RF6-2 Letter of Interest (LOI) for Snowmass 2021: Long-lived particles at Belle II

S. Dreyer,[1] T. Ferber,[1,*] A. Filimonova,[2] C. Hearty,[3,4] S. Longo,[1]
R. Schäfer,[5] M. Tammaro,[6,7] K. Trabelsi,[8] S. Westhoff,[5,*] and J. Zupan[6]

[1] *Deutsches Elektronen–Synchrotron, 22607 Hamburg, Germany*
[2] *NIKHEF, NL-1098 XG Amsterdam, The Netherlands*
[3] *Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia V6T 1Z1, Canada*
[4] *Institute of Particle Physics (Canada), Victoria, British Columbia V8W 2Y2, Canada*
[5] *Institute for Theoretical Physics, Heidelberg University, 69120 Heidelberg, Germany*
[6] *Department of Physics, University of Cincinnati, Cincinnati, Ohio 45221,USA*
[7] *Jozef Stefan Institute, Jamova 39, Ljubljana, Slovenia*
[8] *Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France*

We plan to explore the full potential of Belle II to search for GeV-scale hidden sectors with long-lived particles. This requires the development of new search strategies for charged and neutral final states, including new reconstruction algorithms and optimized triggers. Motivated by the particle dark matter hypothesis, we plan to define simple models as representatives of a mechanism that sets the relic abundance in the early universe, like co-scattering or freeze-in. Based on these models, we predict typical signatures with long-lived particles that guide the new searches at Belle II. In addition we plan to explore the reach of a dedicated long-lived particle project called GAZELLE. This detector would be placed $\mathcal{O}(10\,\mathrm{m})$ away from the Belle II interaction point.

Belle II is expected to be able to probe phenomenologically interesting new physics scenarios with long-lived particles (LLPs). We plan to focus on hidden sectors of new particles in the MeV to GeV range and explore the full range of LLP signatures at Belle II. While such hidden sectors are predicted in many extensions of the standard model (SM) [1], in this LoI we base our predictions on feebly-interacting dark matter. Viable scenarios of GeV-scale dark matter often require suppressed couplings to standard model particles, in order to obtain the observed relic abundance from freeze-out via co-annihilation [2] or co-scattering [3], or from freeze-in [4]. By searching for long-lived mediators of such a new force at Belle II, we may learn about dark matter production in the early universe. Previous searches for hidden sectors at e^+e^- experiments have focused mostly on final states with prompt particles or missing energy. These categories probe mediators that are heavy and/or strongly coupled (prompt decays), or mediators that either decay into dark matter or are so light that they leave the detector before decaying (missing energy). Signatures with long-lived particles, in turn, probe mediators with displaced decays to visible particles, as they are predicted in viable scenarios of dark matter. Searches for visible displaced decays of long-lived mediators bridge the existing sensitivity gap in regions that cannot be accessed by searches for prompt decays or missing energy.

LONG-LIVED PARTICLES IN BELLE II

Depending on the interactions with the standard model, mediators Φ can be produced in different processes at Belle II. Mediators with lepton couplings can be produced directly through $e^+e^- \to \Phi$ [2, 3, 5, 6], while mediators with couplings to quarks can be produced via Υ decays, $\Upsilon \to \Phi X$ [4], or in meson or decays like $M_1 \to M_2\Phi$ [7–9]. The LLP is not necessarily the mediator of the dark force, but can also be an additional state from a larger dark sector, as for instance in models for inelastic dark matter [2]. The decay modes of a mediator are model-dependent and allow us to probe a large variety of possible interactions. We classify these in terms of the signatures we expect at Belle II (see Fig. 1 left). It should be noted that Belle II has very good sensitivity for fully invisible LLP decays ($e^+e^- \to \gamma + \text{inv.}$, $B \to K\nu\bar{\nu}$, $B \to \text{inv.}$, $\Upsilon \to \text{inv.}$, ...) [10], which sometimes offer an alternative way to look for the same physics.

