PROCEEDINGS OF SCIENCE

Recent results on dark sector physics at Belle II

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The possibility of a dark sector weakly coupling to Standard Model (SM) particles through new light mediators is explored at the Belle II experiment. We present here the latest results from searches for a long-lived (pseudo-)scalar particle in rare B decays; for a di-tau resonance in $\mu\mu\tau\tau$ final states and a complementary Belle result on a dark leptophilic scalar in τ decays. Moreover we show the search for a Z′ boson decaying invisibly and the most recent study of the search for a di-muon resonance in four-muon final states. These studies are performed on samples from data collected by the Belle II detector during 2019-2021 data taking.

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1. Introduction

A variety of astrophysical observations suggest the existence of the Dark Matter (DM), consisting of particles that do not interact through strong or electromagnetic forces. The lack of evidence for non-Standard Model (SM) physics at the electroweak scale drives us to the possibility that DM and particles mediating its interaction with the SM particles may have a mass at or below the GeV scale. In this scenario, particles interact feebly with ordinary matter through a limited number of possible "portals",where the type of portal depends on the mediator: vector portal, pseudo-scalar portal, scalar portal, neutrino portal. The efforts to detect dark matter in the sub-GeV mass bracket as well as the particle mediating the interactions with SM states, have been actively pursued at fixed target experiments and with high intensity, low-energy colliders. The features that will be briefly described in the following, allow Belle II to lead in this field. Belle II [1, 2] is a full upgrade of the Belle experiment located at the KEK laboratory (Tsukuba, Japan). It is built around the interaction region of SuperKEKB, an asymmetric e^+e^- collider that operates at a center-of-mass energy of 10.58 GeV, which corresponds to the Υ(4S) resonance mass. The higher beam currents, the smaller interaction region with respect to its predecessor, and the usage of the large crossing-angle nano-beam scheme allow SuperKEKB unprecedented instantaneous luminosities. Furthermore, Belle II is a fitting environment to search for dark matter particles and mediators, thanks to its charged and neutral particle reconstruction performance and dedicated triggers.

2. Recent dark sector results

Search for a long-lived (pseudo-)scalar particle in b→s transitions [3]. Extensions of the SM allow for the existence of new particles produced in rare B meson decays involving $b \to s$ transitions. The first model-independent upper limits on long-lived (pseudo-)scalar particles decaying into visible final states of two oppositely charged leptons or hadrons are set using a data set of 190 fb^{-1} collected during 2019-2021 data-taking period. We search for $B \to K^{(*)}S$ events selecting candidates for $S \to \ell^+\ell^-$, h$^+$h$^-$ decays, with ℓ= e, μ and h = π, K, to form a displaced vertex, accompanied by a charged kaon (and additionally a pion for the decay $B^0 \to K^{*0}(\to K^+\pi^-)S$). The combined $K^{(*)}$ meson are required to satisfy the B kinematics constraints. The signal is extracted with extended maximum likelihood fits to the reduced invariant mass $m_S = \sqrt{M^2_{S\to xx} - 4m^2_x}$, in order to improve the modeling at the threshold. The only long-lived SM background is due to K^0_S candidates, whose mass region is vetoed and used as control samples in data to evaluate systematic uncertainties. No significant excess is found and 95% confidence level (CL) upper limits are computed on the product $\mathcal{B}(B \to K_S) \times \mathcal{B}(S \to x^+x^-)$ as a function of the searched new particle mass m_S and for different lifetimes, $c\tau$ (Figure 1). Figure 2 shows the exclusion region in the plane of the sine of the mixing angle with the SM Higgs boson θ, versus the scalar mass m$_S$, together with previous results.

Search for an invisible Z′ [4]. The Z′ is a light gauge boson predicted by the $L_\mu - L_\tau$ model [5, 6], according to which the Z′ interacts only with the second and third generation of leptons. This model could explain the long-standing (g-2)$_\mu$ anomaly [7], the observed DM relic abundance and other flavor anomalies. We search for $e^+e^- \to \mu^+\mu^-$Z′ events, where the Z′ is radiated off one of the

