Search for a $\tau^+\tau^-$ Resonance in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$ Events with the Belle II Experiment

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We report the first search for a nonstandard-model resonance decaying into τ pairs in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$ events in the 3.6–10 GeV$/c^2$ mass range. We use a 62.8 fb^{-1} sample of e^+e^- collisions collected at a center-of-mass energy of 10.58 GeV by the Belle II experiment at the SuperKEKB collider. The analysis probes three different models predicting a spin-1 particle coupling only to the heavier lepton families, a Higgs-like spin-0 particle that couples preferentially to charged leptons (leptophilic scalar), and an axionlike particle, respectively. We observe no evidence for a signal and set exclusion limits at 90% confidence level on the product of cross section and branching fraction into τ pairs, ranging from 0.7 to 24 fb, and on the couplings of these processes. We obtain world-leading constraints on the couplings for the leptophilic scalar model for masses above 6.5 GeV$/c^2$ and for the axionlike particle model over the entire mass range.

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Despite its successes, the standard model (SM) of particle physics is known to provide an incomplete description of nature. For example, it does not address the phenomenology related to the existence of dark matter [1], specifically in the prediction of the observed relic density. In addition, experimental observations showed inconsistencies with the SM. Prominent examples are the long-standing difference between the measured and the expected value of the muon anomalous magnetic moment [2–4] and the tensions in flavor observables reported by the BaBar, Belle, and LHCb Collaborations [5–12]. Some of these observations can be explained with the introduction of additional, possibly lepton-universality-violating interactions mediated by non-SM neutral bosons. Examples are the $L_\mu - L_\tau$ extension of the SM, a Higgs-like spin-0 particle (leptophilic scalar), and axionlike particles (ALPs). The $L_\mu - L_\tau$ model gauges the difference between the muon and the τ-lepton numbers through the introduction of a neutral spin-1 boson Z' that couples only to the second and third generations of leptons [13–15]. The Z' could also mediate interactions between SM and dark matter. The leptophilic scalar S is an hypothetical particle that couples preferentially to charged leptons through a parameter ξ and Yukawa-like couplings to the individual families proportional to the lepton masses [16]. Axionlike particles appear in many models with spontaneous breaking of global symmetries as relics of high-energy extensions of the SM [17,18]. In some models, they couple to charged leptons through parameters $C_{\ell\ell}$ with $\ell = e, \mu, \tau$, with a decay rate to leptons proportional to the squared lepton masses. The coupling to charged leptons is parametrized as $|C_{\ell\ell}|/\Lambda$, where Λ is the scale of the global symmetry breaking [18]. For the ALP model, we follow the approach of Refs. [17,18], in which the coupling of ALPs to charged leptons is studied assuming no coupling to all the other particles, in particular, photons.

Searches for a Z' decaying to muons have been reported by the BaBar, Belle, and CMS Collaborations [19–21]. An invisibly decaying Z' has been searched for by the Belle II [22,23] and NA64-e [24] experiments. The leptophilic scalar decaying into electrons and muons is constrained by BaBar for masses up to approximately 6.5 GeV$/c^2$ [25]. Decays of ALPs into leptons are constrained mostly through reinterpretations of other measurements [17,18]. For all these particles, decays into pairs of τ leptons are unconstrained due to the experimental difficulties in fully reconstructing the final state that has multiple neutrinos.

In this Letter, we search for a $X \to \tau^+\tau^-$ resonance, where $X = Z'$, S, or ALP, in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$ events.

