EPJ Web of Conferences **312**, 05002 (2024) https://doi.org/10.1051/epjconf/202431205002
FPCP 2024

Searches for Dark Sector Particles at Belle and Belle II

Savino Longo[1,*] on behalf of the Belle and Belle II Collaborations

[1]Department of Physics and Astronomy, University of Manitoba,
30a Sifton Rd, Winnipeg, MB, R3T 2N2, Canada

Abstract. The Belle and Belle II experiment have collected samples of e^+e^- collision data at centre-of-mass energies near the $\Upsilon(nS)$ resonances. These data have constrained kinematics and low multiplicity, which allow searches for dark sector particles in the mass range from a few MeV to 10 GeV. The latest dark sector results by Belle and Belle II, which constrain a variety of dark mediators, are discussed.

1 Introduction

Astronomical and cosmological observations provide indirect evidence that the majority of our universe's matter content corresponds to dark matter [1]. Understanding its nature is one of the highest priority topics in particle physics. Dark sector theories postulate new interactions between a dark sector and the Standard Model via new dark mediators. The dark sector could include dark matter and other new particles, and would not be charged under the Standard Model. Searches for dark sectors focus on detecting the presence of the dark mediator, which facilitates interactions between the Standard Model and particles in the dark sector. The experimental signature depends on the characteristics of the dark mediator. If the dark mediator's dominant decay mode is to dark matter, then this will result in an "invisible" detector signature. If the dark mediator preferentially decays to Standard Model particles then this will produce a "visible" detector signature [2].

High luminosity electron-positron colliders operating at or near the $\Upsilon(4S)$ resonance ($\sqrt{s} \sim 10.6$ GeV), such as Belle and Belle II, provide numerous opportunities for dark sector searches. These experiments can detect dark mediators with mass in the MeV to GeV range through their direct production from the e^+e^- annihilation, or their production in particle decays. The latter takes advantage of the large cross-sections for $B\bar{B}, c\bar{c}$, and $\tau^+\tau^-$ production from the e^+e^- annihilation [3]. The e^+e^- collision environment features minimal collision pile-up, well-known initial collision energy and momentum, and hermetic detectors with high detection efficiency for charged and neutral particles, which allows precise measurements of the missing energy and momentum in an event. This is advantageous to search for invisible and visible dark sector detector signatures. This paper discusses the most recent dark sector searches completed by the Belle and Belle II collaborations.

2 Recent Dark Sector Results from the Belle Collaboration

The Belle Experiment operated at the KEKB asymmetric-energy e^+e^- collider from 1999 to 2010 and collected a total collision dataset of 1040 fb^{-1} at a $\sqrt{s}$ near 10.6 GeV. The Belle

*e-mail: Savino.Longo@umanitoba.ca

detector has a cylindrical geometry and is described in detail in reference [4]. It reconstructs charged particles with a four-layer Silicon Vertex Detector and a small cell Central Drift Chamber. A Time of Flight system surrounding the barrel region, and Aerogel Ring Cherenkov Counter installed in the forward region, are used for charged particle identification. Photons are reconstructed with the electromagnetic calorimeter, which consists of CsI(Tl) scintillation crystals. The outer detector is a μ/K_L^0 detector constructed from alternating layers of Resistive Plate Chambers and iron plates. The iron also serves as the flux return for the 1.5 T magnetic field present in the central region of the detector [4].

2.1 Search for a Dark Leptophilic Scalar

A Dark Leptophilic Scalar refers to a scalar dark mediator with coupling to leptons but not quarks and is denoted as ϕ_L. Its leptophilic nature allows it to evades constraints set by Flavour Changing Neutral Current searches [5–7]. By mixing with the Standard Model Higgs boson, the scalar acquires couplings to the Standard Model leptons that is proportional to their mass. The ϕ_L has been discussed in literature to impact the current muon g-2 anomaly [8] while providing an interaction between the Standard Model and dark matter [6, 7].

The Belle Collaboration search for ϕ_L production uses the channel $e^+e^- \to \tau^+\tau^-\phi_L, \phi_L \to \ell^+\ell^-, (\ell = e, \mu)$ [5]. The analysis requires the τ lepton decay to emit a single charged particle, resulting in an event containing four tracks and missing energy. The ϕ_L can decay promptly or be a long-lived particle, producing a two track vertex displaced from the collision point. The presence of ϕ_L can be inferred by searching for a localized excess in the $m_{\ell\ell}$ distribution. The backgrounds, mainly from τ-pair and $q\bar{q}$ events, are suppressed using a Boosted Decision Tree (BDT) classifier trained on kinematic variables as detailed in reference [5]. Backgrounds remaining after cuts on the BDT output in the electron channel correspond to π^0 Dalitz decays where the π^0 originates from a ρ produced in a τ decay. In the muon channel, the remaining backgrounds at low mass are from $\tau \to 3\pi\nu$ where the $\pi^\pm$ are mis-identified as a muon and at high mass are from $B\bar{B}$ events containing semi-leptonic decays [5].

