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Searches for invisible new particles at Belle II

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Belle II has unique sensitivity for a broad class of models postulating the existence of dark matter particles with masses in the MeV–GeV range. We present the recent world-leading physics results from Belle II searches for several non-SM particles: Z' bosons, axion-like particles and dark scalars, through their decays to dark or SM particles; as well as long-lived (pseudo) scalars in B-meson decays; and invisible α-particle in τ-decays.

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1. INTRODUCTION

Several astrophysical observations suggest the existence of Dark Matter (DM), a component of matter that does not interact through strong or electromagnetic forces. Although DM constitutes approximately 85% of the total matter in our Universe, its nature remains unknown. To date DM is one of the most compelling phenomena in support for physics beyond the Standard Model (SM).

If DM consists of particles feebly coupled with SM particles, it could be produced in SM particle annihilations at high-energy colliders. However, the lack of evidence of non-SM physics at the electroweak scale, leads to hypothesize sub-GeV DM particles feebly interacting with SM particles through non-SM mediators. Sub-GeV DM as well as the non-SM mediators constitute the dark sector (DS), and efforts to detect them have been actively pursued at beam dump and high-intensity frontier experiments.

Belle II [2] is a high-intensity frontier experiment that operates at the SuperKEKB e^+e^- asymmetric-energy collider [3]. SuperKEKB is a second generation B-factory designed to reach the instantaneous luminosity of 6×10^{35} cm^{-2}s^{-1} thanks to the usage of the large crossing-angle nano-beam scheme. The Belle II detector [1] is a magnetic spectometer, composed of several sub-detectors installed around the interaction point, that allow to reconstruct all the products of the e^+e^- interaction. During the first data taking run (2019-2022), 424 fb^{-1} of data were collected, of which 363 fb^{-1} at the at the energy in the center-of-mass $\sqrt{s} = 10.58$ GeV.

Thanks to the excellent reconstruction capabilities for low multiplicity and missing energy signatures, and dedicated triggers, Belle II has a unique sensitivity to the DS and will progressively lead its exploration at the luminosity frontier [17].

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2. RECENT DARK SECTOR RESULTS AT BELLE II

2.1. Search for an invisible Z'.

The Z' is a light gauge boson introduced by the $L_\mu - L_\tau$ model [4–6]. We search for the invisible decay of Z' through the process $e^+e^- \to \mu^+\mu^- Z'(\to \text{inv.})$, where Z' is radiated off one of the muons. The Z' could decay invisibly to SM neutrinos, with a branching fraction of $\mathcal{B}(Z' \to \text{inv.}) \sim 33\%$, or to kinematically accessible DM candidates with $\mathcal{B}(Z' \to \text{inv.}) = 100\%$. Signal appears as a narrow enhancement in the recoil mass against the two final-state muons, in events where nothing else is detected. The main backgrounds are QED radiative di-lepton and four-lepton final states, which are suppressed using a neural-network trained simultaneously for all Z' masses [9], and fed with kinematic variables sensitive to the origin of the missing energy: in the signal, the Z' is produced as final-state radiation (FSR); in the background, the missing energy is due to neutrinos or undetected particles. From 2D template fits to the recoil mass squared, in bins of recoil polar angle, we did not observe any significant excess in 79.7 fb^{-1} of data, and we set 90% C.L. upper limits on the coupling of the $L_\mu - L_\tau$ model, g', as a functions of the Z' mass, $M_{Z'}$. We exclude the region favored for the $(g-2)_\mu$ anomaly in the mass range $0.8 < M_{Z'} < 5$ GeV/c^2 for the fully invisible $L_\mu - L_\tau$ model (Fig. 1) [7, 8].

2.2. Search for $e^+e^- \to \mu^+\mu^- X(\to \tau^+\tau^-)$

We search for a $X \to \tau^+\tau^-$ resonance, where X could be a Z', a leptophilic dark spin-0 particle (scalar) S or an axion-like particle (ALP), in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$ events, with τ decaying to one charged particle. The S is an hypothetical particle that couples preferentially to charged leptons through Yukawa-like couplings [11]. Axion-like particles are pseudo-scalars that appear in many SM extensions [12, 13].