The signal signature is a narrow enhancement in the distribution of the recoil mass against two oppositely charged muons $M_{\rm recoil}(\mu\mu)$. This exploits the fact that in electron-positron colliders the beam energy is entirely transferred to the final-state collision products. We use a sample of e^+e^- collisions produced at a c.m. energy $\sqrt{s} = 10.58$ GeV in 2019–2020 by the SuperKEKB asymmetric-energy collider [26] at KEK. The data, recorded by the Belle II detector [27,28], correspond to an integrated luminosity of 62.8 fb^{-1} [29]. The $L_\mu - L_\tau$ model is used as a benchmark to devise the analysis selections through the process $e^+e^- \to Z'(\to \tau^+\tau^-)\mu^+\mu^-$. We then check the selection performance on the two additional models. In all the cases, the X resonance is predominantly emitted as final-state radiation (FSR) off one of the two muons. We restrict our analysis to τ-lepton decays to one charged particle and any number of neutral particles. We therefore select events with exactly four charged particles, where at least two are identified as muons (tagging muons). The main expected backgrounds are the processes $e^+e^- \to q\bar{q}(\gamma)$ with $q = u, d, s, c, b$, $e^+e^- \to \tau^+\tau^-(\gamma)$, where one τ lepton decays into a one-charged-particle state (one prong) and the other to a three-charged-particle state (three prong), and four-lepton processes $e^+e^- \to e^+e^-\mu^+\mu^-$, $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$, and $e^+e^- \to e^+e^-\tau^+\tau^-$. A multivariate analysis exploits kinematic variables to enhance the signal-to-background ratio. A control sample is used to compare data to simulation, from which the most important systematic uncertainties are estimated. The signal yield is extracted through fits to the $M_{\rm recoil}(\mu\mu)$ distribution, which allows an estimate of the background directly from data. To minimize bias, the analysis techniques are defined using simulated events prior to examining data.

The Belle II detector [27,28] consists of several subdetectors arranged in a cylindrical structure around the e^+e^- interaction point. The longitudinal direction, the transverse plane, and the polar angle θ are defined with respect to the detector's cylindrical axis in the direction of the electron beam. Charged-particle trajectories (tracks) are reconstructed by a tracking system consisting of a two-layer silicon-pixel detector, surrounded by a four-layer double-sided silicon-strip detector, and then a central drift chamber (CDC) covering $17° < \theta < 150°$. The second pixel layer was only partially installed for the data sample we analyze, covering one-sixth of the azimuthal angle. Outside the CDC, time-of-propagation and aerogel ring-imaging Cherenkov detectors cover $31° < \theta < 128°$ and $14° < \theta < 30°$, respectively, to provide charged-particle identification. The electromagnetic calorimeter (ECL) reconstructs photons and identifies electrons in the range $12° < \theta < 155°$. It fills the remaining volume inside a superconducting solenoid that generates a 1.5-T field. A K_L^0 and muon detection subsystem (KLM) is installed in the iron flux return of the solenoid and covers $18° < \theta < 155°$.

The identification of muons relies mostly on charged-particle penetration in the KLM for momenta larger than 0.7 GeV/c and on information from the CDC and ECL otherwise. Electrons are identified mostly by comparing measured momenta with energies of the associated ECL depositions. We identify charged hadrons as particles not compatible with both electrons and muons. Charged pions are identified combining the information from all subdetectors except the silicon detectors. Photons are reconstructed from ECL-energy depositions greater than 100 MeV not associated with any track. Neutral pions are identified as pairs of photons with an invariant mass within 3 standard deviations from the known π^0 mass. Details of particle reconstruction and identification are given in Refs. [28,30].

