PROCEEDINGS OF SCIENCE

Recent τ and dark-sector results at Belle II

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The Belle II experiment investigates the potential interactions between Standard Model (SM) particles and dark sector particles by means of weak couplings mediated by new particles. We present the outcomes of two distinct searches. First, we present a search for B decays to a final state that includes a long-lived (pseudo)scalar particle. Then, we provide an update on the search for an invisibly decaying Z' boson. Furthermore, we look into lepton-flavor violation by exploring τ decays into $\ell\alpha$, where α represents a novel, invisible boson. We also report on the first inclusively tagged reconstruction of τ pair events, focusing on the neutrinoless decays $\tau \to \ell\phi$. Lastly, we present the most precise measurement of the τ lepton mass. All of these studies utilize data collected by the Belle II detector during the period of 2019-2021.

21st Conference on Flavor Physics and CP Violation (FPCP 2023)
29 May - 2 June 2023
Lyon, France

*Speaker

PoS(FPCP2023)071

1. Introduction

Dark matter (DM) continues to captivate scientists as one of the most intriguing mysteries in the realm of physics beyond the standard model (SM). Its existence has been confirmed through a range of astrophysical and cosmological observations, yet its origins and characteristics remain elusive. Direct searches for heavier DM candidates have yielded no conclusive results, prompting researchers to explore alternatives such as light dark particles [1]. In these scenarios, new light mediators serve as conduits between SM particles and the DM.

The study of light dark sectors has gained considerable attention in recent years, offering promising opportunities for the detection and understanding of DM. Electron-positron (e^+e^-) colliders play a pivotal role in investigating these light dark sectors. By colliding e^+e^- at high energies, these colliders create an ideal environment to search for and study interactions mediated by light particles.

In the quest to comprehend the elusive nature of DM, which constitutes a significant portion of the universe, τ physics emerges as a rigorous branch of particle physics, delving into the properties and behavior of the τ lepton. By studying the τ lepton's mass, charge, and decay modes, researchers gain insights into the fundamental forces and constituents of the universe. This field contributes to our understanding of the Standard Model and potential extensions. Through collider experiments, a dedicated pursuit is underway to unravel the mysteries of τ physics, thereby contributing to the expansion of our knowledge of the intricate mechanisms that govern the universe.

2. Belle II experiment

The Belle II experiment, situated at the SuperKEKB asymmetric-energy e^+e^- collider, stands at the forefront of the investigation into light dark sectors. Operating at a center-of-mass energy of 10.58 GeV and implementing a nano-beam scheme, SuperKEKB achieves unprecedented instantaneous luminosity. This high luminosity facilitates the production of rare and low-energy processes, making it a prime platform for exploring light mediators and their interactions with SM particles.

Furthermore, the production cross-section for $e^+e^- \to \tau^+\tau^-$ events is 0.919 nanobarns at a center-of-mass energy ($\sqrt{s}$) of 10.58 GeV. This substantial cross-section enables Belle II to probe the realm of τ physics, particularly to conduct precision measurements of τ lepton properties and to explore extremely rare processes such as charged lepton flavor violation (LFV).

The Belle II detector [2] is a multi-purpose spectrometer encompassing the interaction point and providing coverage of over 90% of the solid angle. This state-of-the-art detector ensures high reconstruction efficiency for neutral particles and excellent resolutions despite the challenging beam background environment. These qualities are particularly crucial when dealing with recoiling systems and final states involving missing energy. Additionally, the detector is equipped with dedicated low-multiplicity trigger lines at the hardware level, primarily relying on calorimetric information. It also incorporates novel triggers, such as the single-photon or single-muon triggers, which were not available during the predecessor Belle experiment. Leveraging its comprehensive coverage and knowledge of the initial state of e^+e^- collisions, Belle II boasts a unique capability to probe signatures involving invisible final states and long-lived particles produced at displaced decay vertices.

The accomplishments of the accelerator, including its attainment of the peak luminosity world record at an impressive 4.7×10^{34} cm^{-2} s^{-1}, complement the efforts of the Belle II experiment. Belle II has already collected a data sample equivalent to an integrated luminosity of 424 fb^{-1}. While the experiment is currently undergoing its first long shutdown, there is great anticipation as it prepares to resume operations by the end of this year.

