Dark sectors and τ physics at Belle II

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The possibility of dark sectors weakly coupling to Standard Model (SM) particles through new light mediators is explored at the Belle II experiment. We present here results from three different searches, for a long-lived (pseudo)scalar particle; for a di-tau resonance in four-muon final states events and the update on the search for a Z' boson decaying invisibly in events with two muons plus missing energy, performed on samples from the data collected by the Belle II detector during 2019-2021 data taking. We report the search for $\tau \to \ell\alpha$ decays, with α a new invisible boson, and the first successful untagged reconstruction of tau pairs events searching for the neutrinoless decays $\tau \to \ell\phi$. Finally, we present the world's most precise measurement of the τ lepton mass.

1 Introduction

Dark matter (DM) is one of the most compelling reasons for physics beyond the standard model (SM). Its existence has been established by several astrophysical and cosmological observations, but its origins and nature are still unknown. In recent years, especially after the null results from direct searches for heavier DM candidates, light dark sectors have become attractive, and could imply new light mediators acting as portal between SM particles and DM. Belle II has also a unique capability to probe charged lepton flavor violation (LFV) in tau decays. Processes involving LFV can occur in the SM via weak interaction charged currents, due to neutrino oscillations, and are predicted at the level of 10^{-50}, which is beyond the reach of current and future experiments. Therefore any observation of LFV signatures would be an unambiguous hint of non-SM physics. We report searches for new dark sectors particles, tau LFV decays and the measurement of the τ lepton mass using the data collected by the Belle II detector [1], which is built around the interaction region of the SuperKEKB asymmetric energy e^+e^- collider. SuperKEKB mainly runs at a centre-of-mass energy of 10.58 GeV and adopts a nano-beam scheme to reach unprecedented instantaneous luminosity. As at the time of this conference, the accelerator achieved the peak luminosity world's record of $4.7{\times}10^{34}$ cm$^{-2}/s$ and Belle II is during its first long-shutdown. It has collected up to 424 fb^{-1} data, including unique energy scan samples.

2 Belle II experiment

The Belle II detector is a multi-purpose spectrometer surrounding the interaction point and ensuring hermetic coverage of more than 90% of the solid angle. The details of the Belle II detector can be found elsewhere [1]. Belle II ensures a very high reconstruction efficiency for neutral particles and excellent resolutions despite the harsh beam background environment, which are crucial when dealing with recoiling system and missing-energy final states. Profiting from the well known initial state of e^+e^- collisions, and thanks to its hermetic coverage, it has a unique capability to probe signatures involving invisible final states and long-lived particles producing a displaced decay vertex. Moreover, the cross section production for $e^+e^- \to \tau^+\tau^-$ events is 0.919 nb at a c.m. energy $\sqrt{s} = 10.58$ GeV, which allows Belle II to collect large samples to test tau lepton properties. For this kind of studies, it's crucial to dispose of the new dedicated low-multiplicty trigger lines at hardware level, like the single-photon or single-muon triggers, which were not available at Belle.

3 Dark sectors results

Belle II can directly access the mass range that is favored by the light dark sectors models, looking for new particles with masses between hundreds of MeV and few GeV. An interesting possibility is to look for new particles produced in rare B meson decays involving $b \to s\ell^+\ell^-$ 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 $\ell = e, \mu$ and $h = \pi, K$, to form a displaced vertex, accompanied by a charged kaon (and additionally a pion). The combined S and $K(^*)$ candidates are required to satisfy the B kinematics constraints. The signal is extracted with extended maximum likelihood fits to the reconstructed scalar mass m_S reduced by twice the rest mass of the final-state particles to improve the fit modeling at threshold. The only long-lived SM background is due to K^0_S candidates, whose mass region is vetoed and used as excellent control samples in data to evaluate systematic uncertainties. No significant excess is found in 190 fb^{-1} data and 95% confidence level (CL) upper limits are computed on the product $\mathcal{B}(B \to KS) \times \mathcal{B}(S \to x^+x^-)$, shown as a function of the searched new particle mass m_S in Figure 1. These are the first limits set on decays to hadrons. A new massive vector boson that