Signal events are simulated using MadGraph5@NLO [31], including initial-state radiation (ISR). The $M_{\rm recoil}(\mu\mu)$ resolution varies with the Z' mass: it is 30 MeV/c^2 at the kinematic threshold $2m_\tau$ and decreases smoothly to 10 MeV/c^2 at 6 GeV/c^2 and to 1 MeV/c^2 at 10 GeV/c^2. We generate events for Z' masses ranging from 3.6 to 10 GeV/c^2 in steps of 25, 20, 10, and 5 MeV/c^2, following the $M_{\rm recoil}(\mu\mu)$ resolution. The background processes are simulated using the following generators: $e^+e^- \to u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$ with KKMC [32] interfaced with PYTHIA 8 [33] and EvtGen [34]; $e^+e^- \to b\bar{b}$ with EvtGen; $e^+e^- \to \tau^+\tau^-(\gamma)$ with KKMC interfaced with TAUOLA [35]; $e^+e^- \to e^+e^-\mu^+\mu^-$, $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$, $e^+e^- \to e^+e^-\tau^+\tau^-$, $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$, and $e^+e^- \to e^+e^-e^+e^-$ with AAFH [36]; $e^+e^- \to e^+e^-\pi^+\pi^-$ with TREPS [37]; and $e^+e^- \to \mu^+\mu^-(\gamma)$ with KKMC. Electromagnetic FSR is simulated with PHOTOS [38,39] for processes generated with EvtGen. All the four-lepton processes generated with AAFH do not include ISR effects. Additional nonsimulated backgrounds include $e^+e^- \to \mu^+\mu^-\pi^+\pi^-$ processes and two-photon processes $e^+e^- \to e^+e^-h$, where h is typically a low-mass hadronic system. The detector geometry and interactions of final-state particles with detector material are simulated using GEANT4 [40] and the Belle II software [41,42].

The online event selection (trigger) is a logical OR of a three-track trigger and a single-muon trigger. The former requires the presence of at least three tracks in $37° < \theta < 120°$. The latter is based on the match between CDC tracks and signals in the $51° < \theta < 117°$ KLM polar range. An unbiased measurement of the efficiency of both triggers is performed using a reference trigger, which requires that the total ECL-energy deposition in $22° < \theta < 128°$ exceeds 1 GeV. This is achieved by requiring the presence of one electron with energy above 1 GeV. The three-track-trigger efficiency is measured in four-track events containing at least two pions and one electron. The single-muon-trigger efficiency is measured in events with one electron and one muon: the efficiency for events with multiple muons is computed using the single-muon efficiency, assuming no correlation. The overall trigger efficiency is 96% for Z' masses up to 8 GeV/c^2, then it decreases smoothly to 90% at 9 GeV/c^2 and to 50% at 10 GeV/c^2.

To suppress misreconstructed and beam-induced background tracks, we require that the transverse and longitudinal projections of their distance of closest approach to the interaction point be smaller than 0.5 and 2.0 cm, respectively. We require that events have exactly four charged particles with zero net charge, with at least a pair of oppositely charged particles identified as muons and the remaining two particles separately identified as electrons, muons, or charged hadrons, for which we assume the electron, muon, and pion mass hypotheses, respectively. Events with more than two muons produce up to four candidates. We require that the four-track invariant mass $M(4\ \text{tracks})$ be below 9.5 GeV/c^2 to suppress the four-lepton backgrounds that peak at the c.m. energy, such as $e^+e^- \to e^+e^-\mu^+\mu^-$, $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$, and $e^+e^- \to e^+e^-e^+e^-$. The remaining background is largely dominated by $e^+e^- \to q\bar{q}(\gamma)$ and $e^+e^- \to \tau^+\tau^-(\gamma)$ and, to a lesser extent, by $e^+e^- \to e^+e^-\mu^+\mu^-$ processes. The final signal-from-background discrimination relies on signal-event properties: presence of a resonance recoiling against the two tagging muons, FSR emission of the resonance, and compatibility of the system recoiling against the tagging muons with a $\tau^+\tau^-$ pair. We identify 14 variables (see Supplemental Material [43]), among which the most discriminating are the following: the momenta of the two tagging muons in the c.m. frame; the components of the recoil momentum (the Z' momentum, for signal events) transverse to the momentum direction of each of the two tagging muons in the c.m. frame; and topological variables defined in the rest frame of the system recoiling against the two muons, such as the thrust value [44,45], the first Fox-Wolfram moment shape variable [46], and the angles between the thrust direction and the directions of the muons. We preprocess some variables to reduce their dependence on the Z' mass. For example, the momentum variables are scaled by the maximum momentum of the system with mass $M_{\text{recoil}}(\mu\mu)$ recoiling against the two tagging muons.

