Snowmass 2021 Letter of Interest:
Dark sector studies at Belle II

on behalf of the U.S. Belle II Collaboration

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Abstract:

Belle II will collect 50 ab^{-1} of data at the SuperKEKB e^+e^- collider over the next decade. This large data set—a factor of 50 greater than the original Belle experiment—will enable Belle II to undertake world-leading searches relevant to a wide range of dark sector models.

The large dataset and clean e^+e^- environment, combined with a trigger designed to have high efficiency for events with a small number of particles in the final state, will enable Belle II to undertake many new physics searches inspired by dark sector models. In some cases, these are updates of searches that have been previously performed by *BABAR*, Belle, or KLOE-2. The substantial increase in integrated luminosity is essential in this case. For example, the limit on the mixing parameter ε between the dark photon A' and the photon improves as the fourth root of integrated luminosity. In other cases, the searches that will be undertaken by Belle II are unique. We welcome new contributions from the theoretical and experimental community that may expand the scope and reach of Belle II in the dark sector.

Examples of specific searches in the context of the RF6 benchmark models follow.

Vector mediator

The dark photon can be produced in the reaction $e^+e^- \to \gamma A'$. If the dark photon decays invisibly (or is long-lived), the visible final state consists of a single photon. The Belle II reach for a small dataset is outlined in Ref.[1]. *BABAR* has previously performed this analysis[2]. It may be that decays to dark matter are kinematically forbidden, in which case the dark photon will decay to standard model particles. In this case, the projected Belle II reach in the e^+e^- and $\mu^+\mu^-$ final states[1] is extrapolated from the reach of the corresponding *BABAR* analysis[3]. Better limits have been obtained in the ρ–ω region by the KLOE experiment[4] using the $\pi^+\pi^-$ final state.

Indirect dark matter (iDM) models predict a final state that is a mixture of invisible dark matter and visible standard model particles, as do dark shower models. In much of the parameter space of these models, the standard model particles are produced in the decay of a long-lived dark sector particle, giving a production vertex that is displaced from the e^+e^- interaction point. The Belle II sensitivity in the iDM case is discussed in Ref.[5].

Previous measurements significantly constrain models in which a dark sector vector mediator directly couples to standard model first generation particles. The $L_\mu - L_\tau$ model predicts a vector boson Z' that couples only to second and third generation leptons. The first Belle II physics paper is a search for an invisibly decaying Z'[6]. Lepton-flavour violation variations, in which the final state includes two different charged leptons recoiling against an invisible Z', are also studied. Belle II will search for visible Z' decays, the subject of an earlier *BABAR* analysis[7], with increased statistics.

Scalar mediator

The dark sector may include a dark Higgs, which could be produced in association with a dark photon, a process labeled dark Higgsstrahlung. If the dark Higgs is long lived, the visible final state contains only a pair of tracks from the decay of the dark photon. This process has been searched for by KLOE-2[8]. *BABAR* and Belle searched for an alternative process, in which the dark Higgs decays to a pair of dark photons, producing a six-track final state[9;10].

A dark Higgs S mixing with the standard model Higgs would inherit the coupling to mass, and could be produced through its coupling to the virtual top quark in B decay, $B \to K^{(*)}S$[11].

The dark Higgs could decay to standard model particles within the detector, producing a displaced vertex, or could have a long enough lifetime to be invisible. In the latter case, Belle II will rely on its ability to fully reconstruct one B in an event to search for invisible particles in the decay of the other B.

A leptophilic dark scalar would preferentially be produced in association with a pair of tau leptons. *BABAR* has recently completed a search for such a scalar decaying to an electron pair or a muon pair [12].

Neutrino mediator

The large tau lepton sample that will be produced at SuperKEKB can be used by Belle II to search for sterile neutrinos that mix predominantly with the tau, and have masses low enough to be produced in tau decay [13]. The lifetime of the sterile neutrino will produce displaced vertices, which significantly reduces backgrounds, and sufficient kinematic constraints are available to determine the sterile neutrino mass.

Axion-like particle mediator

An axion-like particle (ALP) can be produced in e^+e^- collisions through its coupling to photons, producing a final state consisting of a photon and an axion-like particle. Belle II has completed a search for the case where the ALP decays to two photons [14]. Other topologies are possible [15]. The ALP could be long lived, in which case the analysis is similar to the search for an invisibly decaying dark photon, or two of the photons could merge into a single cluster in the calorimeter.

This first analysis relies only on the ALP coupling to photons. The ALP (a) could also be produced through its coupling to the virtual W in the decay $B \to K^{(*)}a$, followed by a decay to two photons [16].

Long-lived particles

Long-lived particles that are not consistent with the standard model are a generic indication of new physics. They can arise in each of the mediator categories discussed above. Often the resulting signature is a pair of charged tracks displaced from the interaction point. The trigger and reconstruction code may need optimization in such cases. Other signatures are also possible. Slightly longer lifetimes will produce signals only in the calorimeter or muon system, or may be long enough that the particle escapes the detector entirely, producing invisible particles.

