Searches for dark sector particles at Belle and Belle II

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Abstract. Belle and Belle II experiments gathered around 1.5 ab^{-1} of dataset near $\Upsilon(nS)$ resonances, which have constrained kinematics and low multiplicity suitable for dark sector searches. Both experiments have excellent sensitivity for dark sector searches in the few MeV - 10 GeV range. The latest dark sector searches performed by both collaborations, which constrain a variety of dark mediators, are discussed.

Keywords: Dark sector, Dark mediators, Belle, Belle II.

1 Introduction

The "dark sector" is a theoretical extension of particle physics that suggests the existence of hidden particles and forces beyond the Standard Model (SM). Searches for dark sectors focus on detecting the presence of various dark sector mediators through different SM and dark sector portals [1].

The Belle and Belle II experiments, which are previous and current generation high luminosity asymmetric electron-positron colliders operating at or near the $\Upsilon(4S)$ resonance at the SuperKEKB collider in Japan, provide unique opportunities for exploring the dark sector particles. These experiments can detect dark mediators with mass, particularly in the few MeV-GeV ranges, where certain dark sector particles might reside. The well-known initial collision energy, minimal collision pile-up, and high detection efficiency for charged and neutral particles allow precise measurements of the missing energy and momentum in an event, which is advantageous to search for invisible and visible dark sector detector signatures [2]. This article discusses the most recent dark sector searches completed by the Belle and Belle II collaborations.

2 Recent Dark Sector Results

Search for a dark leptophilic scalar at Belle [3]

A dark leptophilic scalar, ϕ_L, refers to a dark scalar mediator that couples only to leptons. In this model, ϕ_L mixes with SM Higgs boson and produces coupling proportional to lepton masses [4]. Depending on the coupling strength, ϕ_L could be long-lived or decay promptly.

The Belle collaboration looks for the process $e^+e^- \to \tau^+\tau^-\phi_L(\to l^+l^-)$, $l = e, \mu$. For the scalar mass m_{ϕ_L} below the dimuon threshold they investigated the $\phi_L \to e^+e^-$ and explored the several different lifetimes upto 0.1 GeV/c^2. For mass above the dimuon threshold, they investigated $\phi_L \to \mu^+\mu^-$ promptly upto 6.5 GeV/c^2. The analysis requires the τ lepton to decay in a single charged particle, resulting in an event containing four tracks and missing energy in the final state. The main source of background is $\tau^+\tau^-$ and $q\bar{q}$ events. Bhabha, $\mu^+\mu^-$, and the two-photon processes are suppressed based on the rectangular selection criteria on the two-dimensional plane of missing energy and momentum. Further Boosted Decision Trees are used to suppress the remaining backgrounds, and the classifier response is used to define different control regions for validation purposes.

No significant excess was observed in 626 fb^{-1} of data. 90% Confidence Level (CL) upper limits on the production cross-section $\sigma(e^+e^- \to \tau^+\tau^-\phi_L(\to l^+l^-))$ and coupling constant ξ is shown in Fig. 1a. The limits are, on average, 19% more constraining than BaBar and ruled out the leptophilic scalar with mass less than 4 GeV that could explain the observed excess in muon $g - 2$ [3].

Search for heavy neutral leptons in τ decays at Belle [5]

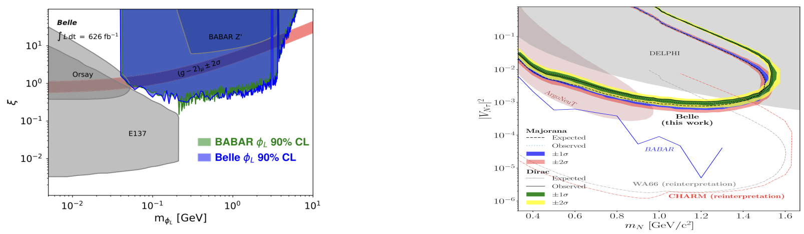
Heavy neutral leptons, N, are predicted by different beyond-SM theories to explain the neutrino flavor oscillations. The Belle Collaboration searched for N, which predominantly mixes with the τ neutrino and considers couplings with other neutrinos to be negligible [6]. N could be long-lived due to the small coupling. They search for the production of N in the decay $\tau^- \to \pi^- N$, where N undergoes the weak-neutral-current decay $N \to \mu^+\mu^-\nu_\tau$. Thus, the signal signature is a pion that originates from the interaction point (IP) and a $\mu^+\mu^-$ pair originating from a displaced vertex, which is significantly displaced from the IP.

The momentum vector of reconstructed tracks of $\mu^+\mu^-$ pair will not point to the IP due to large missing energy, which helps to reduce backgrounds significantly. The main SM background $K^0_S \to \pi^+\pi^-$ is vetoed (420-520 MeV/c^2). The constraints of the signal τ decay allow the m_N for each candidate to be determined up to two solutions denoted by m_+ and m_-. The Signal events tend to localize in the region $m_+ = m_-$.