No significant excess is observed in 626 fb^{-1} of data. Limits on the cross-section for the process $e^+e^- \to \tau^+\tau^-\phi_L$, $\phi_L \to \ell^+\ell^-, (\ell = e, \mu)$ are set at a function of the ϕ_L mass. In the electron channel, limits are set for several different ϕ_L lifetimes [5]. Shown in Figure 1 are the observed upper limits at 90% CL for the ϕ_L coupling constant as a function of its mass. This search covered a similar region in parameter space to a search by the BaBar Collaboration [9] and its results constrain the ϕ_L explanation for the muon g-2 discrepancy for ϕ_L masses below 4 GeV [5].

2.2 Search for Heavy Neutral Leptons Produced in Tau Decays

Heavy Neutral Leptons are predicted by theories that explain neutrino mass generation [10]. When their mass is at the GeV-scale, they can also address the baryon asymmetry of the universe [10]. Heavy Neutral Leptons with enhanced ν_τ coupling are challenging to probe experimentally. The Belle Collaboration took advantage of their large τ-pair production cross section to search for Heavy Neutral Leptons, N, produced in the decay $\tau^- \to N\pi^-$ with $N \to \nu_\tau\mu^+\mu^-$ [11].

In the region of m_N and $|V_{N\tau}|$ parameter space explored by the analysis, the N is predicted to have a macroscopic decay length [11, 12]. The N decay thus produces a two track vertex that is displaced from the collision point. The momentum vector of the reconstructed tracks that form the displaced vertex will not point back to the interaction point due to the missing energy from the neutrino. These unique features are exploited to provide significant background rejection. Additionally, the observable kinematics of the decay of the signal τ allow

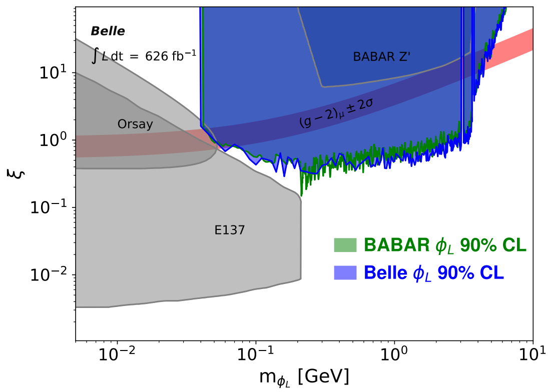

Figure 1. Observed upper limits set by Belle for the ϕ_L coupling constant, ξ , as a function of the ϕ_L mass [5].

the m_N for each candidate to be determined up to two solutions denoted m_+ and m_- [13]. Signal events tend to localize in the region $m_+ = m_- = m_N$ [11].

In 915 fb^{-1} of data no significant excess is observed. The observed upper limits set on $|V_{N\tau}|$ are shown in Figure 2. This analysis probed a higher mass region relative to a BaBar Heavy Neutral Lepton search, which employed a different search strategy that used missing momentum [11, 14].

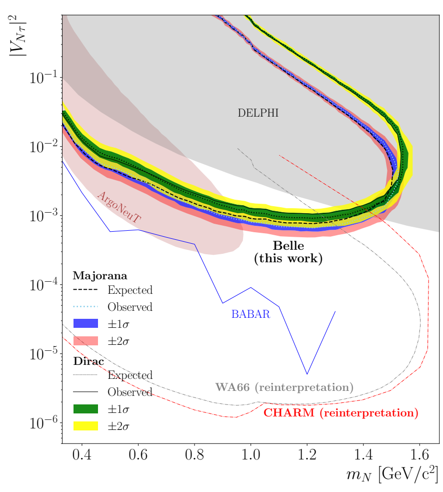

Figure 2. Observed upper limits set by Belle on $|V_{N\tau}|$ as a function of the N mass [11].

3 Recent Dark Sector Results from the Belle II Collaboration

The Belle II Experiment at the SuperKEKB asymmetric-energy collider is a major detector and accelerator upgrade relative to the previous generation of B-Factories. The experiment began operations in 2019 and has collected a total dataset to-date of 498 fb^{-1} with a target total dataset of 50 ab^{-1} over the experiment's lifetime.