Belle II offers a uniquely clean environment to probe B decays with LLPs by reconstructing the full final state (see Fig. 1 right). On the other hand, if LLPs are produced directly in e^+e^- collisions, Belle II track-triggers are currently not sensitive to the displaced vertex. Instead the events must be triggered on associated particles such as initial-state radiation photons. Note that LLPs from B meson decays are generally triggered with high efficiency by the prompt decay products of the other B in the event, that Belle II does not have a *missing energy* trigger, and that Belle II calorimeter hardware cluster triggers are very efficient also for displaced photons (but they have no discrimination power on whether the event contained a displaced photon).

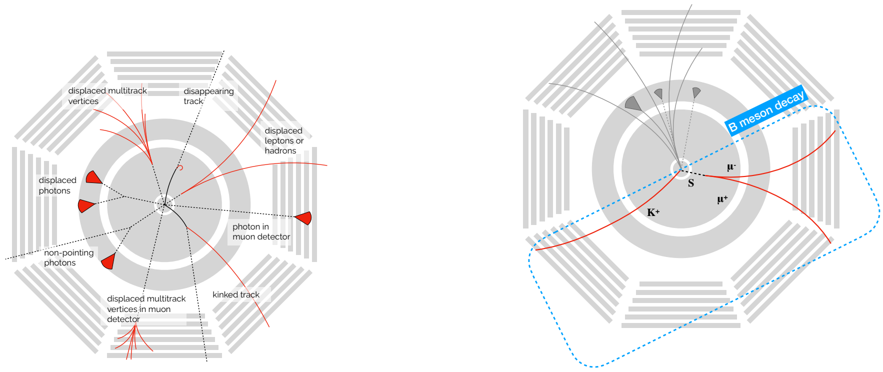

FIG. 1. Schematic display of LLP final state signatures (left) and a $B \to KS$ decay with displaced muon pair (right) in Belle II. The displayed detector plane is perpendicular to the beam axis.

Displaced charged final states Long-lived neutral mediators Φ can decay into pairs of displaced SM charged particles. The final state can be fully visible ($\Phi \to \ell\ell$, e.g. a dark photon A' [11]) or include missing energy ($\Phi \to \ell\ell + \text{inv.}$, e.g. inelastic DM [2]).

Displaced neutral final states If decays to SM fermions are kinematically forbidden or suppressed (e.g. $B \to KS$ with $m_S < 2m_e$), long-lived neutral mediators Φ will generally decay into pairs of (displaced) photons. Neutral final states also arise in models with long-lived pseudo-scalar mediators a with decoupled production and decay, e.g. in models with multiple axion-like particles (ALPs) $a_1 \to a_2 a_2, a_2 \to \gamma\gamma$, or in $B \to Ka, a \to \gamma\gamma$ decays. Light vector mediators A' may decay into 3γ if $m_{A'} < 2m_e$ [12]. The Belle II calorimeter offers excellent energy and timing reconstruction of $\mathcal{O}$(ns), but the lateral segmentation does not allow to reconstruct displaced photons directly. We plan to explore the option to use shower shape information or advanced reconstruction methods, as well as pair-conversions or Dalitz-decays to detect non-pointing photons and displaced multi-photon vertices. Using the Belle II muon detector, we plan to investigate longer lifetimes, however at the expense of a significantly lower energy resolution.

Disappearing and kinked tracks Light charged mediators $\Phi^\pm$ may result in decays of $\Phi^\pm \to \ell^\pm + \text{inv.}$ (kinked track) or $\Phi^\pm \to \text{inv.}$ (disappearing tracks if the charged decay daughter is too soft). While these scenarios are often severely constrained from precision measurements of $\alpha_{\text{QED}}(Q)$ or the electron magnetic moment $(g-2)_e$, we plan to study possible signatures that may have escaped detection so far.