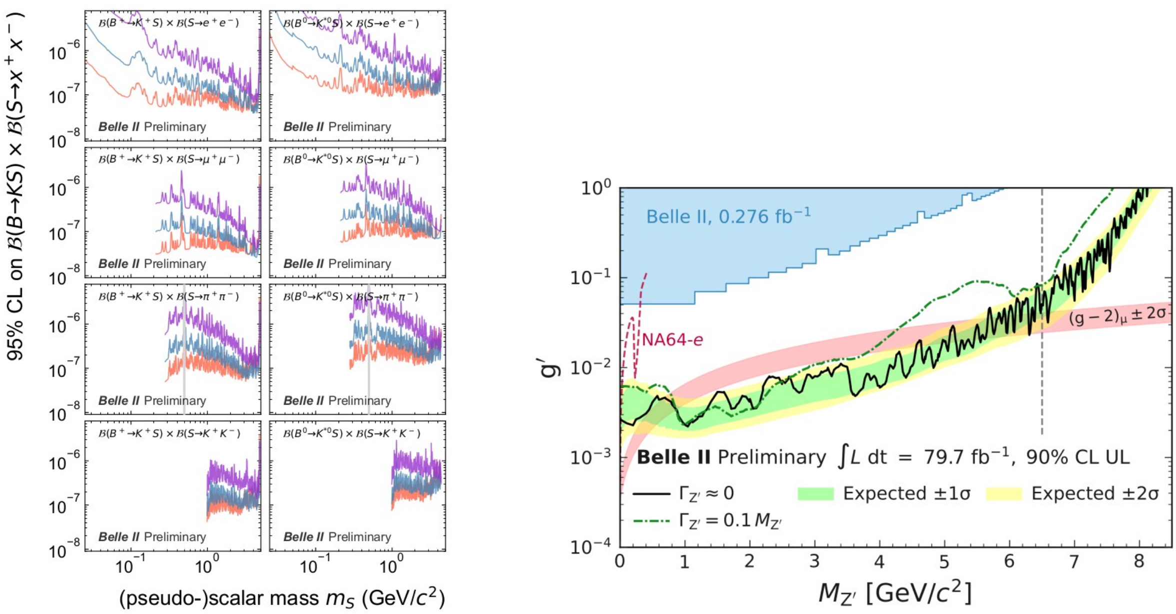

Figure 1 – On the left, upper limits at 95% CL on the product $\mathcal{B}(B \to KS) \times \mathcal{B}(S \to x^+x^-)$ as a function of the searched (pseudo)scalar mass m_S are reported. On the right, 90% CL upper limits on the coupling constant g' as a function of the searched $M_{Z'}$ are displayed.

couples only to the second and third generation of leptons according to the $L_\mu - L_\tau$ model, could explain the long-standing $(g-2)_\mu$ anomaly, the observed DM relic abundance [6] and other flavor anomalies. The targeted processes are $e^+e^- \to \mu^+\mu^- Z'$ events, where the Z' is radiated off one of the final muons and decays to an invisible final state with a branching fraction between 33% and 100%. If DM candidates are kinematically accessible, $\mathcal{B}(Z' \to \chi\bar{\chi}) \sim 1$. The analysis strategy is to search for a bump in the invariant mass distribution of the recoil in the centre-of-mass system against the two muons, in events where nothing else is detected. The main background are QED processes, namely radiative di-lepton and four-lepton final states, that mimic the signal signature of two tracks plus missing energy. The kinematic properties of the signal as final-state radiation are fed into a neural-network [4] trained simultaneously for all Z' masses with a final signal efficiency of approximately 5%. Signal yields are extracted from template fits to the recoil mass squared, in bins of recoil polar angle. We find no excess consistent with signal in 80 fb^{-1} data and set 90% CL upper limits on the cross section $\sigma(e^+e^- \to \mu^-\mu^- Z', Z \to invisible)$, also translated into upper limits on the g' coupling constant as a function of the searched Z' mass, within the $L_\mu - L_\tau$ framework and assuming $\mathcal{B}(Z' \to \chi\bar{\chi}) = 1$. These results, shown in the right plot in Figure 1, exclude all the region favored by the $(g-2)_\mu$ anomaly for the range $0.8 < M_{Z'} < 5$. Similarly, we look for a narrow bump in the mass distribution of the recoil against two muons, in events where an additional tau pair is reconstructed as one charged particle decays $\tau \to h, \ell\nu(\bar{\nu})$. 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, in eight different mass regions. The expected background is fitted directly from the recoil mass distribution in the data to avoid the impact of known mis-modeling in the simulation. No significant excess is found in 63 fb^{-1} data by fitting the recoil mass range $(3.6 < M_{recoil}(\mu\mu) < 10)$ GeV/c^2 in steps of half mass resolutions, and 90% CL upper limits are set on the quantity $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$, which could be re-interpreted in several classes of models. This search set the world's best limits on the scalar coupling constant ξ in leptophilic scalar models [3] for $M_S > 6.5$ GeV/c^2 (left plot in Figure 2).

