PROCEEDINGS OF SCIENCE

Dark sector searches at Belle II

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The Belle II experiment at the SuperKEKB e^+e^- collider has a unique sensitivity for a broad class of dark sector particles with masses in the MeV–GeV range. This paper presents the latest results from Belle II searches for dark sector mediators and their decays to dark or Standard Model particles using the dataset collected until July 2022.

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1. Introduction

The hypothesis of a dark sector (DS), i.e. a set of fields and particles neutral under the Standard Model (SM), has emerged as a possible explanation for the Dark Matter (DM) puzzle, as well as a solution to still open fundamental questions such as the lightness of the neutrino masses, the baryon-antibaryon asymmetry in the universe, the strong-CP problem, or as explanation of experimental anomalies such as the discrepancy between theoretical and experimental values for the anomalous magnetic moment of the muon. Dark sector particles would only feebly couple to the SM particles via so-called "portals", i.e. mediating interaction particles that possess both SM and dark sector quantum numbers [1]. Depending on the properties of portal mediators, few models have been proposed: the "vector" portal which introduces a new vector gauge mediator, e.g. a dark photon A' or a Z'; the "neutrino" portal where a sterile neutrino interacts with SM neutrinos through a Yukawa coupling term; the "scalar" portal where a Higgs-like mediator has a Yukawa coupling with the SM Higgs boson; or the "pseudo-scalar" portal where the interaction is mediated by axions, or axion-like particles. The dark sector may contain new light particles well below the weak scale, only feebly interacting with the ordinary matter, so they could easily have escaped previous experimental research. Experiments at the intensity frontier offer a unique window into the physics of the dark sectors. This paper aims to give an overview of the dark sector searches performed at the Belle II experiment at the SuperKEKB e^+e^- collider, with the data collected until July 2022.

2. Belle II and SuperKEKB

Belle II [2] is a full upgrade of the Belle experiment operating at the KEK laboratory. It is located at the interaction region of the SuperKEKB e^+e^- energy-asymmetric collider [3] and operates mainly at a center-of-mass energy of 10.58 GeV. Belle II has collected 428 fb^{-1} of data until July 2022, and, after a first long shutdown period during which both accelerator and detector have been improved, it will resume data collection in February 2024.

While the primary purpose of Belle II is to study the properties of B-mesons and their rare decays, the experiment is ideally suited for a wide range of new physics searches, which include the existence of light DS mediators and their interactions with SM particles. Belle II boats a well-defined initial state kinematic, a near hermetic detector, excellent resolutions, high reconstruction efficiencies for neutral particles, and specifically designed triggers for low multiplicity final states (most notably, the single-photon, single-track, and single-muon triggers). These features guarantee a unique capability to probe dark sector signatures involving missing energy final states.

3. Dark sector searches

The phenomenology of dark sector particle production in e^+e^- collisions is quite rich and depends on the specific models. Dark sector light mediators can either be directly produced in e^+e^- collisions or emerge from the decay of mesons (such as B, D) or fermions (such as τ). Depending on the DS mediator mass hypothesis, the coupling strength with the SM, and the existence of kinematically accessible DM, invisible or visible (possibly displaced) decays are expected. A brief description of Belle II's recent results is presented below.

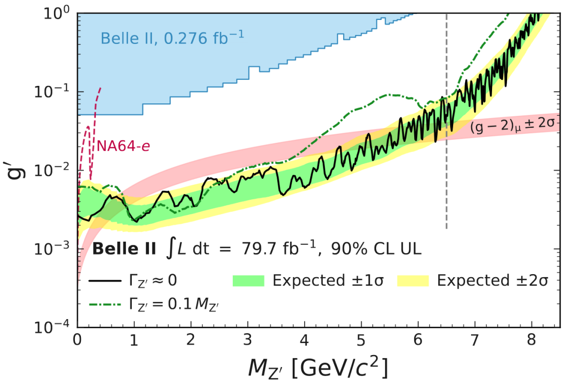

Figure 1: Observed 90% CL upper limits on the coupling g' for the fully invisible $L_\mu - L_\tau$ model as functions of the Z' mass for the cases of negligible mass width $\Gamma_{Z'}$ and for $\Gamma_{Z'} = 0.1 M_{Z'}$. The red band in the top plot shows the region that explains the muon anomalous magnetic moment $(g-2)_\mu \pm 2\sigma$.