A DEDICATED LLP DETECTOR: GAZELLE

We propose to study the search potential for LLPs with longer lifetimes at a new experiment GAZELLE (GAZELLE is the Approximately Zero-background Experiment for Long-Lived Exotics) at SuperKEKB, to search for LLPs. GAZELLE would be housed in the same building as Belle II and observe the same e^+e^- collisions. The relatively quiet background environment will allow GAZELLE to search for LLPs in a large variety of neutral and charged final states. The low boost of decay products typically results in wide angular separation which will allow a precise LLP mass determination. If the GAZELLE readout is synchronized with the Belle II readout, the visible decay products associated with the production of the LLP can be measured in Belle II and can lead to significant improvements of the LLP mass determination and rejection of backgrounds in GAZELLE. We will study the possibility to use GAZELLE as L1 and/or software trigger for Belle II, which is expected to increase the sensitivity to detect directly produced LLPs that leave little energy deposition in Belle II. Background levels are expected to be small compared to the LHC and beam-dump experiments. One focus will be the optimization of position of shielding against background that arise from K_L^0 decays produced in meson decays. The GAZELLE detector will require a timing resolution of $\mathcal{O}(100\,\text{ps})$ and a position resolution of $\mathcal{O}(10\,\text{cm})$ to detect displaced charged final states. For displaced neutral final states or charged particles with very low momentum, a highly-segmented electromagnetic calorimeter could increase the sensitivity significantly. We plan to include studies of an optional add-on detector that utilizes emulsion/lead brick targets and is positioned in front of GAZELLE to search for neutrinos and very low momentum particles.

In conclusion, we plan to study the LLP reach of Belle II and its connection to dark matter models and work out the complementary with other ongoing and planned experiments. We plan to utilize the full potential of the Belle II sub-detectors to also detect neutral final states which will likely drive the need to develop new reconstruction and trigger algorithms. In the context of the Snowmass process we also plan to contribute a proposal for a new detector, GAZELLE, that would extend the Belle II reach towards longer lifetimes.

* Corresponding authors: torben.ferber@desy.de, westhoff@thphys.uni-heidelberg.de

[1] R. Alemany et al. Summary Report of Physics Beyond Colliders at CERN. 2019. arXiv:1902.00260.
[2] M. Duerr et al. Invisible and displaced dark matter signatures at Belle II. *JHEP*, 02:039, 2020. doi: 10.1007/JHEP02(2020)039.
[3] R. T. D'Agnolo et al. Thermal Relic Targets with Exponentially Small Couplings. *Phys. Rev. Lett.*, 124(15):151801, 2020. doi:10.1103/PhysRevLett.124.151801.
[4] G. Bélanger et al. Dark Matter Abundance from Sequential Freeze-in Mechanism. 2020. arXiv:2005.06294.
[5] M. J. Dolan et al. Revised constraints and Belle II sensitivity for visible and invisible axion-like particles. *JHEP*, 12:094, 2017. doi:10.1007/JHEP12(2017)094.
[6] Search for Axion-Like Particles produced in e^+e^- collisions at Belle II. *submitted to PRL*, 2020. arXiv:2007.13071.
[7] A. Filimonova and other. Probing dark sectors with long-lived particles at Belle II. *Phys. Rev. D*, 101(9):095006, 2020. doi:10.1103/PhysRevD.101.095006.
[8] A. Kachanovich et al. Higgs portal to dark matter and $B \to K^{(*)}$ decays. *Eur. Phys. J. C*, 80(7):669, 2020. doi: 10.1140/epjc/s10052-020-8240-z.
[9] J. Martin Camalich et al. Quark Flavor Phenomenology of the QCD Axion. *Phys. Rev. D*, 102(1):015023, 2020. doi: 10.1103/PhysRevD.102.015023.
[10] E. Kou et al. The Belle II Physics Book. *PTEP*, 2019(12):123C01, 2019. doi:10.1093/ptep/ptz106. [Erratum: PTEP 2020, 029201 (2020)].
[11] R. Essig et al. Constraining Light Dark Matter with Low-Energy e^+e^- Colliders. *JHEP*, 11:167, 2013. doi: 10.1007/JHEP11(2013)167.
[12] S. D. McDermott et al. Dark Photon Decay Beyond The Euler-Heisenberg Limit. *Phys. Rev. D*, 97(7):073005, 2018. doi:10.1103/PhysRevD.97.073005.