3. Dark sector

Belle II has the unique capability to explore the mass range favored by light dark sector models, allowing for the direct search of new particles with masses ranging from a few hundred MeV to a few GeV. One intriguing possibility lies in the investigation of rare B meson decays involving $b \to s\ell\ell$ transitions, which could provide valuable insights into the existence of new particles. Using data collected during the 2019-2021 data-taking period, we have established the first model-independent upper limits on long-lived (pseudo)scalar particles S decaying into visible final states of two oppositely charged leptons or hadrons x^+x^-. To identify these particles, we search for $B^\pm \to K^\pm S$ or $B^0 \to [K^{*0} \to K^\pm\pi^\mp]S$ events, where S represents the new particle, forming a displaced vertex accompanied by a charged kaon (and possibly a pion). The combined candidates of S and $K^\pm$ are subjected to B kinematics constraints, and the signal is extracted through extended maximum likelihood fits to the reduced invariant mass $m^{\text{reduced}}_{S\to x^+x^-} = \sqrt{m^2_{S\to x^+x^-} - 4m^2_x}$, which is easier to model than the invariant mass near threshold. The only significant long-lived Standard Model background arises from K^0_S candidates, whose mass region is vetoed and used as control samples to evaluate systematic uncertainties. No significant excess is observed in the 190 fb^{-1} dataset, and 95% confidence level (CL) upper limits are computed on the product $\mathcal{B}(B \to KS) \times \mathcal{B}(S \to x^+x^-)$ as a function of the new particle mass m_S. These results, displayed on the left of Figure 1, establish the first limits on decays to hadrons [3].

Furthermore, we investigate the possibility of a new massive vector boson Z' that exclusively couples to the second and third generation of leptons, as proposed by the $L_\mu - L_\tau$ model [4] [5]. This theoretical framework provides a potential explanation for the long-standing $(g-2)_\mu$ anomaly, the observed relic abundance of dark matter, and other flavor anomalies. In our analysis, we search for $e^+e^- \to \mu^+\mu^- Z'$ events, where the Z' boson is radiated off one of the muons and subsequently decays into an invisible final state with a branching fraction between 33% and 100%. If the dark matter candidates χ are kinematically accessible, $\mathcal{B}(Z' \to \chi\bar{\chi}) \approx 1$. To identify the signal, we examine the invariant mass distribution of the recoil in the center-of-mass system against the two muons in events where no other particles are detected. The primary background arises from QED processes, specifically radiative di-lepton and four-lepton final states, which mimic the signal signature of two tracks plus missing energy. By employing a neural network trained simultaneously for all Z' masses [6], utilizing kinematic properties specific to the production mechanism via radiation off one muon, we achieve a final signal efficiency of approximately 5% across the entire mass range. Signal yields are extracted through template fits to the recoil mass squared, binned by recoil polar angle. No significant excess consistent with the signal is observed in 80 fb^{-1} of data, and we establish 90% CL upper limits on the cross section $\sigma(e^+e^- \to \mu^+\mu^- Z', Z' \to \text{invisible})$. Additionally, upper limits on the coupling constant g' as a function of the Z' mass, within the $L_\mu - L_\tau$ framework and assuming $\mathcal{B}(Z' \to \chi\bar{\chi}) = 1$, are calculated. The obtained results, displayed in the