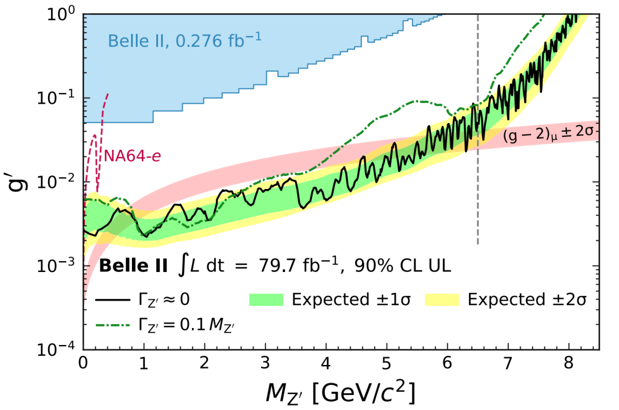

Figure 1. Observed 90% C.L. upper limits and corresponding expected limits on the g' coupling as a function of the Z' mass, assuming $\mathcal{B}(Z' \to \text{inv.}) = 100\%$.

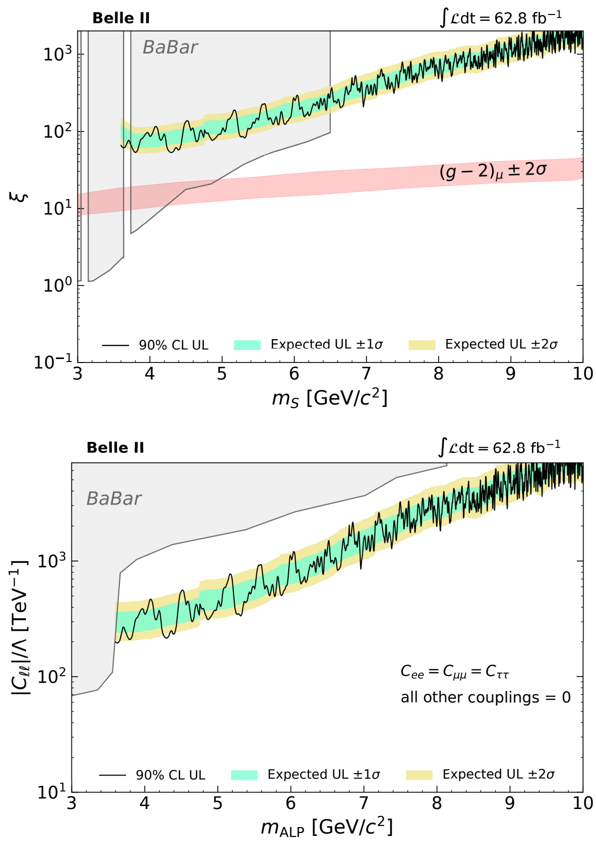

Figure 2. Observed 90% C.L. upper limits (UL) and corresponding expected limits as a function of the mass on (*top*) the leptophilic scalar coupling ξ, and on (*bottom*) the ALP-lepton coupling $|C_{\ell\ell}|/\Lambda$.

Similarly to the $Z' \to$ inv. analysis, we search for a narrow enhancement in the recoil mass against two oppositely charged muons, in four-track events with zero net charge. Standard Model backgrounds are suppressed with eight neural-networks fed with kinematic variables sensitive to the X-production mechanism as FSR off one of the two muons, and trained in different X-mass regions. From extended maximum likelihood fits to the recoil mass distribution, we did not observe any significant excess in 62.8 fb^{-1} of data. We derive world-leading 90% C.L. upper limits on the S-coupling ξ for $m_S > 6.5$ GeV$/c^2$, and on the ALP-lepton coupling $|C_{\ell\ell}|/\Lambda$, assuming equal ALP-couplings to the three lepton families and zero couplings to all other particles (Fig. 2) [10].

2.3. Search for $e^+e^- \to \mu^+\mu^- X(\to \mu^+\mu^-)$

We search for a $X \to \mu^+\mu^-$ resonance in $e^+e- \to \mu^+\mu^-\mu^+\mu^-$ events as a narrow enhancement in the dimuon mass distribution in four-track events with zero net charge and no extra-energy. The dominant background are SM four-muon final-state processes. Background is suppressed applying five neural-networks fed with kinematic variables sensitive to the X-production mechanism as FSR off one of the two muons, and on the presence of a resonance in both the candidate and the recoil muon pairs, and trained in different X-mass ranges. From extended maximum likelihood fits to the dimuon mass distribution, we did not observe any significant excess in 178 fb^{-1} of data, and we set 90% C.L. upper limits on the cross section of the process. We interpret the results obtained on the cross section as 90% C.L. limits on the g' coupling of the $L_\mu - L_\tau$ model, and on the coupling of a muonphilic scalar S with muons [14]. Despite the small data-set used, we obtain competitive results with the existing limits on g' from BABAR and Belle, which performed the analysis with 514 fb^{-1} and 643 fb^{-}1 respectively. We set the first limits for the muonphilic scalar model from a dedicated search (Fig. 3).