3.1 Invisible Z'

Belle II searched for the invisible decay of a Z' boson which couples only to the second and third generation of leptons (according to the $L_\mu - L_\tau$ model [4]) in the process $e^+e^- \to \mu^+\mu^- Z'$, $Z' \to$ invisible, using 79.7 fb^{-1} of data [5]. The Z' candidate kinematics is reconstructed as the recoil to the two muons. The analysis strategy relies on searching for a bump in the invariant mass distribution of the system recoiling against the two muons, in events where nothing else is detected. The main background are QED processes, namely $e^+e^- \to \mu^+\mu^-(\gamma)$, $e^+e^- \to \tau^+\tau^-(\gamma)$, and $e^+e^- \to e^+e^-\mu^+\mu^-$ events. The background suppression strategy exploits kinematic variables that are sensitive to the signal production mechanism via radiation off by one muon, fed into a neural network trained simultaneously for all the Z' mass hypotheses [6]. Signal yields are extracted from template fits in bins of the recoil squared mass and the recoil polar angle. No significant excess consistent with the signal hypotheses is observed and 90% confidence level (CL) upper limits on the cross-section $\sigma(e^+e^- \to \mu^-\mu^- Z', Z' \to \text{invisible})$ are established. Additionally, upper limits on the coupling constant g' as a function of the Z' mass, within the $L_\mu - L_\tau$ framework and assuming $\mathcal{B}(Z' \to \chi\bar{\chi}) = 1$, have been computed. These results, shown in Figure 1, exclude the region favoured by the $(g-2)_\mu$ anomaly for the range $0.8 < M_{Z'} < 5$ GeV/c^2.

3.2 Dark photon and invisible dark Higgs

The simultaneous production of a dark photon A' and a dark Higgs h' via dark higgsstrahlung production $e^+e^- \to A'h'$ has been searched at Belle II with the data collected during 2019, corresponding to 8.34fb^{-1} [7]. The search focused on the case where the dark photon decays into muons, while the dark Higgs is long-lived ($M_{h'} < M_{A'}$), leaving no visible signal in the detector. For signal events, a peak both in the dimuon invariant mass and in the invariant mass of the system recoiling against the two muons is expected. The two-dimensional mass phase space is scanned looking for a local excess with respect to the expected backgrounds, estimated with a counting technique in mass windows of size proportional to the experimental resolution. Background sources are the same as for the invisible Z' analysis and part of the analysis selections are then very similar. The final step of the background suppression exploits the helicity angle

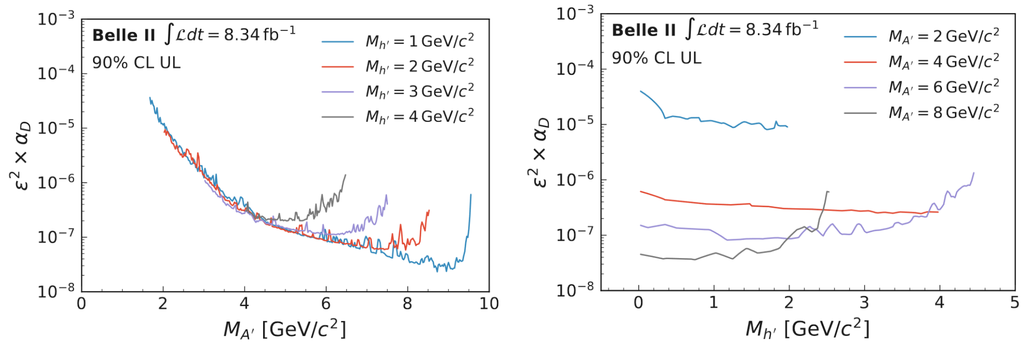

Figure 2: Observed 90% CL upper limits on the coupling constant product $\epsilon^2 \times \alpha_D$ (left) as functions of $M_{A'}$ for four values of $M_{h'}$ and (right) as functions of $M_{h'}$ for four values of $M_{A'}$.

distribution, defined as the angle in the dimuon rest frame between the momentum direction of the c.m. system and the momentum direction of the μ^-. Belle II set 90% CL upper limits on the dark higgsstrahlung cross-section and translated them in terms of the coupling constant product $\varepsilon^2 \times \alpha_D$, where α_D is the coupling constant of the dark sector and ε is kinetic mixing with the SM hypercharge field. These results, shown in Figure 2, are world-first in the explored mass range.

3.3 Dark bosons decay $X \to ll$ in 4-lepton final states

Belle II searched for a $X \to \tau^+\tau^-$ resonance in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$ events, with τ decaying to one charged particle, using 62.8 fb^{-1} of data [8]. The X boson has been interpreted as a Z', a leptophilic dark scalar S, or an axion-like particle (ALP), and searched as a narrow enhancement in the invariant mass of the system recoiling against two oppositely charged muons, in four-track events with zero net charge. Standard Model backgrounds are suppressed by exploiting kinematic variables sensitive to the X production mechanism as final-state-radiation off one of the two muons fed into multiple neural networks, trained in different X mass regions. The recoil mass spectrum is fit in steps corresponding to half of the mass resolution, with the expected background derived directly from the fit to data. No significant excess is found and 90% CL upper limits are set on the cross-section $\sigma(e^+e^- \to \mu^+\mu^- X)\times\mathcal{B}(X \to \tau^+\tau^-)$, and on the coupling constants for the Z', S, and ALP models. This search sets the world's best constraints on the coupling for the leptophilic scalar for masses above 6.5 GeV/c^2 and on the axion-like particle for the entire explored mass range, as shown in Figure 3.

