Dark Sector Physics at Belle II

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Abstract. The first dark sector physics analyses for Belle II are currently underway. Belle II detects collisions at the SuperKEKB asymmetric-energy e^+e^- collider in Tsukuba, Japan and has already collected 6.5 fb^{-1} of data at the $\Upsilon(4S)$ resonance ($\sqrt{s}$ = 10.58 GeV). The collider has a design luminosity of 8×10^{35} cm^{-2} s^{-1} and the detector will collect 50 ab^{-1} of data in its lifetime, making it the most luminous experiment in the world. In addition to early performance studies on particle identification, tracking quality, energy resolution, and more, Belle II is preparing to release its first physics results. These include the first official time-integrated luminosity measurements, as well as searches for the dark photon, A', in a monophoton signature, and the invisible Z' in both $L_\mu - L_\tau$ and Lepton Flavour Violation models. Even with this early data set, it is clear that Belle II is and will continue to be competitive in various dark sector searches at the MeV-GeV scale.

1. Introduction

There is ample evidence for the existence of dark matter — cosmology indicates that it is over five times more abundant than visible matter. Although gravitational evidence exists, the full interactions and constituents of dark matter remain a mystery. In the event of non-WIMP dark matter, we must search for a portal to the dark sector via interactions with light mediators. This portal can present itself in many ways: a vector portal, a pseudoscalar portal, a scalar portal, or a neutrino portal. At Belle II, we are performing many dark sector searches [1]. Herein, we will emphasize two in particular: the dark photon, A', in a monophoton signature, and the Z' in both $L_\mu - L_\tau$ and Lepton Flavour Violation (LFV) models.

SuperKEKB is an asymmetric-energy electron-positron collider located in Tsukuba, Japan. It typically operates at a center-of-mass energy corresponding to the $\Upsilon(4S)$ resonance ($\sqrt{s}$ = 10.58 GeV) and is thus a *B-factory* (with the majority of events proceeding as $\Upsilon(4S) \to B\bar{B}$). Surrounding the interaction point is the Belle II detector which consists of various subdetector layers; an inner vertex detector for tracking, a central drift chamber for tracking and measurement of dE/dx, a CsI(Tl) electromagnetic calorimeter, and an outer detector for tracking and K_L and muon reconstruction [2].

Belle II has successfully completed its commissioning phases and has begun to ramp up towards its design luminosity of 8×10^{35} cm^{-2} s^{-1}. In 2018, with a partial vertex detector in place and during the final commissioning phase of the detector, Belle II detected its first collisions. During this phase, Belle II collected approximately 0.5 fb^{-1} of data before shutting down to upgrade to a near-full vertex detector geometry. By March of 2019, data-taking resumed, and in only two months, 6.5 fb^{-1} of $\Upsilon(4S)$ on resonance data was collected [3]. This early data has proven competitive for various dark sector searches, and Belle II expects to remain at the

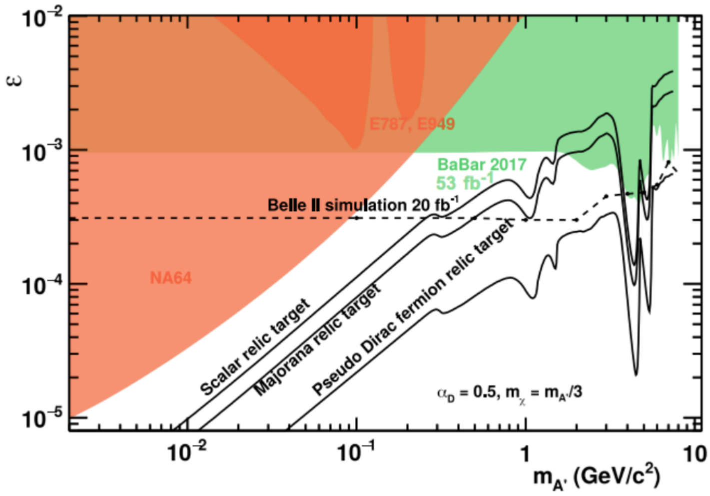

Figure 1. Expected Belle II sensitivity to the kinetic mixing strength, ε, as a function of dark photon mass for $A' \rightarrow$*invisible* decays.

forefront of dark sector collider searches as the years progress and we reach our data taking goal of 50 ab^{-1} (expected in 2027).