References

[1] E. Kou *et al.* [Belle-II], "The Belle II Physics Book," PTEP **2019**, no.12, 123C01 (2019) doi:10.1093/ptep/ptz106 [arXiv:1808.10567 [hep-ex]].

[2] J. P. Lees *et al.* [BABAR], "Search for Invisible Decays of a Dark Photon Produced in e^+e^- Collisions at BABAR," Phys. Rev. Lett. **119**, no.13, 131804 (2017) doi:10.1103/PhysRevLett.119.131804 [arXiv:1702.03327 [hep-ex]].

[3] J. P. Lees *et al.* [BABAR], "Search for a Dark Photon in e^+e^- Collisions at BABAR," Phys. Rev. Lett. **113**, no.20, 201801 (2014) doi:10.1103/PhysRevLett.113.201801 [arXiv:1406.2980 [hep-ex]].

[4] A. Anastasi *et al.* [KLOE-2], "Limit on the production of a new vector boson in $e^+e^- \to U\gamma$, $U \to \pi^+\pi^-$ with the KLOE experiment," Phys. Lett. B **757**, 356-361 (2016) doi:10.1016/j.physletb.2016.04.019 [arXiv:1603.06086 [hep-ex]].

[5] M. Duerr, T. Ferber, C. Hearty, F. Kahlhoefer, K. Schmidt-Hoberg and P. Tunney, "Invisible and displaced dark matter signatures at Belle II," JHEP **02**, 039 (2020) doi:10.1007/JHEP02(2020)039 [arXiv:1911.03176 [hep-ph]].

[6] I. Adachi *et al.* [Belle II], "Search for an Invisibly Decaying Z' Boson at Belle II in $e^+e^- \to \mu^+\mu^-(e^\pm\mu^\mp)$ Plus Missing Energy Final States," Phys. Rev. Lett. **124**, no.14, 141801 (2020) doi:10.1103/PhysRevLett.124.141801 [arXiv:1912.11276 [hep-ex]].

[7] J. P. Lees *et al.* [BABAR], "Search for a muonic dark force at BABAR," Phys. Rev. D **94**, no.1, 011102 (2016) doi:10.1103/PhysRevD.94.011102 [arXiv:1606.03501 [hep-ex]].

[8] A. Anastasi *et al.* [KLOE-2], "Search for dark Higgsstrahlung in $e^+e^- \to \mu^+\mu^-$ and missing energy events with the KLOE experiment," Phys. Lett. B **747**, 365-372 (2015) doi:10.1016/j.physletb.2015.06.015 [arXiv:1501.06795 [hep-ex]].

[9] J. P. Lees *et al.* [BABAR], "Search for Low-Mass Dark-Sector Higgs Bosons," Phys. Rev. Lett. **108**, 211801 (2012) doi:10.1103/PhysRevLett.108.211801 [arXiv:1202.1313 [hep-ex]].

[10] I. Jaegle *et al.* [Belle], "Search for the dark photon and the dark Higgs boson at Belle," Phys. Rev. Lett. **114**, no.21, 211801 (2015) doi:10.1103/PhysRevLett.114.211801 [arXiv:1502.00084 [hep-ex]].

[11] A. Filimonova, R. Schaefer and S. Westhoff, "Probing dark sectors with long-lived particles at BELLE II," Phys. Rev. D **101**, no.9, 095006 (2020) doi:10.1103/PhysRevD.101.095006 [arXiv:1911.03490 [hep-ph]].

[12] J. P. Lees *et al.* [BABAR], "Search for a Dark Leptophilic Scalar at BABAR," [arXiv:2005.01885 [hep-ex]].

[13] C. O. Dib, J. C. Helo, M. Nayak, N. A. Neill, A. Soffer and J. Zamora-Saa, "Searching for a sterile neutrino that mixes predominantly with ν_τ at B factories," Phys. Rev. D **101**, no.9, 093003 (2020) doi:10.1103/PhysRevD.101.093003 [arXiv:1908.09719 [hep-ph]].

[14] F. Abudinen *et al.* [Belle II], “Search for Axion-Like Particles produced in e^+e^- collisions at Belle II,” [arXiv:2007.13071 [hep-ex]].

[15] M. J. Dolan, T. Ferber, C. Hearty, F. Kahlhoefer and K. Schmidt-Hoberg, “Revised constraints and Belle II sensitivity for visible and invisible axion-like particles,” JHEP **12**, 094 (2017) doi:10.1007/JHEP12(2017)094 [arXiv:1709.00009 [hep-ph]].

[16] E. Izaguirre, T. Lin and B. Shuve, “Searching for Axion-like Particles in Flavor-Changing Neutral Current Processes,” Phys. Rev. Lett. **118**, no.11, 111802 (2017) doi:10.1103/PhysRevLett.118.111802 [arXiv:1611.09355 [hep-ph]].