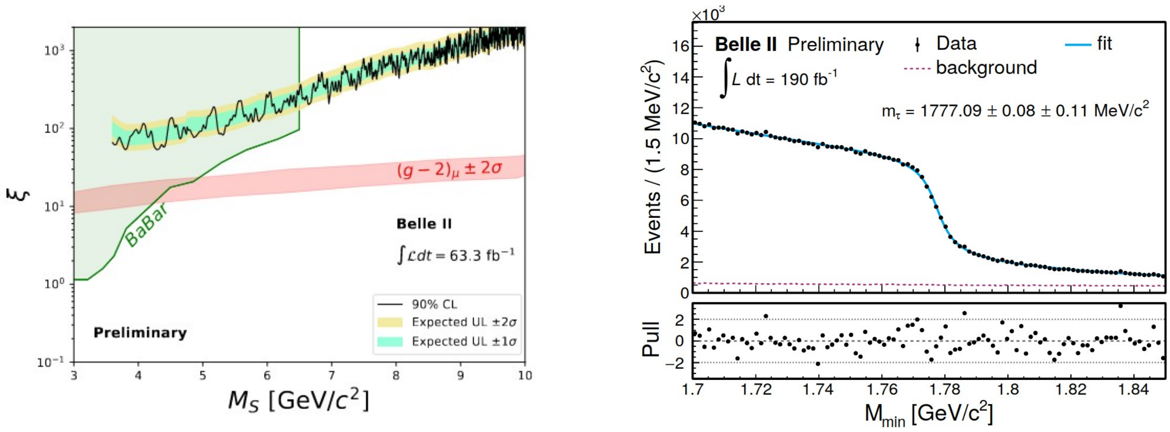

Figure 2 – The 90% CL upper limits on the leptophilic coupling constant ξ as a function of the searched M_S are displayed in the left plot. On the right, the pseudo-mass distribution M_{min} in 190 fb^{-1} data, with the endpoint fit superimposed, and the measured value of the tau mass m_τ are shown.

4 Tau physics results

Decays of τ leptons to new LFV bosons are postulated in many models. The process searched in this study is $e^+e^- \to \tau^+(\to \ell\alpha)\tau^-(\to \pi^+\pi^-\pi^-\nu)$ and its charged conjugated, where the first tau is defined as the signal and the second one as the tag. The signal tau is searched for as a final invisible decay of the new boson α accompanied by a lepton $\ell = e, \mu$. Its rest-frame is approximated using as energy half the collision energy $\sqrt{s}/2$ and as momentum direction the opposite to the one of the reconstructed tag tau. We look for a narrow peak corresponding to the two-body decay of the signal tau in the distribution of the normalized lepton energy over a smooth contribution coming from the irreducible background of $\tau \to \ell\nu\bar{\nu}_\ell$ processes. In absence of any signal excess in 63 fb^{-1}data, 95% CL upper limits are computed on the ratio of branching fractions $\mathcal{B}(\tau \to \ell\alpha)$ normalized to $\mathcal{B}(\tau \to \ell\nu\bar{\nu}_\ell)$. This analysis provides limits between 2-14 times more stringent than the previous one set by ARGUS.

Possible new mediators may enhance the branching fraction for tau LFV decays $\tau^- \to \ell^-\phi$ up to observable levels of $10^{-11} - 10^{-8}$, and accommodate for flavor anomalies observed in lepton flavor universality tests with B decays [2]. In contrast to previous searches for $\tau^- \to \ell^-\phi$ decays performed at Belle [5] on $e^+e^- \to \tau^+\tau^-$ events, we apply for the first time a new *untagged* approach. Only the signal tau decay to a ϕ meson candidate and a lepton, either muon or electron, is explicitly reconstructed and the other tau (*tag*) is not required to decay to any specific known final state. Event kinematics features and signal properties are used in a BDT classifier to suppress the background, with double the final signal efficiency for the muon mode with respect to previous analyses. Yields are extracted with a Poisson counting experiment approach from windows peaking at the the known tau mass and at zero in the plane $(M_\tau, \Delta E_\tau)$, with ΔE_τ the difference between the reconstructed energy of the signal tau in the c.m. frame and half the collision energy. We find no significant excess and set 90% CL upper limits on the branching fractions to be $\mathcal{B}_{\rm UL}(\tau^- \to e^-\phi)$=23$\times$10^{-8} and $\mathcal{B}_{\rm UL}(\tau^- \to \mu^-\phi)$=9.7$\times$10^{-8}.

Lepton properties are fundamental parameters of the SM and need to be measured with the highest precision. Belle II is suitable to access several τ lepton properties. By applying the pseudo-mass M_{min} technique to reconstructed $e^+e^- \to \tau^+\tau^-$ events from 190 fb^{-1} data, we provide the world's most precise measurement of the tau mass M_τ. The measured value is extracted from a fit to the endpoint of the distribution $M_{min} = \sqrt{M^2_{3\pi} + 2(\sqrt{s}/2 - E^*_{3\pi})(E^*_{3\pi} - P^*_{3\pi})}$, computed from events where the signal tau is reconstructed as the decay to three charged pions and the other tau decaying into one charged particle. An excellent control of the systematic sources, dominated by the calibration of the beam energies and the charged-particle momenta scale, is required to shrink down the total systematic uncertainty to 0.11 MeV/c^2, achieving the most precise measure to date of the tau lepton mass of $1777.09 \pm 0.08_{\rm stat} \pm 0.11_{\rm sys}$.

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