gamma(\gamma)$, where only one photon is detected; $e^+e^- \to e^+e^-\gamma$, with both final state electrons out of the detector acceptance; cosmic rays; and beam backgrounds. The analysis relies on quantifying each of these backgrounds in the missing mass squared vs. polar angle plane. Belle II, in its initial analysis, will have sensitivity to regions of the parameter space that would correspond to that expected for the observed astronomical dark matter (Fig. 2a).

Visible decays of the dark photon: For visible decays of the dark photon, the final state consists of a photon and a pair of leptons. The initial search at Belle II will reconstruct all three particles. The signal consists of a narrow resonance in the $\ell^+\ell^-$ pair on top of a large but generally smooth standard model background. The J/ψ and similar mass regions are excluded from the search.

Belle II has a considerably larger drift chamber than BaBar, which will give better mass resolution. The Belle II projection [5], shown in Fig. 2b, is derived from the BaBar limits [16], assuming a factor of two improvement in resolution.

Belle II is also studying the statistically independent sample in which the initial-state-radiation photon is at low angles, and only the lepton pair is reconstructed. A larger data set will enable a displaced vertex search, with significant reach [11]. The BaBar analysis

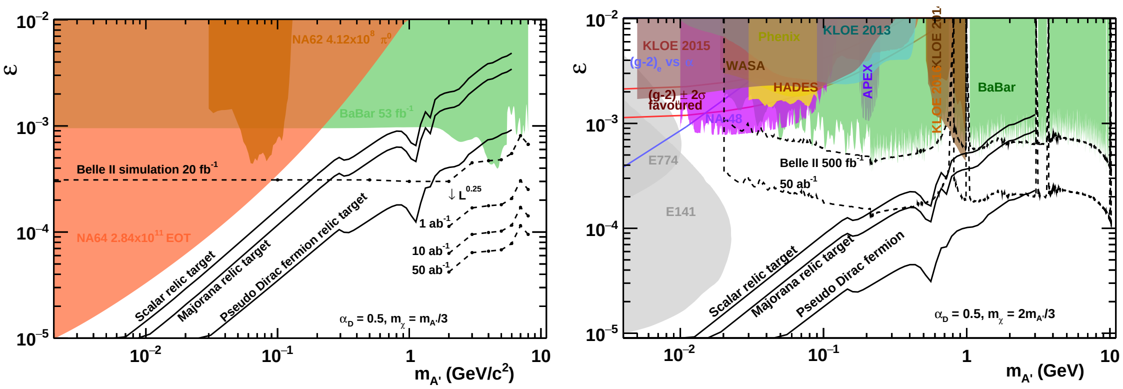

Figure 2: Projected Belle II sensitivity for (a) invisible dark photon decay and (b) visible dark photon searches in the kinetic mixing parameter ε versus dark photon mass plane. Adapted from [5]. Also shown are the dark matter relic density targets.

did not set limits below $20\,\mathrm{MeV/c^2}$. Given the importance of investigating the ATOMKI anomaly [14], Belle II is undertaking an analysis focused on this mass region.

Dark photon with invisible dark Higgs: A natural dark sector extension is to include a dark Higgs (h'), which can be produced in association with a dark photon. This model has two additional parameters, the dark Higgs mass $m_{h'}$ and the coupling between the dark Higgs and the dark photon, α_D. Belle II has studied the case where the dark photon decays visibly ($m_{A'} < 2m_\chi$), and the dark Higgs is long lived ($m_{h'} > m_{A'}$), leaving no visible signal in the detector. KLOE has previous studied this configuration, at much lower masses [6]; BaBar [15] and Belle [13] have published searches for the case where the dark Higgs decays to a pair of dark photons.

Belle II searches for dark photons decaying to a muon pairs. The final state is a pair of muons and missing momentum, in synergy with the invisible Z' analysis. There are additional kinematic constraint: the invariant mass of the muon pair is equal to the dark photon mass, while the missing mass is equal to the dark Higgs mass.

A signal would be a concentration of events in the m^2_{recoil} vs. $m_{\mu^+\mu^-}$ plane. The largest background is from $e^+e^- \to \mu^+\mu^-\gamma(\gamma)$ events with undetected photons. The resulting limits, in the $\alpha_D\varepsilon^2$ vs. $m_{h'}$ or $m_{A'}$ planes, are the first in this mass range [2]. For $\alpha_D = 1$, the limits are stronger than those from existing visible dark photon decay analyses (Fig. 3).

4 Summary

Belle II has accumulated a near-BaBar sized data set, which has been used to produce several world-leading dark sector searches. The current data will be used for several other

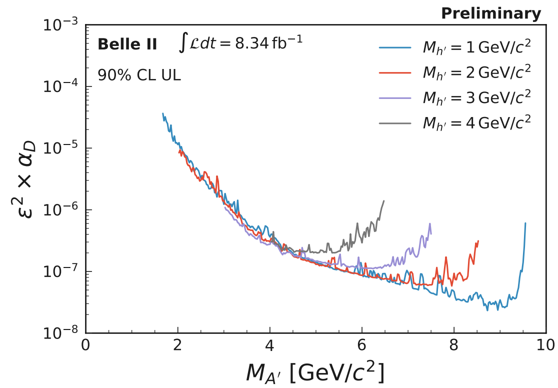

Figure 3: Belle II upper limits on $\alpha_D \varepsilon^2$ as a function of dark photon mass, for four different dark Higgs masses [2].

high-profile analyses, including searches for invisible and visible dark photon decays, and leptophilic / muonphilic scalars decaying to muon pairs. Over the next decade, increases in the SuperKEKB luminosity, including an upgrade of the final focus, will increase the data size by a factor of 100. This data set, the clean e^+e^- environment, and inclusive triggers, will give Belle II unique sensitivity to dark sector physics.

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