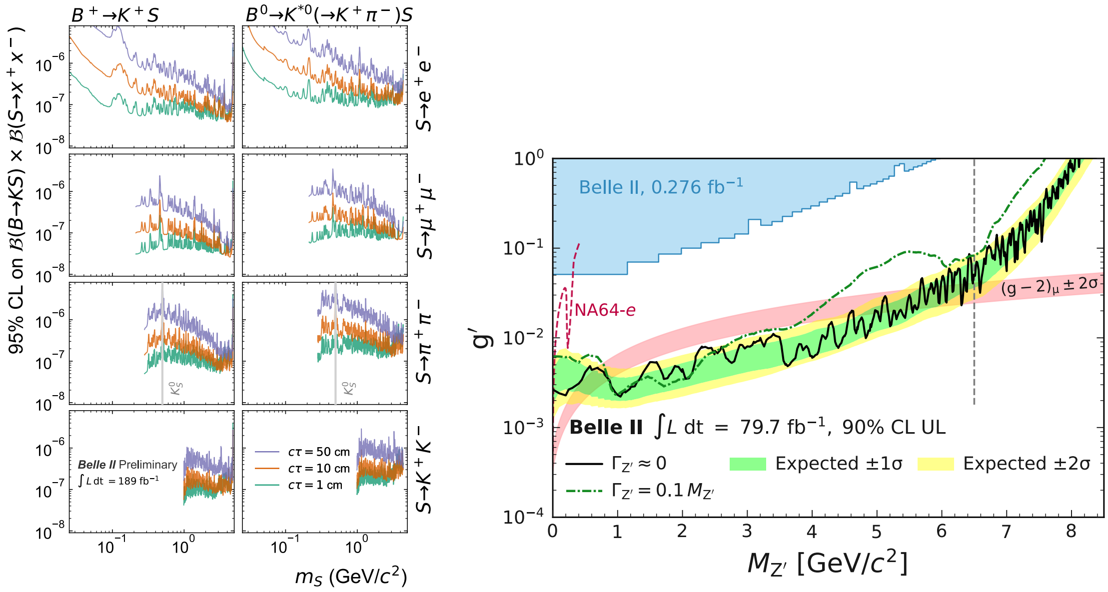

Figure 1: Upper limits (95% CL) on the product of branching fractions $\mathcal{B}(B^+ \to K^+ S) \times \mathcal{B}(S \to x^+x^-)$ and $\mathcal{B}(B^0 \to [K^{*0} \to K^+\pi^-]S) \times \mathcal{B}(S \to x^+x^-)$ as functions of scalar mass m_S (left) and observed 90% CL upper limits on the coupling g' for the fully invisible $L_\mu - L_\tau$ model as functions of the Z' mass for the cases of negligible $\Gamma_{Z'}$ and for $\Gamma_{Z'} = 0.1 M_{Z'}$ (right).

right plot of Figure 1, exclude the region favored by the $(g-2)_\mu$ anomaly for Z' masses in the range of $0.8 < M_{Z'} < 5$ GeV/c^2 [7].

4. τ physics

In many models, the possibility of τ lepton decays to new lepton flavor violating (LFV) bosons is postulated [8]. This study focuses on the process $e^+e^- \to \tau^+(\to \ell^+\alpha)\tau^-(\to \pi^-\pi^+\pi^-\nu_\tau)$, along with its charged conjugate, where the first τ lepton is considered as the signal and the second τ lepton as the tag. The signal τ lepton decays to a new invisible boson α, accompanied by a lepton (either an electron or a muon). 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 as its momentum direction. We search for a narrow peak corresponding to the two-body decay of the signal τ lepton in the distribution of the normalized lepton energy, while accounting for the smooth contribution from the irreducible background of $\tau \to \ell\nu\nu$ decays. With no observed excess in the 63 fb^{-1} of data, 95% confidence level (CL) upper limits are calculated on the ratio of branching fractions $\mathcal{B}(\tau \to \ell\alpha)$ normalized to $\mathcal{B}(\tau \to \ell\nu\nu)$ [9]. These limits, shown in Figure 2 are between 2-14 times more stringent than the previous limits set by ARGUS [10].

New mediators that could enhance the branching fraction for τ LFV decays $\tau \to \ell\phi$ to observable levels of $10^{-11} - 10^{-8}$ have been proposed to account for flavor anomalies observed in lepton flavor universality tests with B decays. Unlike previous searches for $\tau \to \ell\phi$ decays conducted at Belle on $e^+e^- \to \tau^+\tau^-$ events, a new untagged approach is employed in this study: only the signal τ lepton decay to a ϕ meson candidate and a lepton (muon or electron) are explicitly reconstructed, while the other τ lepton (tag) is not required to decay to any specific known final state.