We use multilayer perceptrons (MLPs) [47], trained on simulated signal and background events, with 14 input nodes and one output node for the signal-from-background discrimination. To improve performance, we use eight separate MLPs in different $M_{\text{recoil}}(\mu\mu)$ intervals, which we refer to as MLP ranges, approximately 1 GeV/c^2 wide. The selection applied on the node output is optimized separately in each MLP range with a figure of merit [48] and then expressed as a function of $M_{\text{recoil}}(\mu\mu)$ by interpolation. The resulting signal efficiency varies with the Z' mass from 12% near the kinematic threshold $2m_\tau$ to 2% at 10 GeV/c^2 [43]. The background suppression reduces the $e^+e^- \to q\bar{q}(\gamma)$ and $e^+e^- \to \tau^+\tau^-(\gamma)$ processes by 2–3 orders of magnitude, so that the resulting expected

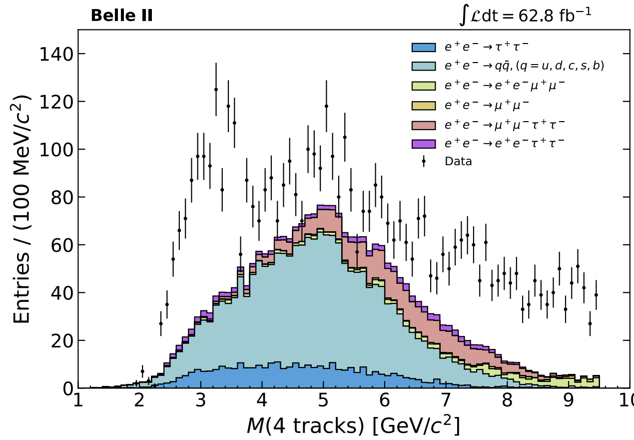

FIG. 1. Observed four-track invariant mass distribution compared to the expectations of the simulation. Contributions from the various simulated processes are stacked.

background contains significant contributions from the four-lepton $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$ and $e^+e^- \to e^+e^-\tau^+\tau^-$ processes, which were small before the MLP selection. The fraction of surviving events with more than one candidate is negligible.

We apply the full selection on signal events simulated according to the two additional models and compare the signal efficiencies with those estimated for the $L_\mu - L_\tau$ model: relative differences are in the range 10%–20%.

The $M(4\ \text{tracks})$ distribution after all selections are applied is compared with the simulation in Fig. 1. The discrepancies between data and simulation are due to large contributions from nonsimulated two-photon processes $e^+e^- \to e^+e^-h$ for $M(4\ \text{tracks}) < 4\ \mathrm{GeV}/c^2$ and to missing ISR in simulated four-lepton processes for $M(4\ \text{tracks}) > 7\ \mathrm{GeV}/c^2$. Additional contributions to the observed discrepancies come from the process $e^+e^- \to \mu^+\mu^-\pi^+\pi^-$. The origin of these discrepancies is confirmed by specific studies on the $M(4\ \text{tracks})$ distribution before the MLP selection [43] and on a control sample after all the selections. A pion-tagged control sample is selected by applying the analysis requirements with the two tagging muons replaced by two charged pions. Both samples are dominated by $e^+e^- \to q\bar{q}(\gamma)$ and $e^+e^- \to \tau^+\tau^-(\gamma)$ processes, which include ISR in the respective generators. In both cases, we observe good agreement for dimuon or dipion masses greater than 2 GeV/c^2, where the two-photon processes $e^+e^- \to e^+e^-h$ do not contribute [43].

