# Latest results in the $\tau$ physics and the dark sector from the Belle II experiment

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**Summary.** — Belle II has a leading role in the $\tau$ sector and dark sector due to its large $\tau$ sample and unique sensitivity for a broad class of models postulating the existence of dark matter particles with masses in the MeV-GeV range. We present recent world-leading results from the Belle II collaboration for: lepton universality test through the leptonic $\tau$ decay; search for a lepton flavor violating $\tau$ decay; production of an $X$ state decaying in two muons, interpretable both as a $Z^{'}$ boson or a muonphilic dark scalar; search for a long-lived scalar or axion-like particle produced in decays of B-mesons.

## 1. – Description

Belle II [1] is a high-intensity frontier experiment that operates at the SuperKEKB $e^+e^-$ asymmetric-energy collider with center of mass energy of $\sqrt{s} = 10.58$ GeV [2]. During the first data taking run (2019–2022), Belle II collected a sample of $e^+e^-$ collision data corresponding to 424 $\text{fb}^{-1}$ of integrated luminosity. The SuperKEKB - Belle II can be considered a $\tau$-factory: due to the clean environment plus the hermicity of the Belle II detector, it is possible to make accurate analyses in the $\tau$ sector. Thanks to the excellent reconstruction capabilities for low multiplicity and missing energy signatures, along with the use of dedicated triggers, Belle II has a unique or world-leading sensitivity to the dark sector [6].

## 2. – Recent results at Belle II for $\tau$ physics

The rich Belle II $\tau$-lepton program covers, among other topics, lepton universality tests, determination of fundamental Standard Model (SM) parameters, and searches of non-SM interactions via lepton flavor violation processes. The $\tau$ leptons are produced in pairs with known center-of-mass energy; the events are geometrically split in *signal* and *tag* side, and for each one the $\tau$ flight direction is approximated via the thrust vector [7] [8].

**2**˙1. *Lepton flavor universality test with* $\tau^{\pm} \to l^{\pm}\bar{\nu}_l\nu_\tau$. – The $\tau$ decays allow high precision tests of the fundamental SM assumption of lepton flavor universality (LFU). In such hypothesis, all three leptons have equal coupling strength $g$ to the charged gauge bosons of the electroweak interaction, but this does not hold in several SM extensions. One possible LFU test can be done in the $\mu - e$ charged current, so we perform the measurement of the ratio $R_\mu = Br(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)/Br(\tau^- \to e^-\bar{\nu}_e\nu_\tau)$ which can be converted as a measure of the ratio between the coupling constants for muon and electron $g_\mu, g_e$. The analysis uses $\tau \to l\bar{\nu}_l\nu_\tau$ with $l = e, \mu$ as signal side, and $\tau$ decaying in a charged hadron and at least one $\pi^0$ as tag side. The main background processes, $e^+e^- \to \tau^+\tau^-$, with $\tau$ decaying into different final states with respect to the signal side decay, and $e^+e^- \to e^+e^-\tau^+\tau^-$, are suppressed with the use of a neural network, obtaining 94% of signal purity and 9.6% signal efficiency. The value of the ratio is extracted through a maximum-likelihood fit based on template distributions of the signal lepton momentum. The ratio value obtained using on 362 $\mathrm{fb}^{-1}$ of data is $R = 0.9675 \pm 0.0007\mathrm{stat} \pm 0.0036\mathrm{syst}$. This result is consistent with the PDG values at $1.4\sigma$ (as shown in Fig.1), and is the most precise test of the $e - \mu$ LFU produced by a single experiment.