2. The Dark Photon

One promising dark sector search at Belle II is the search for a vector portal, the dark photon A' [4]. The dark photon is charged under a dark sector gauge group, $U(1)_X$, and undergoes kinetic mixing with the Standard Model (SM) $U(1)_Y$ gauge boson with some kinetic mixing strength, ε. It can present itself in electromagnetic interactions where it "replaces" the SM photon. The dark photon can decay visibly as $A' \rightarrow e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$, or to *hadrons*. However, in the case of a dark photon which is not the least massive dark matter particle (*i.e.* $m_{A'} > m_\chi$), invisible decays of the dark photon are dominant and we search for it as $e^+e^- \rightarrow A'\gamma$, $A' \rightarrow$*invisible* — the so-called *monophoton* signature.

Due to the expected low mass of the dark photon (10 MeV −10 GeV), it can be produced in electron-positron collisions like those studied at Belle II. For visible decays of the dark photon, the search proceeds by searching for a resonance in the invariant mass distribution of the reconstructed daughter particles. For invisible decays of the dark photon however, the search occurs as a scan of the recoil-mass squared distribution (*i.e.* via four-momentum conservation, $P_{A'} = P_{beam} - P_\gamma$), since the final state has a single initial-state radiation photon plus missing energy. For the latter case, the resolution of the recoil-mass squared peak depends heavily on the energy resolution of the monoenergetic photon as $E_\gamma = (s - M_{A'}^2)/2\sqrt{s}$.

This monophoton signature is masked by many QED background processes (*e.g.* $e^+e^- \rightarrow e^+e^-\gamma(\gamma)$ or $e^+e^- \rightarrow \gamma\gamma(\gamma)$) with all final state particles except a single photon lying outside of the detector acceptance or in non-instrumental regions. The similarity between these signatures, in conjunction with a cap of $\mathcal{O}(10)$ kHz on trigger rates (corresponding to an acceptance of $\sim \mathcal{O}(10)$ nb of processes) provide a difficult challenge for Belle II — the QED background processes have a fiducial cross section of ≈ 400 nb which must be cut down, without throwing away our signal. Thus, we employ a special dark sector trigger in which we trigger on events with a monoenergetic photon striking the barrel region of our calorimeter.

Preliminary studies for the monophoton search have been performed and expected sensitivities of the parameter space have been determined, as shown in Fig 1. Despite the small integrated luminosity shown in the projection figure, a competitive result is still achievable.

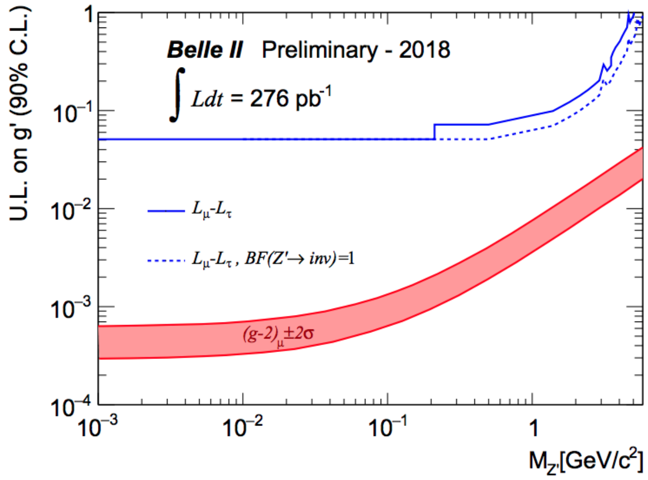

Figure 2. Belle II 90% CL upper limits on the coupling, g', in the $Z' \rightarrow invisible$ $L_\mu - L_\tau$ model.

This is largely due to the *orientation of the calorimeter crystals.* In BaBar [5], the crystals were pointed very nearly at the interaction region, introducing a large irreducible background of events such as $e^+e^- \rightarrow \gamma\gamma$ in which one photon escapes detection by passing through projective cracks between adjacent crystals. In Belle II, however, this irreducible background does not exist since the crystals of the electromagnetic calorimeter do not point towards the interaction region. Additionally, SuperKEKB beam energies provide a smaller boost and larger electromagnetic calorimeter angular coverage, allowing for a larger acceptance of signal events.

3. The Invisible Z'

Another possible vector portal arises in the form of the invisible Z'. This low-mass Z' boson belongs to an Abelian symmetry indicated by the $L_\mu - L_\tau$ model [6] — a model allowing the boson to couple to muons, taus, and their respective neutrinos. Given the high QED cross section at Belle II, we would expect to see the Z' in processes such as $e^+e^- \rightarrow \mu^+\mu^- Z'$ where the Z' radiates off of a final state muon and decays either visibly as $Z' \rightarrow \mu^+\mu^-$ or $Z' \rightarrow \tau^+\tau^-$, or invisibly to neutrinos or dark matter.