The mass region $300 < m_N < 1600$ MeV/c^2 was investigated with 915 fb^{-1} of data, and no significant excess was observed. The 95% CL upper limits on coupling are shown in Fig. 1b. This analysis probed a higher mass region relative to the BaBar search and implemented a different search strategy [5].

Search for dark mediator decaying to $\mu^+\mu^-$ at Belle II [7]

This analysis search for the process $e^+e^- \to \mu^+\mu^- X$, $X \to \mu^+\mu^-$, where X could be a Z' [8] or a muonphilic scalar [(S) [9]. Two different models, $L_\mu - L_\tau$ and muonphilic scalar, are probed. The search for the Z' was already performed by BaBar [10] and Belle using $\approx$ 2-3 times more datasets targeted for this analysis.



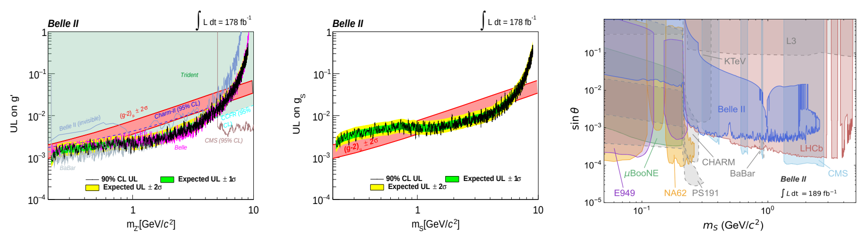
(a) Dark Leptophilic Scalar [3]. (b) Heavy Neutral Leptons [5].

Fig. 1: Observed upper limits set by Belle on coupling constant, ξ, for ϕ_L (a) and $|V_{N\tau}|^2$ (b) as a function mass.

The aim was to obtain a similar or better performance by aggressive background suppression using machine learning techniques. The muonphilic scalar model was investigated for the first time.

0.212 - 9 GeV/c^2 mass region was explored. Events containing only four tracks with total energy consistent with collision energy in the center-of-mass frame are selected. Three of the four tracks are required to be identified as muons, and the other track is not an electron. The remaining backgrounds are further suppressed using Neural Networks by exploiting different kinematic and angular variables.

No significant excess was found in the 178 fb^{-1} dataset; a competitive 90% CL upper limit for the coupling constant (g') was set, and the result was similar to previous searches despite using a smaller available dataset. In both dark mediator cases, regions of parameter space that could address the muon $g-2$ anomaly are mostly ruled out, as shown in Fig. 2a and 2b [7].



(a) $L_\mu - L_\tau(Z')$ [7]. (b) muonphilic scalar [7]. (c) long-lived scalar [11].

Fig. 2: Observed upper limits set by Belle II on coupling constant for Z' (a) and muonphilic scalar (b). (c) shows the exclusion regions in the plane of the sine of the mixing angle θ as a function of long-lived scalar mass.

Search for long-lived scalar in B decays at Belle II [11]

Different extensions of the SM predict the existence of the light spin-0 (scalar) S that may give mass to the dark matter particles. Such a new scalar would mix with the SM Higgs boson through a mixing angle θ, and for weaker couplings [12], S could be long-lived. The analysis searched for the long-lived S in B-meson decays mediated by $b \to s$ quark transition. The search was performed model independently and the targeted 189 fb^{-1} of dataset. For the charged mode $B^+ \to K^+S$, and for the neutral mode $B^0 \to K^{*0}(K^+\pi^-)S$ was studied, where $S \to x^+x^-,\ x = e,\ \mu,\ \pi,\ K$ and forms a displaced vertex. The signal B-meson is fully reconstructed by the tracks originating from the interaction point and a vertex separated macroscopic distance (very far from the interaction point). Most of the prompt SM backgrounds are rejected by the kinematics requirements for the displaced nature of the signal, and the remaining backgrounds are reduced by requiring kinematics similar to B-meson expectations. The only long-lived SM background is due to K_s^0 candidates, whose mass region is vetoed and used as a control sample to evaluate the systematics.

The mass region, 22 MeV/c^2 - 4.78 GeV/c^2 for the charge transition, and 22 MeV/c^2 - 4.38 GeV/c^2 for the neutral transition was explored. No significant excess was found, and the first model-independent 95% CL upper limits on the product of branching fraction for exclusive $B^0 \to K^{(*)}S; S \to$ hadrons as a function of mass and lifetime (cτ) given at the level of 10^{-7}. The interpretation as dark scalar with the sine of the mixing angle θ with SM Higgs is given in Fig. 2c together with previous results [12].

3 Summary

The dark sector searches performed by both experiments produced competitive and world-leading measurements, strongly constraining the parameter space of dark sector mediators. The studies performed by Belle II used limited datasets and will benefit from additional data to be collected in its next data-taking period. With many more measurements ongoing, Belle II will play a central role in the field of light-dark matter searches in the coming years.

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