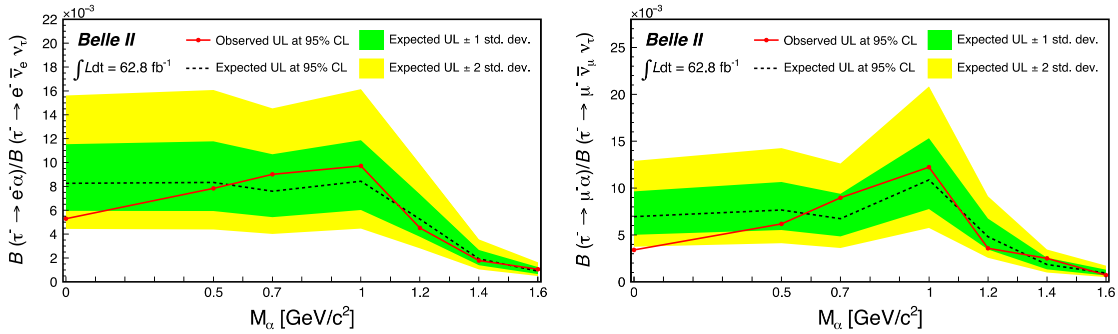

Figure 2: Upper limits at 95% CL on the branching-fraction ratios $\mathcal{B}(\tau^- \to e^-\alpha)$ / $\mathcal{B}(\tau^- \to e^-\bar{\nu}_e\nu_\tau)$ (top) and $\mathcal{B}(\tau^- \to \mu^-\alpha)$/ $\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)$ (bottom) as a function of the α mass, as well as their expectations from background-only hypothesis.

A Boosted Decision Tree (BDT) classifier is utilized, leveraging event kinematic features and signal properties to suppress the background. This approach achieves twice the final signal efficiency for the muon mode compared to previous analyses. Signal yields are extracted using a Poisson counting experiment approach from windows centered at the known τ mass and at zero in the two-dimensional plane of M_τ, Δ_{E_τ}, where Δ_{E_τ} represents the difference between the reconstructed energy of the signal τ lepton in the center-of-mass frame and half the collision energy. No significant excess is observed, as reported in Figure 3, and 90% CL upper limits on the branching fractions are set as $\mathcal{B}_{UL}(\tau \to e\phi) = 23 \times 10^{-8}$ and $\mathcal{B}_{UL}(\tau \to \mu\phi) = 9.7 \times 10^{-8}$ [3].

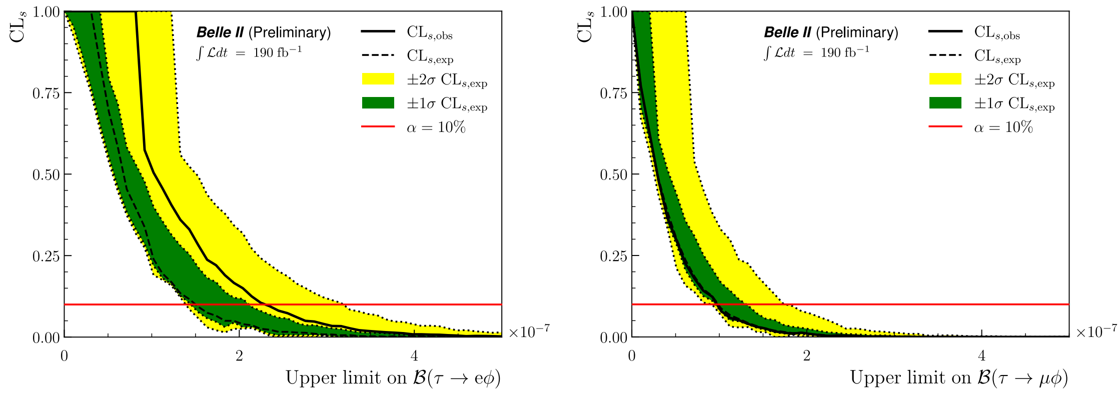

Figure 3: Observed (solid black curve) and expected (dashed black curve) CLs as a function of the assumed branching fractions of $\tau \to e\phi$ (left) and $\tau \to \mu\phi$ (right). The red lines correspond to the 90% CLs.