2.4. Search for a long-lived (pseudo) scalar in $b \to s$ transitions

Extensions of the SM introduce a new light scalar S that may give mass to DM particles. The scalar S would mix with the SM Higgs boson through a mixing angle θ, and would be naturally long-lived for small values of θ.

We search for $B^0 \to K^{*0}(\to K^+\pi^-)S$ and $B^+ \to K^+S$ events, with $S \to x^+x^-$ and $x = e, \mu, \pi, K$. The signal signature is a prompt decay of the kaon and two opposite-charged particles from a displaced vertex. The signal yield is extracted through extended maximum likelihood fits to the reduced invariant mass of S, $m^{reduced}_{S\to xx} = \sqrt{M^2_{S\to xx} - 4m^2_x}$, in order to improve the modeling of the signal width close to the kinematic thresholds. Main background components are the combinatorial $e^+e^- \to q\bar{q}$, suppressed by requiring a kinematics similar to B-meson expectations, peaking K^0_S, vetoed in the invariant mass $m_{S\to\pi\pi}$, and further peaking backgrounds, suppressed by tightening the displacement selections. We did not observed any significant excess in 189 fb^{-1} of data, and we set the first model-independent limits at 95% C.L. on $\mathcal{B}(B \to KS) \times \mathcal{B}(S \to x^-x^+)$ as a function of the scalar mass m_S for different S-lifetimes (Fig. 4) [15].

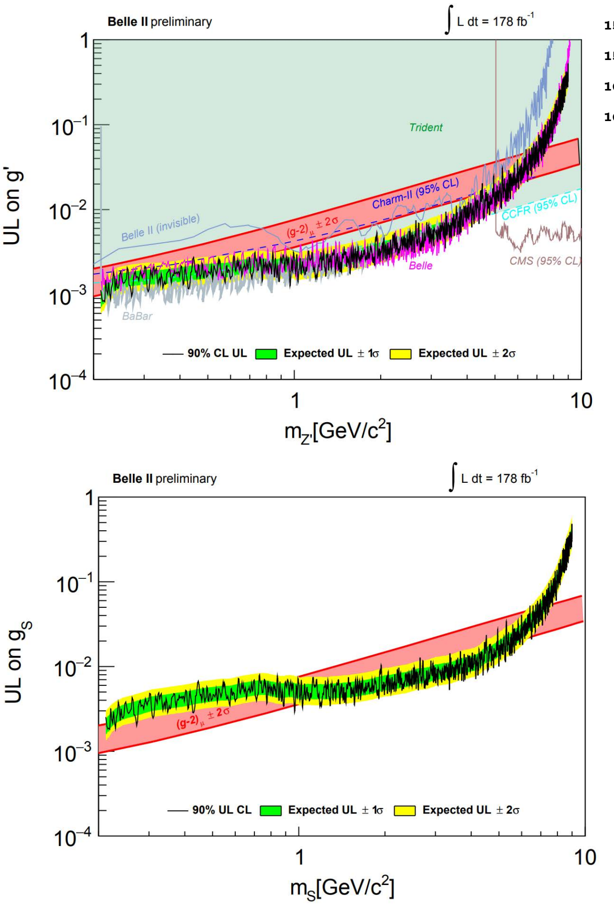

Figure 3. Observed 90% C.L. upper limits and corresponding expected limits as a function of the mass on (*top*) the g' coupling of the $L_\mu - L_\tau$ model, and on (*bottom*) the muonphilic dark scalar model.