Belle II searched also for a $X \to \mu^+\mu^-$ resonance in $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$ events, where X could be a Z' or a muonphilic scalar S, using 178 fb^{-1} of data. In the case of signal events, a narrow enhancement in the dimuon mass distribution in four-track events with zero net charge and no extra energy is expected. The dominant backgrounds come from SM four-muon final-state processes, which are suppressed by using neural networks that exploit the kinematic characteristics of the signal (final-state radiation off one of the two muons and the presence of a resonance in both the muon pair candidate and its recoil system). The networks are trained in different X-mass ranges. After performing unbinned maximum likelihood fits on the di-muon mass distribution, no significant excess has been found, and 90% CL upper limits have been set on the cross-section $\sigma(e^+e^- \to X)\times\mathcal{B}(X \to \mu^+\mu^-)$ and then translated in terms of upper limits for the coupling

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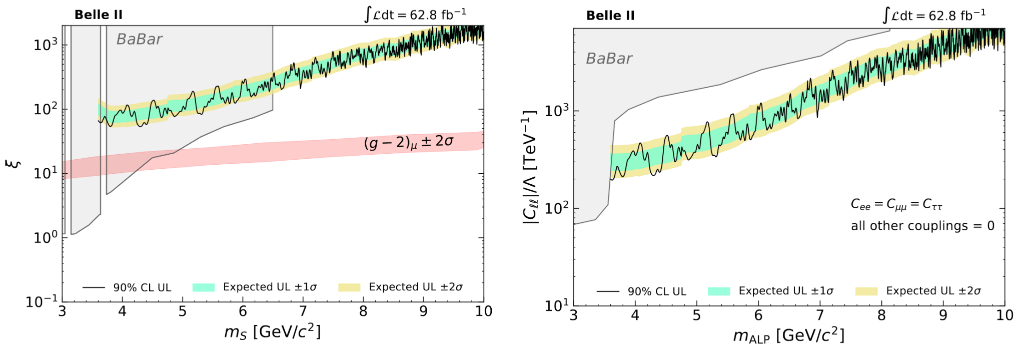

Figure 3: Observed 90% CL upper limits as functions of mass on (left) the leptophilic scalar coupling ξ, and on (right) the ALP coupling to leptons $|C_{\ell\ell}|/\Lambda$ in the hypothesis of equal couplings to the three lepton families and zero couplings to all other particles.

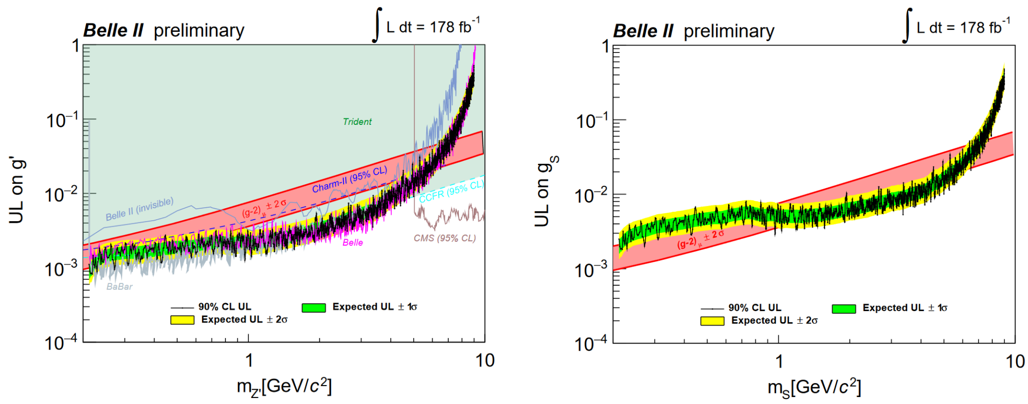

Figure 4: Observed 90% CL upper limits on (left) the $L_\mu - L_\tau$ model coupling g' and on (right) the muonphilic scalar model coupling g_S.

constants, as shown in Figure 4. Competitive results with the existing limits on the visible Z' coupling, and first limits for the muonphilic scalar model from a dedicated search have been set.