The $M_{\text{recoil}}(\mu\mu)$ distribution after all the selections are applied is shown in Fig. 2. Discrepancies induced by the lack of ISR effects in four-lepton simulation appear mainly for $M_{\text{recoil}}(\mu\mu)$ below approximately 6 GeV/c^2. Above 9 GeV/c^2, the discrepancies are due to two-photon $e^+e^- \to e^+e^-h$ processes. Also visible are variations among the eight MLP ranges. Neither of these effects produce narrow peaking structures at the scale of the signal

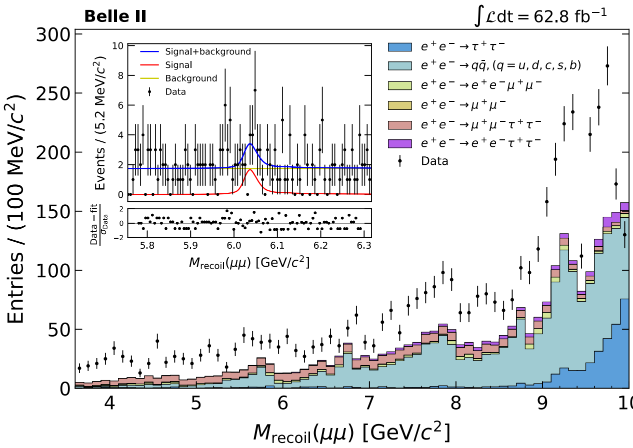

FIG. 2. Observed distribution of the recoil mass against the two tagging muons, compared to the expectations of the simulation. Contributions from the various simulated processes are stacked. Inset: an example fit at a signal mass hypothesis of 6.036 GeV$/c^2$ and the difference between the number of observed and fitted events, divided by the statistical uncertainty of the former.

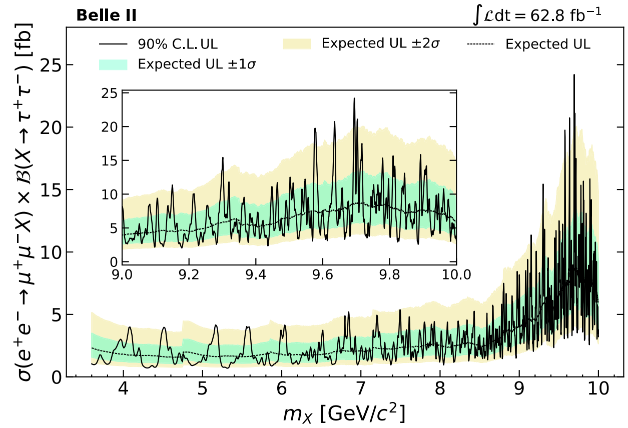

FIG. 3. Observed 90% C.L. upper limits (UL) and corresponding expected limits on the cross section for the process $e^+e^-\to X(\to\tau^+\tau^-)\,\mu^+\mu^-$ with $X = Z', S$, ALP as functions of the X resonance mass. Inset: a magnification of the region above 9 GeV$/c^2$.

resolution in the $M_{\rm recoil}(\mu\mu)$ distribution, as shown by the inset in Fig. 2.

The signal yields are obtained from a scan over the $M_{\rm recoil}(\mu\mu)$ spectrum through a series of unbinned maximum likelihood fits. The signal $M_{\rm recoil}(\mu\mu)$ distributions are parametrized from the simulation as sums of two Crystal Ball functions [49] sharing the same mean value. The scan step size is half the mass resolution. Each fit extends over an interval 40 times larger than the Z' mass resolution. The background is described with a constant. Higher-order polynomials for the background parametrization are investigated, but their coefficients are compatible with zero over the full recoil-mass spectrum. A total of 2384 fits are performed, covering the range 3.6–10 GeV$/c^2$. If a fitting interval extends over two different MLP ranges, we use data selected by the MLP corresponding to the range where the central mass value is located. The fit determines the signal and background yields using a fixed signal shape. We then convert signal yields into cross sections, after correcting for signal efficiency and luminosity.