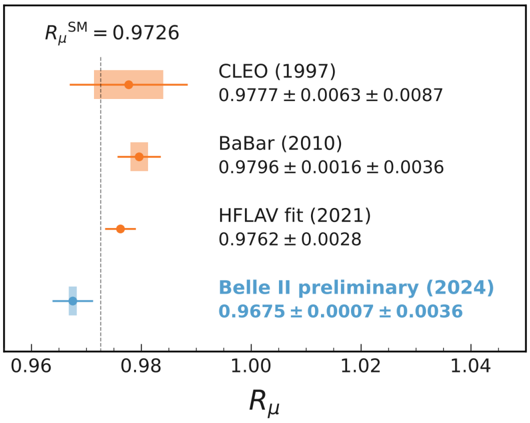



Fig. 1.: Results of the $R_\mu$ measurement given by Belle II, in comparison with the PDG value (solid line) and the results from CLEO [3], BaBar [4] and the average computed by the Heavy Flavor Averaging Group [5]

**2**˙2. *Search for LFV* $\tau^{\pm} \to \mu^{\pm}\mu^{\pm}\mu^{\mp}$ *decays.* – Charged lepton flavor violation processes have never been observed. In minimal SM extension they are allowed, but predicted with branchig ratios too small to be observed in current and planned experiments. New physics with non-SM interactions predict lepton flavor violation in $\tau$ decays at $10^{-10} - 10^{-8}$ level, which is in the sensitivity range of Belle II. We perform a search for a LFV decay of a $\tau$ into three muons, using an inclusive approach for the tag side. The signal region is defined in a 2-dimensional space given by the difference in energy $\Delta E = E_{3\mu} - E_{beam}$ and the invariant mass $M_{3\mu}$ of the three reconstructed muons. For correctly reconstructed signal candidates $\Delta E$ peaks at zero and $M_{3\mu}$ at the tau mass. Background processes are suppressed with a boosted decision tree; the number of background events expected inside the signal region is computed studying the background levels in the sideband regions, which are again defined in the $\Delta E - M_{3\mu}$ plane, outside the signal region as such to contain

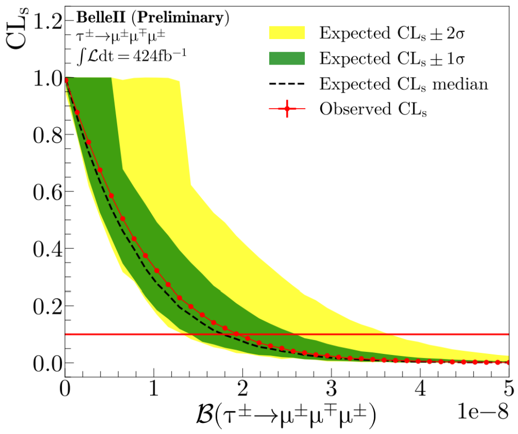


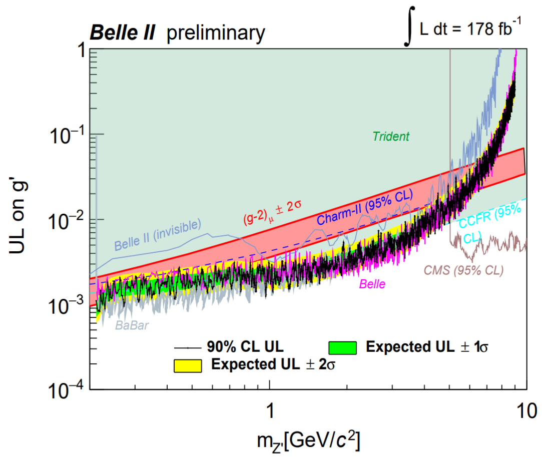

Fig. 2.: Observed 90% C.L. upper limits (UL) on the $\mathcal{B}(\tau^{\pm} \to \mu^{\pm}\mu^{\pm}\mu^{\mp})$

a negligible fraction of the latter. Using 424 $\mathrm{fb}^{-1}$ of collected data, we find one event in the signal region, compatible with the expected background yield; thus no significant excess has been registered and we set a 90% C.L. limit on $\mathcal{B}(\tau^{\pm} \to \mu^{\pm}\mu^{\pm}\mu^{\mp}) = 1.9 \times 10^{-8}$. This is the most stringent upper limit up to date [11] [10] [12] [9]. The Belle II upper limit is shown in Fig. 2