3.4 Long-lived scalar in B-meson decays

Using data collected during 2019-2021, long-lived (pseudo-)scalar particles S decaying into two oppositely charged tracks x^+x^- have been searched in B meson decays involving $b \to s$ quark transitions, with $x = e, \mu, \pi, K$ [9]. The analysis strategy relies on searching for a bump in the invariant mass of tracks coming from a displaced vertex accompanied by a charged kaon (and possibly a pion). The kinematics of the $SK^\pm$ system is required to be consistent with that of a B decay. The signal is extracted with extended maximum likelihood fits to the reduced invariant mass $m_S = \sqrt{M^2_{S\to xx} - 4m^2_x}$. The main background source is from K^0_S, whose mass region is excluded from the search and used as control sample in data to evaluate systematic uncertainties. No significant excess is found, and 95% CL upper limits are computed on the product $\mathcal{B}(B \to KS)\times\mathcal{B}(S \to x^+x^-)$ for different lifetime hypotheses, and used to constrain the $\sin\theta - \mathrm{m_S}$ parameter space, being θ the mixing angle of a dark Higgs scalar with the SM Higgs boson, as

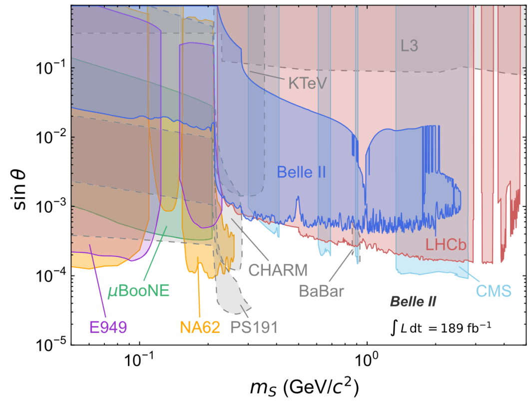

Figure 5: Exclusion regions in the plane of the sine of the mixing angle θ and scalar mass M_S from the Belle II analysis (blue) together with existing constraints.

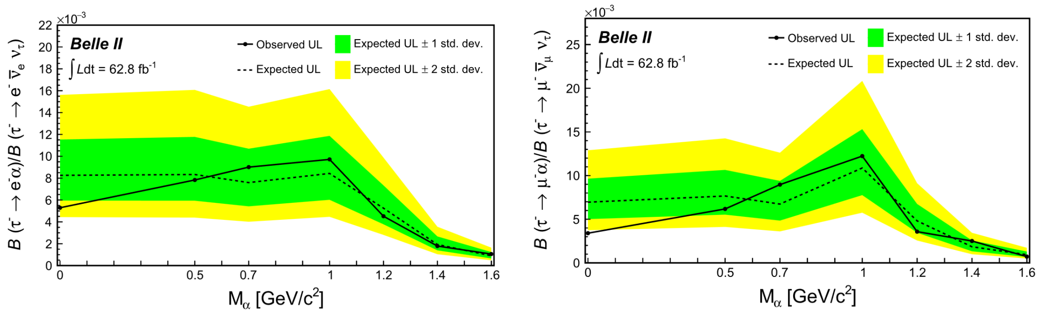

Figure 6: Upper limits at 95% CL on the branching-fraction ratios $\frac{B(\tau^- \to e^- \alpha)}{B(\tau^- \to e^- \bar{\nu}_e \nu_\tau)}$ (left) and $\frac{B(\tau^- \to \mu^- \alpha)}{B(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}$ (right) as a function of the α mass, as well as their expectations from a background-only hypothesis.

shown in Figure 5.

3.5 Invisible boson in tau-lepton decays

Belle II searched for an invisible boson α in lepton flavor violating τ decays in $e^+e^- \to \tau^+(\to \ell^+\alpha)\tau^-(\to \pi^-\pi^+\pi^-\nu_\tau)$ events (along with charge conjugates) using 62.8 fb^{-1} of data [10]. The analysis relies on searching for a narrow peak in the distribution of the lepton energy in the signal τ rest frame (expected for a two-body decay of the signal τ lepton), while accounting for a smooth contribution from the irreducible background of $\tau \to \ell\nu\bar{\nu}$ decays. The rest frame of the signal τ lepton is approximated using half of the collision energy $\sqrt{s}/2$ as its energy and the direction opposite to the reconstructed tag τ lepton ($\tau \to 3\pi\nu_\tau$) as its momentum direction. No signal has been observed, and 95% CL upper limits on $\mathcal{B}(\tau^- \to \ell^-\alpha)/\mathcal{B}(\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau)$, as a function of the α mass, have been set. These results, shown in Figure 6, represent the most stringent limits in these channels to date.

4. Conclusions

This paper summarised the most recent outcomes from Belle II dark sector searches, that brought to world's leading or unique results. Over the next decade, Belle II will collect two orders

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of magnitude more data than it already had. With this vast data set Belle II will have a unique sensitivity to dark sector searches [11], complementary to that of higher-energy experiments.

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