For invisible decays of the Z' produced radiatively from $e^+e^- \rightarrow \mu^+\mu^-$, we have a detector signature consisting of two oppositely charged muons plus missing energy. We can then, similar to the monophoton dark photon search, fit to the recoil-mass squared distribution. Here, we recoil off the two final state muons and calculate a recoil mass as $M^2_{Z'} = s + M^2_{\mu\mu} + 2\sqrt{s}E^{\mathrm{CMS}}_{\mu\mu}$.

This recoil-mass scan search was performed using 276 pb^{-1} of 2018 data — the entirety of the 2018 data set could not be exploited due to trigger conditions for two-track events. After accounting for trigger efficiencies, geometrical acceptance, and reconstruction efficiencies (a complete study is detailed in Ref. [7]), limits on the coupling g' as a function of Z' mass are extracted as shown in Fig 2. The primary backgrounds for this search come from QED processes such as $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$, $e^+e^- \rightarrow \mu^+\mu^-e^+e^-$, and $e^+e^- \rightarrow \tau^+\tau^-(\gamma)$. These backgrounds persist even after implementation of optimized selection criteria. The largest sources of systematic uncertainty with this early data set result from poor agreement between data and MC, limited statistics, and poor access to control modes, all of which are expected to reduce as the data size increases.

There is a LFV extension to this work. Here, rather than having the Z' radiate from a final state muon, we have one of the muons decaying as $\mu^\pm \rightarrow Z'e^\pm$. In this case, our detector

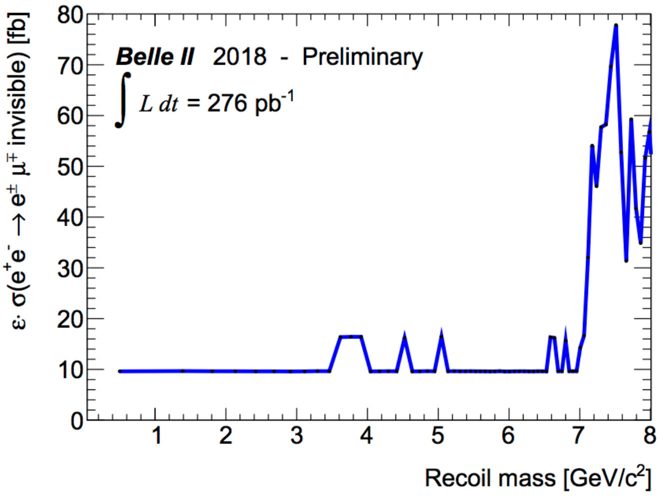

Figure 3. Belle II limits on the $\varepsilon \cdot \sigma$ (where ε is the efficiency) as a function of Z' mass for the LFV model. Results cannot be expressed as limits on a coupling since the efficiencies are model-dependent and no LFV Z' model currently exists.

signature consists of two oppositely charged tracks of different flavours plus missing energy. For this case, the most important SM backgrounds we have are $e^+e^- \to \tau^+\tau^-(\gamma)$, with $\tau^+ \to \mu^+\nu\bar{\nu}$ or $\tau^- \to e^-\nu\bar{\nu}$, and $e^+e^- \to e^+e^-\mu^+\mu^-$. Because the efficiencies are model dependent, the search is performed in a model independent way and the results are expressed as limits on the efficiency times the cross section, as shown in Fig 3.

4. Conclusion

In this work, the monophoton signature A' search and two Z' searches have been discussed. These are among the first dark sector searches achievable at Belle II with our early data set. Most notably, the 2018 data set was used to extract 90% CL upper limits on the coupling, g', of $\sim \mathcal{O}(10^{-1})$ for the dark Z' $L_\mu - L_\tau$ model. In addition to the aforementioned searches, there are early results for an Axion-Like Particle, a, in a triphoton signature on the publication horizon [8], and various analyses are well underway including: axiflavon searches, dark higgs in higgstrahlung, long-lived particles, magnetic monopoles, and others. It is clear that Belle II has a promising and robust dark sector program. Thanks to the high luminosity and improved detector performance techniques, Belle II expects to remain competitive for light mediators and dark sector portal searches at the MeV-GeV scale.

Acknowledgments

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