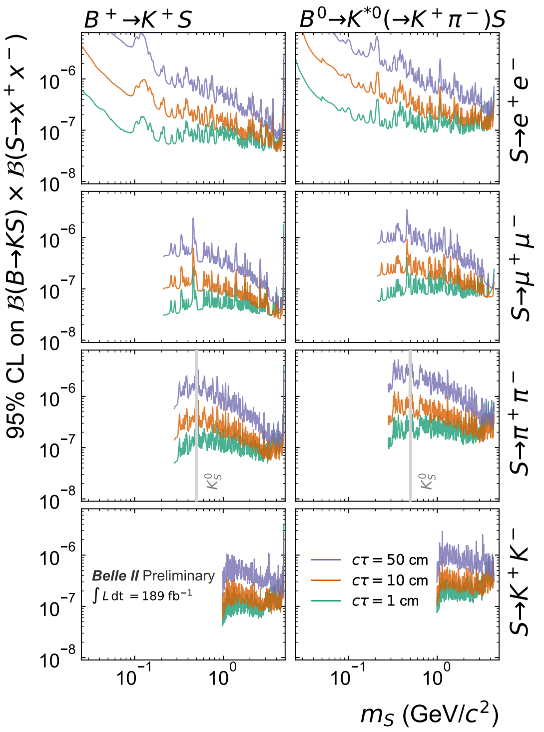

Figure 1: 95 % CL upper limits on the product $\mathcal{B}(B^+ \to K^+S) \times \mathcal{B}(S \to x^+x^-)$ (left) and $\mathcal{B}(B^0 \to K^{*0}(\to K^+\pi^-)S) \times \mathcal{B}(S \to x^+x^-)$ (right) as a function of the scalar mass m_S for three lifetimes [3].

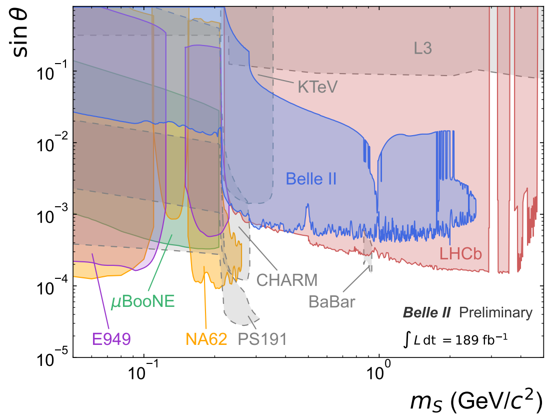

Figure 2: Exclusion regions in the plane of the sine of the mixing angle θ and scalar mass m_S from [3] (blue) together with existing constraints.

muons and decays to an invisible final state with a branching fraction between 33% and 100%. If DM candidates are kinematically accessible, $\mathcal{B}(Z'\to \chi\bar{\chi})\sim 100\%$. The analysis strategy is to search for a bump in the invariant mass distribution of the recoil against the two muons (Figure 3), in events where nothing else is detected. The main background are QED processes, namely radiative di-lepton and four-lepton final states. The kinematic properties of the signal that are specific of the production mechanism are fed into a neural-network trained simultaneously for all Z' masses. Signal yields are extracted from template fits to the recoil mass squared, in bins of recoil polar angle. We find no excess in $\sim$80 fb^{-1} of data and set 90% CL upper limits on the cross section $\sigma(e^+e^- \to \mu^+\mu^- Z', Z' \to$ invisible), translated into upper limits on the coupling constant g$'$ for the $L_\mu - L_\tau$ model as a function of the Z' mass. The latter, assuming $\mathcal{B}(Z' \to \chi\bar{\chi}) = 100\%$ are shown in Figure 4. These results exclude the region favored by the (g - 2)$_\mu$ anomaly for the range 0.8 < M(Z') < 5 GeV/c^2.

Search for a $\tau\tau$ resonance in $\mu\mu\tau\tau$ final states [8]. A similar strategy with respect to the invisible Z' analysis is employed in this case, where we look for a narrow bump in the mass distribution of the recoil against two muons, in events where a τ pair is reconstructed in τ decays to one charged particle and any number of neutrals. Properties of the signal as final state radiation and di-tau resonant process are exploited in multi-layer perceptron neural networks to suppress the QED background,

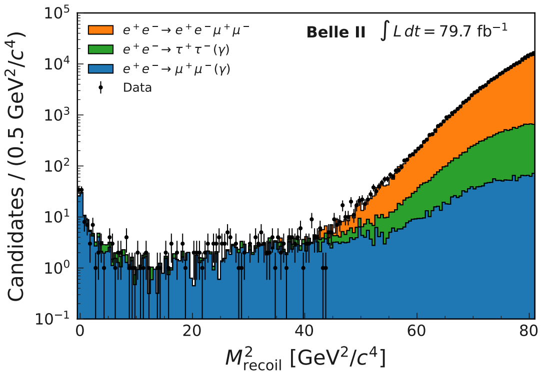

Figure 3: Distribution of the squared invariant mass of the recoil against the two muons in the process: $e^+e^- \to \mu^+\mu^- Z', Z' \to$ invisible. Background sources are stacked and data overlaid [4].