2.5. Search for the $\tau \to \ell\alpha$ decay

Charged-lepton flavour violation (LFV) is allowed in various extensions of the SM, however it has never been observed. In these extensions, the LFV processes could be mediated by a new hypothetical α-boson. We search for an invisible α produced in the $\tau \to \ell\alpha$ decay, with $\ell = e, \mu$, in $e^+e^- \to \tau^+\tau^-$ events. In the center-of-mass frame, τ pairs are produced back-to-back so that each τ-decay products are contained in two separate hemispheres. The *tag* hemisphere contains three charged hadrons from $\tau^-_{\text{tag}} \to h^-h^+h^-\nu_\tau$, with $h = \pi$, K, while the *signal* hemisphere contains only one charged lepton from the $\tau^-_{\text{sig}} \to \ell^-\alpha$ decay.

For this analysis, $\tau \to \ell\nu_\tau\bar{\nu}_l$ is an irreducible background. However, the lepton momentum has a broad distribution for the background, while it depends only on the α-mass for the signal and it appears as a bump over the irreducible background.

In particular, we search for an excess over the normalized lepton energy spectrum x_ℓ of $\tau \to \ell\nu_\tau\bar{\nu}_l$, where $x_\ell = 2E^*_\ell/m_\tau$, performing template fits. The energy E^*_ℓ is defined in the approximate rest frame of τ_{sig}, i.e. where $E_\tau \approx \sqrt{s}/2$ and the τ_{sig} direction is opposite to the τ_{tag} direction. We did not find any significant excess in 62.8 fb^{-1} of data, and we set world-leading 95% C.L. upper limits to $\mathcal{B}(\tau \to \ell\alpha)/\mathcal{B}(\tau \to \ell\bar{\nu}_\ell\nu_\tau)$, as a function of the M_α mass (Fig. 5) [16].

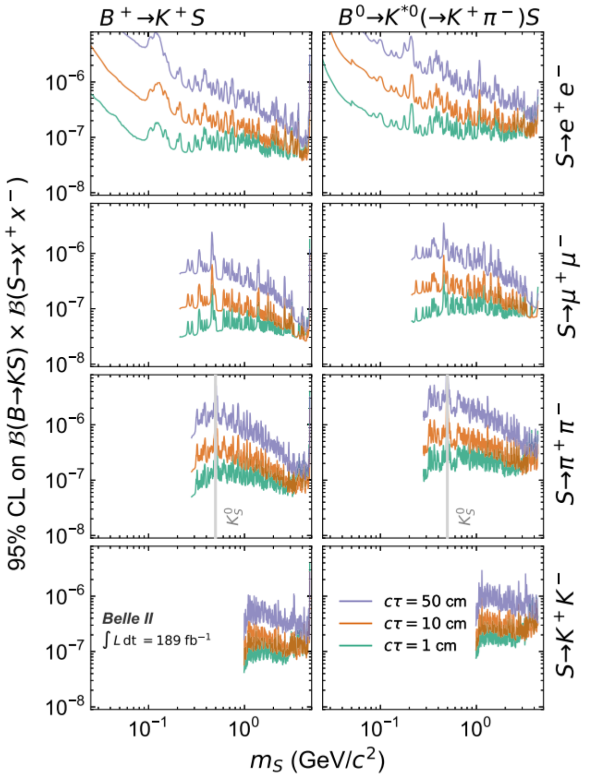

Figure 4. Observed 95% C.L. on $\mathcal{B}(B \to KS) \times \mathcal{B}(S \to l^+l^-/h^+h^-)$ as a function of the scalar mass m_S for different lifetimes $c\tau$.

3. SUMMARY

We presented the latest Belle II world-leading results from DS searches, published with partial data-sets of 424 fb^{-1} collected to date. New results with improved analyses and more data are coming.

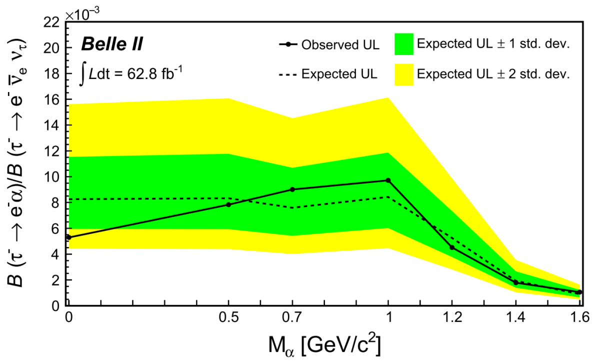

Figure 5. Upper limits at 95% C.L. on the ratio $\mathcal{B}(\tau \to e\alpha)/\mathcal{B}(\tau \to e\bar{\nu}_e\nu_\tau)$.

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