Precise measurements of lepton properties, fundamental parameters of the Standard Model, are of utmost importance. Belle II provides a suitable platform to access several properties of the τ lepton. Using the pseudo-mass $M^2_{min} = 2E^*_{3\pi}(E^*_\tau - E^*_{3\pi}) + M^2_{3\pi} - 2p^*_{3\pi}(E^*_\tau - E^*_{3\pi}) < m^2_\tau$ technique applied to reconstructed $e^+e^- \to \tau^+\tau^-$ events from 190 fb^{-1} of data, the most precise measurement of the τ lepton mass M_τ to date is achieved. The measured value is extracted from a fit to the endpoint of the distribution M_{min}, computed from events where the signal τ lepton decays to three charged pions and the other τ lepton decays into one charged particle. Figure 4 reports these distributions. An excellent control of systematic sources, primarily stemming from the calibration of beam energies and charged-particle momenta scale, is crucial in reducing the total systematic uncertainty to 0.11 MeV/c^2. Consequently, the most precise measurement of the τ lepton mass is obtained, with a value of 1777.09 ± 0.08 (stat) ± 0.11 (sys) [11].

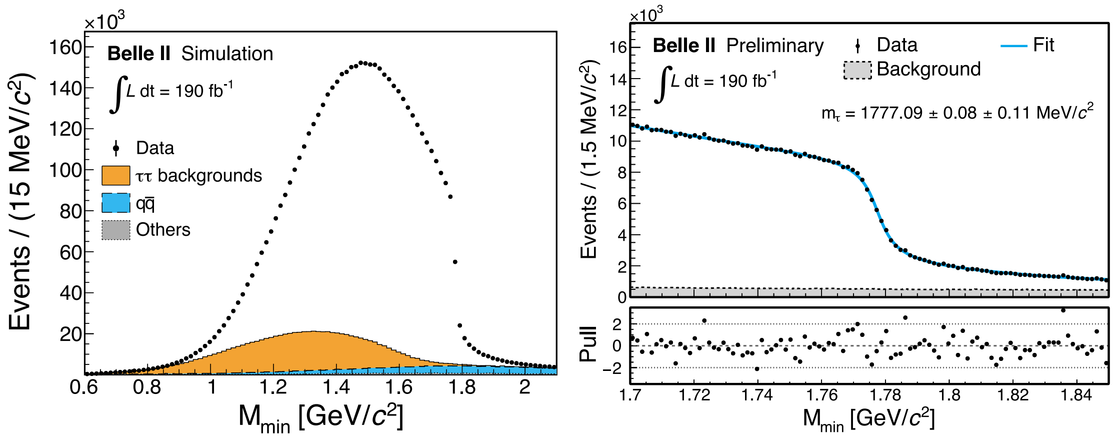

Figure 4: Spectrum of M_{min} in experimental data (dots) with fit result (solid blue line) and background contribution (gray-filled area) overlaid.

5. Conclusion

The researches conducted at Belle II have provided significant insights into the two key areas of particle physics discussed in these proceedings. In terms of the dark sector, the investigation of long-lived (pseudo)scalar in $b \to s\ell\ell$ transitions not only explored the existence and characteristics of this hypothetical particle but also established the first-ever limits on its decays to hadrons. Furthermore, the search for the Z' boson, a hypothetical particle beyond the Standard Model, has yielded important constraints on its existence and whether it is a candidate to explain the $(g-2)_\mu$ anomaly.

In addition, the search for $\tau \to \ell\phi$ decays and $\tau \to \ell\alpha$ decays has provided a probe of lepton flavor violating processes; it provides first insights into increasing the reconstruction efficiency through inclusive tagging. Finally, the precise measurement of the τ mass at Belle II has significantly contributed to our knowledge of the fundamental properties of this particle. The accurate determination of the τ mass is essential for various theoretical calculations and precision tests of the Standard Model.

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