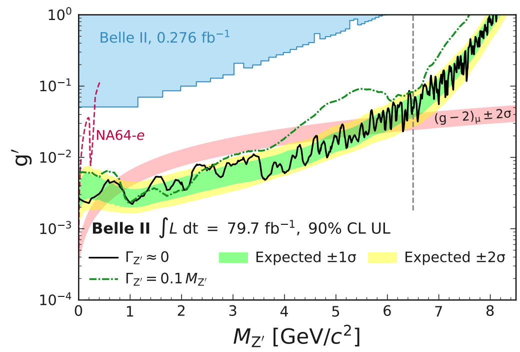

Figure 4: 90% CL upper limits on the coupling for the process $e^+e^- \to \mu^+\mu^- Z', Z' \to$ invisible, as a function of the Z′ mass assuming $\mathcal{B}(Z' \to \chi\bar{\chi}) = 1$ [4].

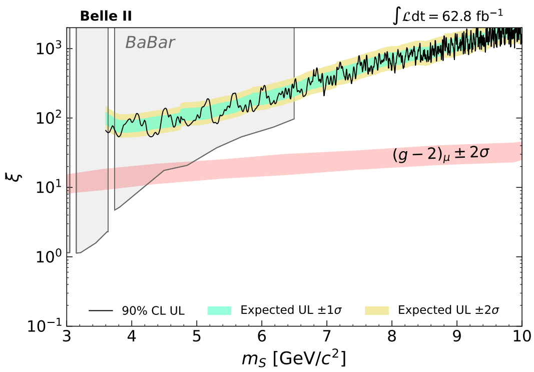

Figure 5: 90% CL upper limits on the coupling for the process $e^+e^- \to \mu^+\mu^- S$, $S \to \tau^+\tau^-$ [8].

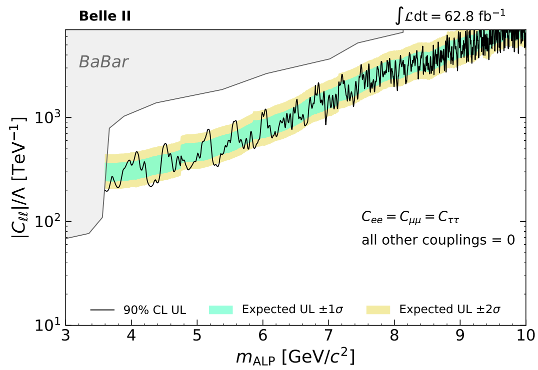

Figure 6: 90% CL upper limits on the coupling for the process $e^+e^- \to \mu^+\mu^- a$, $a \to \tau^+\tau^-$ [8].

separately in eight different mass regions.

The recoil mass spectrum is fit in steps of half the mass resolution, with the expected background derived directly from the fit to avoid the impact of known mis-modelling in the simulation. No significant excess is found in 63 fb^{-1} data by fitting the recoil mass range in steps of half mass resolutions, and 90% CL upper limits are set on the quantity $\sigma(e^+e^- \to \mu^+\mu^- X) \times \mathcal{B}(X \to \tau^+\tau^-)$, which could be re-interpreted in several classes of models. This search set the world's best constraints on the coupling for the leptophilic scalar model for masses above 6.5 GeV/c^2 (Figure 5) and on the axion-like particle model for the entire mass range (Figure 6).