Several sources of systematic uncertainties affecting the cross section determination are taken into account: they are related to signal efficiency, luminosity, and fit procedure. Uncertainties due to the trigger efficiency are evaluated by propagating the uncertainties on the measured trigger efficiencies. The relative uncertainty on the signal efficiency is 2.7% across the entire mass range. Uncertainties due to the tracking efficiency are estimated in $e^+e^-\to\tau^+\tau^-(\gamma)$ events, in the one-prong against three-prong topology. The relative uncertainty on the signal efficiency is 3.6%. Uncertainties due to the particle-identification requirement are studied using $e^+e^-\to\mu^+\mu^-\gamma$, $e^+e^-\to e^+e^-\mu^+\mu^-$, $e^+e^-\to e^+e^-e^+e^-$, and $e^+e^-\to e^+e^-\pi^+\pi^-$ events and final states with either a J/ψ or a K_S^0. The relative uncertainty on the signal efficiency varies between 3.9% and 6.2%, depending on the Z' mass. Uncertainties due to the MLP selection efficiency are evaluated on the pion-tagged control sample. We compare MLP efficiencies in data and simulation in signal-like regions of the control sample and assume that uncertainties estimated in those conditions are representative of the signal conditions. We find good agreement between data and simulation and estimate a 2.8% relative uncertainty on the signal efficiency from the uncertainty of the data-simulation comparison. Uncertainties due to the interpolation of the signal efficiency between simulated mass points are 2.5%, which is assigned as a relative uncertainty on the signal efficiency. Uncertainties due to the fit procedure are evaluated using a bootstrap technique [50]. Signal events from simulation are overlaid on simulated background with a yield corresponding to the excluded 90% C.L. value and fitted for each Z' mass. The distribution of the difference between the overlaid and the fitted yields, divided by the fit uncertainty, has a negligible average bias with a width that deviates from 1 by 4%, which is assigned as a relative uncertainty on the signal-yield determination. Uncertainties due to differences in the recoil-mass resolution between data and simulation are evaluated by introducing an additional smearing on the simulated momenta of the two tagging muons, which reflects the difference in momentum resolution measured with cosmic rays and in $D^{*+}\to D^0\pi^+$ decays with respect to the simulation predictions. The relative uncertainty on the signal-yield determination is 3%. The relative uncertainty on the signal efficiency due to the knowledge of the beam energy is 1% [51]. The uncertainty due to the selection on the four-track invariant mass is negligible. Finally, a relative uncertainty of 1% on the integrated luminosity is considered [29].

All the systematic uncertainties are summed in quadrature: the final relative systematic uncertainty on the cross