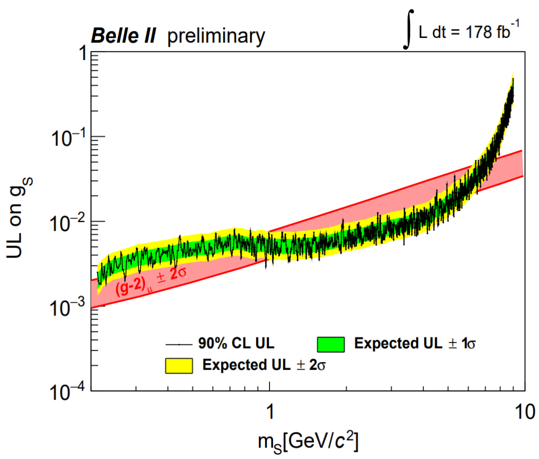
## 3. – Recent dark sector results at Belle II

Several astrophysical observations suggest the existence of dark matter (DM), a component of matter of unknown nature that does not interact through strong or electroweak forces. It is one of the most compelling phenomena in support for physics beyond the Standard Model, and the masses of its constituents could lay in the MeV-GeV mass region, feebly interacting with SM particles through non-SM mediators. The search for these new type of particles has been actively pursued at beam dump and high-intensity frontier experiments.

**3·1.** *Search for a new mediator in* $e^+e^- \to \mu^+\mu^- X(\to \mu^+\mu^-)$. – We search for a resonance decaying into two muons $X \to \mu^+\mu^-$ 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 $X$ can be a *Z'* boson mediating a non-flavor-universal coupling, as proposed in the $L_\mu - L_\tau$ SM extension; or as a new muonphilic scalar $S$ with a Yukawa-like coupling to the muon only. Both hypotheses provide an explanation for the long standing problem of the $(g-2)_\mu$ anomaly, and the new boson *Z'* could also mediate interactions with DM particles. The dominant background is the SM four-muon final-state process $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$. Background is suppressed using neural networks which combine kinematic variables sensitive to the $X$-production mechanism as a final state radiation off one of the two muons, and to the presence of a resonance in both the candidate and the recoil muon pairs. The neural networks are trained in different $X$ mass ranges. From extended maximum likelihood fits to the dimuon mass distribution, we do not observe any significant excess in 178 $\mathrm{fb}^{-1}$ 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 the muonphilic scalar $S$ with muons [15]. Despite the smaller data, we obtain similar results to the existing limits on $g$ from $B_A B_{AR}$ [13] and Belle [14], which performed the analysis with 514 $\text{fb}^{-1}$ and 643 $\text{fb}^{-1}$ respectively (Fig. 3a). We set the first limits for the muonphilic scalar model from a dedicated search (Fig.3b)




(a) Observed 90% C.L. upper limits on the coupling $g$ of a $Z'$ boson in the $L_\mu - L_\tau$ model, as a function of the mass $m_{Z'}$




(b) 90% C.L. limits on the coupling $g$ of a muonphilic scalar $S$ as a function of the scalars mass $m_S$

Fig. 3.: Results for a $X \to \mu\mu$ resonance in two interpretations: at the top, for $X$ as a new boson $Z'$ mediator of a new $L_\mu - L_\tau$ model; on the bottom for $X$ as a muon-philic scalar $S$