Search for a dark leptophilic scalar in τ decays at Belle [9]. A complementary search with respect to the one discussed above has been carried out at Belle, where we search for a leptophilic scalar in the process $e^+e^- \to \tau^+\tau^-\phi_L$, $\phi_L \to \ell^+\ell^-$ ($\ell = e, \mu$) in 626 fb^{-1} of data. We select four-track events with zero total charge, and reconstruct ϕ_L candidates by fitting each e^+e^- and $\mu^+\mu^-$ pair to a common vertex. The main background source is $e^+e^- \to \tau^+\tau^-$ and it is suppressed using a multivariate analysis technique. Signal is searched as a narrow peaks in $e^+e^-(\mu^+\mu^-)$ invariant mass

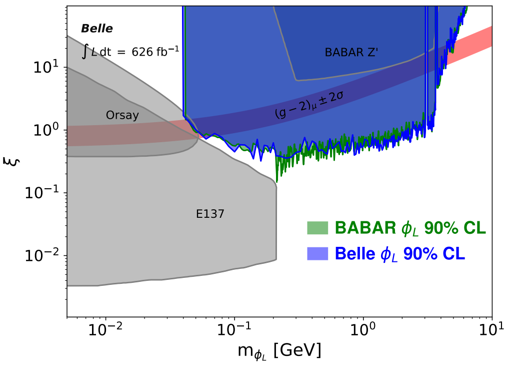

Figure 7: Observed upper limits at 90% CL on the coupling ξ as a function of the ϕ_L mass from Belle search (blue) [9]. Constraints from previous results are overlaid.

distribution by performing binned maximum likelihood fits excluding mass region where peaking backgrounds are expected. No evidence for signal is found and we set 90% CL upper limits on the signal cross-section, translated in upper limits for the coupling ξ between ϕ_L and leptons, which are comparable or more stringent than the ones previously measured (Figure 7).

Search for a $\mu\mu$ resonance in four-muon final states. This analysis aims to search for a resonance decaying into a pair of muon in $e^+e^- \to \mu^+\mu^- X$, $X \to \mu^+\mu^-$ events, looking for a peak in the di-muon mass distribution in 4-track events with zero net charge and no extra energy. The dominant background source comes from the 4-muon SM final states. The main feature of the analysis lies in the multivariate analysis-based background suppression, that exploits the kinematic characteristics of the signal. After performing unbinned maximum likelihood fits on the reduced di-muon reduced mass distribution, no significant excess has been found in ~180 fb^{-1} of data, therefore a 90% CL upper limit is set for the quantity $\sigma(e^+e^- \to \mathrm{X}) \times \mathcal{B}(\mathrm{X} \to \mu^+\mu^-)$ and then translated in terms of upper limits for the coupling constant g$'$ as a function of the resonance mass. Results can be interpreted in terms of two different models. The first one is the $L_\mu - L_\tau$ model [5, 6], for which the analysis is optimized and for which we obtain comparable results with respect to previous analyses performed with much more data than ours (Figure 8); the second is the muonphilic dark scalar S [10], for which we set the first limits coming from a dedicated study accounting for experimental details (Figure 9).

3. Summary

In this report the most recent results from the Belle II dark sector working group are shown, demonstrating that Belle II at SuperKEKB is a fitting environment where to search for light dark matter and mediators. The reported analyses were performed with a subset of the data recorded to date, 424 fb^{-1}, bringing to world's leading or unique outcomes. More results, with additional data and improved analyses, are in the pipeline.

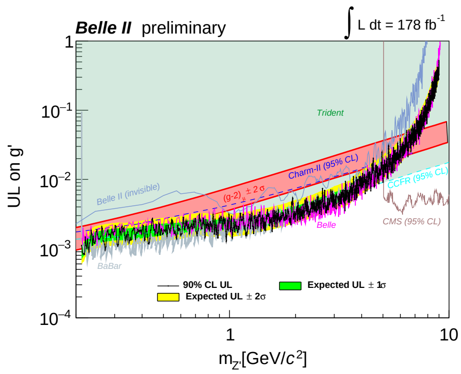

Figure 8: 90% CL upper limits on the coupling constant g′ for the process $e^+e^- \to e^+e^-Z'(\to \mu^+\mu^-)$.

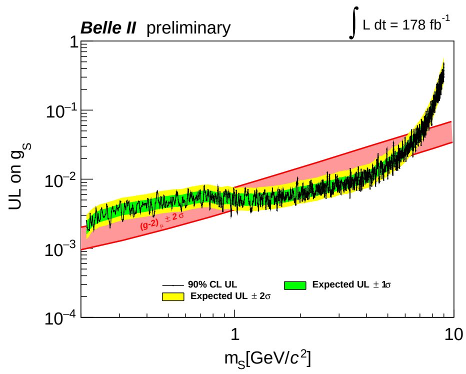

Figure 9: 90% CL upper limits on the coupling constant g_S for the process $e^+e^- \to e^+e^-S(\to \mu^+\mu^-)$.

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