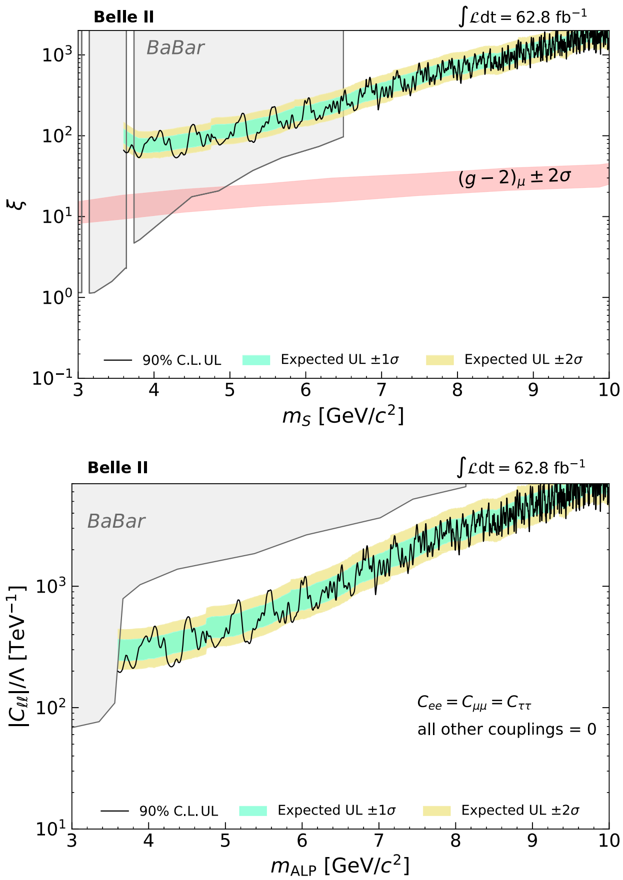

FIG. 4. Observed 90% C.L. upper limits and corresponding expected limits as functions of mass on (top) the leptophilic scalar coupling ξ and on (bottom) the ALP coupling to leptons $|C_{\ell\ell}|/\Lambda$ in the hypothesis of equal couplings to the three lepton families and zero couplings to all other particles. Also shown are (top) constraints for S decaying in electrons or muons from a BaBar search [25] and (bottom) constraints for an ALP decaying to leptons from a reinterpretation [17,18] of BaBar searches. The red band in the top plot shows the region that explains the muon anomalous magnetic moment $(g-2)_\mu \pm 2\sigma$.

section varies in the range 8.8%–10.0% depending on the Z' mass. We account for systematic uncertainties by approximating their effects as a Gaussian smearing of the signal efficiency.

The significance is evaluated as $\sqrt{2\log(\mathcal{L}/\mathcal{L}_0)}$ where $\mathcal{L}$ and $\mathcal{L}_0$ are the likelihoods of the fits with and without signal. The largest local significance observed is 3.0σ, corresponding to a global significance of 1.8σ, at a recoil mass of 9.695 GeV$/c^2$ [43]. Since we do not observe any significant excess above the background, we derive 90% C.L. upper limits on the process cross section $\sigma[e^+e^- \to X(\to \tau^+\tau^-)\mu^+\mu^-] = \sigma(e^+e^- \to \mu^+\mu^- X) \times \mathcal{B}(X \to \tau^+\tau^-)$ with $X = Z', S$, ALP, using the frequentist procedure CL_S [52,53]. The limits are shown in Fig. 3. Expected limits are defined as median limits from background-only simulated samples that use background yields observed from the fits to data. The combination of the variations originating from the MLP ranges and of the overlap between the fit intervals induces an oscillatory behavior. The resulting upper limits are dominated by sample size, with systematic uncertainties worsening them on average by 1% compared to the case in which they are neglected.

The cross section results are translated into upper limits on the coupling constant g' of the $L_\mu - L_\tau$ model [43], on the coupling strength ξ of the leptophilic scalar S, and on the coupling $|C_{\ell\ell}|/\Lambda$ for an ALP decaying to leptons: values as low as 2.5×10^{-2}, 51, and 200 TeV^{-1} are found, respectively. The last two are shown in Fig. 4 as functions of the resonance mass. For the leptophilic scalar model, we constrain the coupling ξ to be smaller than approximately 200 for masses above 6.5 GeV$/c^2$, which are the first results in that region. For the model with the ALP decaying to leptons, these are the first results for the ALP-τ coupling.

In summary, we search for a resonance decaying to $\tau^+\tau^-$ in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$ events in a data sample of e^+e^- collisions at 10.58 GeV collected by Belle II in 2019–2020, corresponding to an integrated luminosity of 62.8 fb^{-1}. We find no significant excess above the background and set upper limits on the cross section, ranging from 0.7 to 24 fb, for masses between 3.6 and 10 GeV$/c^2$. We derive exclusion limits on the couplings for three different models: the $L_\mu - L_\tau$ model; a leptophilic scalar model, for which we probe for the first time masses above 6.5 GeV$/c^2$; and a model with an ALP decaying to leptons, for which we set world-leading limits over the entire mass range considered.

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