The Belle II detector reconstructs charged particles with a 2-layer pixel detector followed by a 4-layer double-sided silicon strip detector and a drift chamber that has larger radius relative to Belle. For charged particle identification, the barrel region is instrumented with a Time of Propagation counter and the forward region has a Aerogel Ring-Imagining Cherenkov counter. The CsI(Tl) calorimeter uses upgraded readout electronics with waveform sampling to provide position, energy, time, and pulse shape information. The outer detector consists of scintillating strips and resisitve plate chambers alternating with iron plates for muon detection and provides flux return for the 1.5 T magnetic field [3].

Beyond the detector improvements, dark sector searches at Belle II significantly benefit from the implementation of new trigger lines to target low-multiplicity final states. This includes triggers for a single muon, single photon, and recently a displaced vertex High-Level Trigger for Long-Lived Particles. These new trigger lines open several unique dark sector search opportunities with the accumulating Belle II dataset.

3.1 Search for Dark Mediator Decaying to $\tau^+\tau^-$

Several dark sector models discussed in literature propose light dark mediators with enhanced couplings to heavier leptons [15–18]. Dark mediators that decay to a pair of τ leptons however are challenging to reconstruct experimentally due to the neutrinos emitted in τ decays. To overcome this challenge, we search for a $\tau\tau$ resonance in the channel $e^+e^+ \to \mu^+\mu^-X, X \to \tau^+\tau^-$. The dark mediator, X, can be an Axion-Like Particle, Dark Scalar, or Z' boson, and is produced by radiating off a final state muon. Its presence can be detected by using energy-momentum conservation to compute mass of the particle recoiling against the muons. For signal, the recoil mass distribution will peak at the mass of the dark mediator [19].

The analysis requires the τ decays to each contain a single charged particle, resulting in a event with four tracks and missing energy. Backgrounds from $e^+e^- \to \tau^+\tau^-(\gamma)$ and $e^+e^- \to q\bar{q}(\gamma)$ are suppressed with a neural network trained on kinematic quantities. Eight neural networks are trained, each covering a separate region of recoil mass [19].

No significant excess is observed in 62.8 fb^{-1} of data. Figure 3 shows the upper limits set on the mass vs. coupling for the Axion-Like Particle and Dark Scalars interpretations [19]. In both cases the analysis excludes previously unexplored regions of parameter space. As the dataset size is the primary limitation of the coupling reach of this search, this analysis will benefit from future Belle II data [19].

3.2 Search for Dark Mediator Decaying to $\mu^+\mu^-$

Dark mediators with a significant branching fraction to decay to a pair of muons arise often in dark sector models that can address the muon g-2 anomaly [8]. Examples include a dark Z' from an $L_\mu - L_\tau$ extension of the Standard Model [15, 16, 20] and a muonphilic scalar [20–22]. We search for the production of such mediators in the channel $e^+e^- \to \mu^+\mu^-X$, $X \to \mu^+\mu^-$ [20]. Events containing four tracks with total energy in the centre-of-mass frame consistent with the collision $\sqrt{s}$ are selected. Three of the four tracks are required to be identified as muons. The decay $X \to \mu^+\mu^-$ can be identified by searching for a narrow peak in the distribution of the invariant mass of pairs of muons [20].

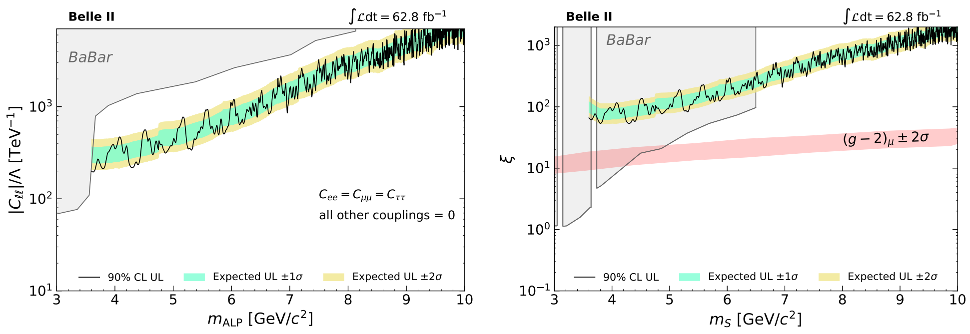

Figure 3. Observed upper limit set by Belle II in the $e^+e^+ \to \mu^+\mu^- X, X \to \tau^+\tau^-$ search on parameter space for Axion-Like Particles (left) and Dark Scalars (right) [19].

The main background that remains after the above selection is from the double-photon-conversion process $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$. The kinematics of the muons in this background however are distinct from the signal process. A neural network is trained to exploit this to provide further background suppression [20].