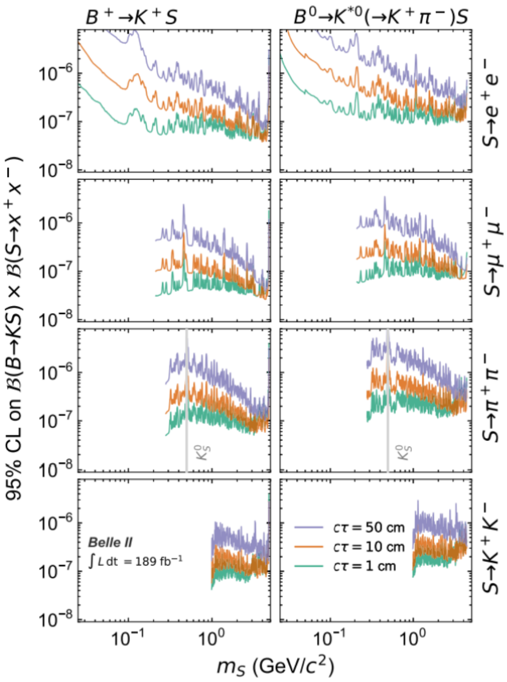



Fig. 4.: Observed 95% C.L. $\mathcal{B}(B \to KS) \times \mathcal{B}(S \to x^+x^-)$ as a function of the scalar mass $m_S$ for different $c\tau_S$.

**3**·2. *Search for a long-lived (pseudo)scalar in $b \to s$ transitions.* – We search for $B^0 \to K^{*0}(\to K^+\pi^-)S$ and $B^0 \to K^+S$ events, where S is a long-lived scalar dacaying as $S \to x^+x^-(x = e, \mu, \pi, K)$ forming a secondary vertex significantly displaced from the $B$ decay position. The signal yield is extracted through extended maximum likelihood fits to the reduced invariant mass of $S$, $m^r_{S\to xx} = \sqrt{M^2_{S\to xx} - 4m^2_x}$ 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 kinematic features compatible with a B meson decay; $B \to KK_S(\to \pi^+\pi^-)$, which is vetoed; and non-resonant $B \to Kx^+x^-$, suppressed by tightening the vertex displacement selections. We do not observe any significant excess in 189 fb$^{-1}$ of data, and we set the 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 mass $m_S$ for different S-lifetimes (Fig. 4)

REFERENCES


[1] E. Kou et al (Belle II collaboration), *Prog. Theor. Exp. Phys.*, **123C01** (2019)

[2] K. Akai, K. Furukawa, and H. Koiso (SuperKEKB Accelerator Team), *Nucl. Instrum. Meth.*, **A 907** (2018) 188

[3] A.Anastassov et al (CLEO collaboration), *Phys. Rev. D* , **55** (1997) 2559

[4] B. Aubert et al (BABAR collaboration), *Phys. Rev. Lett* , **105** (2010) 051602

[5] Y.S. Amhis et al (Heavy Flavor Averaging Group), *Phys. Rev. D* , **107** (2023) 052008
[6] L. Aggarwal et al. (on behalf of the Belle II US group), *arXiv:2207.06307 [hep-ex]*, **188** (2022)
[7] S. Brandt, C. Peyrou, R. Sosnowski, and A. Wroblewski, *Phys. Lett.* , **12** (1964) 57
[8] E. Farhi, *Phys. Rev. Lett.* , **39** (1977) 1587
[9] K. Hayasaka et al, *Physics Letters B*, **687** (2010) 139
[10] J.P. Lees et al (BaBar collaboration), *Physics Review D*, **81** (2010) 111101
[11] R. Aaij et al, *JHEP*, **02** (2015) 121.
[12] A.M. Sirunyan et al, *JHEP*, **01** (2021) 163
[13] J.P. Lees et al (BaBar collaboration), *Phys. Rev. D*, **94** (2016) 011102
[14] T. Czank et al (Belle collaboration), *Phys. Rev. D*, **106** (2022) 012003
[15] D. Forbes, C. Herwig, Y. Kahn, G Krnjaic, C. M. Suarez, N. Tran, and A. Whitbeck, *Phys. Rev. D*, **107** (2023) 116026