A collision dataset of 178 fb^{-1} is searched and no significant excess is observed. Shown in Figure 4 are the upper limits that are set on the coupling strength as a function of mass for a muonphilic scalar interpretation and a $L_\mu - L_\tau$ extension Z'. This analysis set the first limits on the muonphilic scalar. In both dark mediator cases, regions of parameter space that could address the muon g-2 anomaly are ruled out. The reach of the limits are limited by the sample size, demonstrating this search will benefit from future Belle II data [20].

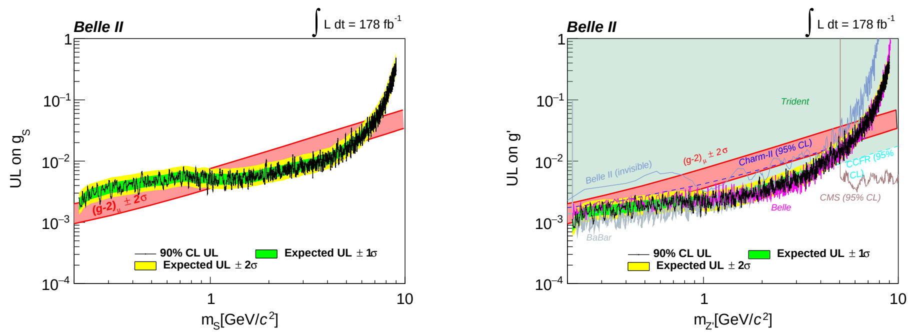

Figure 4. Observed upper limits set by Belle II on the mass vs. coupling for muonphilic scalar (left) and $L_\mu - L_\tau$ extension Z' (right) [20].

4 Conclusion

The clean e^+e^- collision environment at Belle and Belle II presents unique capabilities for dark sector searches. The most recent dark sector searches performed by the Belle and Belle II Collaborations constrained a range of dark sector mediators including dark scalars, $L_\mu - L_\tau$ extension Z' bosons, heavy neutral leptons, and axion-like particles. Belle II is taking advantage of its new low-multiplicity triggers, which have opened new dark sector search opportunities. The limits presented by Belle II are statistically limited and are yet to use Belle II's full recorded dataset. The searches presented, and additional ongoing dark sector searches by Belle II, will benefit from additional data to be collected in its next data-taking period.

References

[1] S. Navas *et al.* (Particle Data Group), Phys. Rev. D **110**, 030001 (2024)
[2] S. Gori *et al.* arXiv:2209.04671 (2022)
[3] E. Kou *et al.* Prog. Theor. Exp. Phys. **2019**, 12 123C01 (2019)
[4] A. Abashian *et al.* (Belle collaboration), Nucl. Instrum. Meth. A 479, 117 (2002)
[5] D. Biswas *et al.* (Belle Collaboration), Phys. Rev. D **109**, 032002 (2024)
[6] P. J. Fox and E. Poppitz, Phys. Rev. D **79**, 083528 (2009)
[7] C.Y. Chen *et al.* , Phys. Rev. D **93**, 035006 (2016)
[8] B. Abi *et al.* (Muon g-2 Collaboration), Phys. Rev. Lett. **126**, 141801 (2021)
[9] J. P. Lees *et al.* (BABAR collaboration), Phys. Rev. Lett.**125**, 181801 (2020)
[10] S. Davidson, E. Nardi, and Y. Nir, Phys. Rep. **466**, 105 (2008)
[11] M. Nayak *et al.* (Belle Collaboration) Phys. Rev. D **109**, L111102 (2024)
[12] K. Bondarenko *et al.*, J. High Energy Phys. 11, 032 (2018)
[13] C. O. Dib *et al.*, Phys. Rev. D **101**, 093003 (2020)
[14] J. P. Lees *et al.* (BABAR Collaboration), Phys. Rev. D **107**, 052009 (2023)
[15] B. Shuve and I. Yavin, Phys. Rev. D **89**, 113004 (2014)
[16] W. Altmannshofer *et al.*, JHEP **12**, 106 (2016)
[17] B. Batell *et al.*, Phys. Rev. D **95**, 075003 (2017)
[18] M. Bauer *et al.*, JHEP. **2022**, 56 (2022)
[19] I. Adachi *et al.* (Belle II Collaboration) Phys. Rev. Lett. **131**, 121802 (2023)
[20] I. Adachi *et al.* (Belle II Collaboration), Phys. Rev. D **109**, 112015 (2024)
[21] D. Forbes *et al.* , Phys. Rev. D **107**, 116026 (2023)
[22] R. Capdevilla *et al.* High Energy Phys. 04, **129** (2022)