PROCEEDINGS OF SCIENCE

Tau physics at Belle

Kenta Uno[a,*]
[a] *Niigata University, , Niigata 950-2181, Japan*
E-mail: uno@hep.sc.niigata-u.ac.jp

Studies of the tau lepton are important to search for new physics beyond the Standard Model. A large number of tau-pair events is recorded at Belle, so this experiment is suitable for several studies of the tau lepton. We summarize recent searches for leptophilic dark scalar, charged lepton-flavor violation and electric dipole moment via the tau lepton from Belle.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

*Speaker

https://pos.sissa.it/

PoS(ICHEP2022)721

1. Introduction

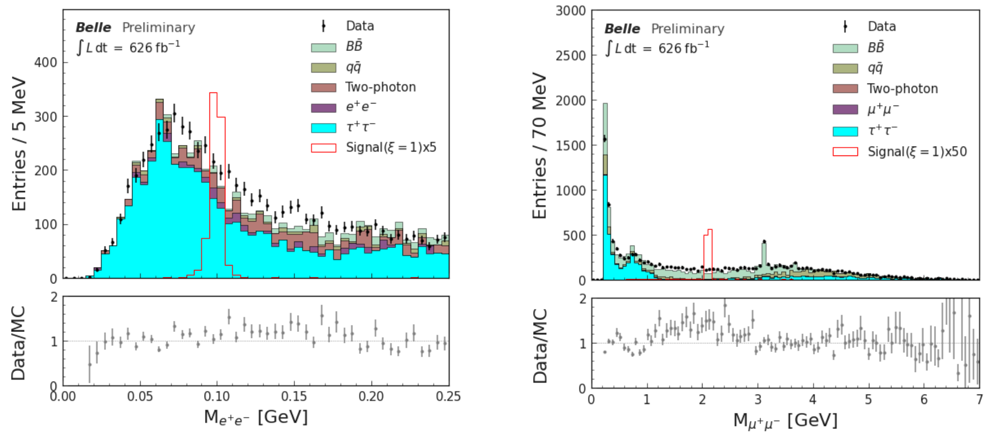
The τ lepton is the heaviest lepton in the Standard Model (SM) and is the only lepton that can be able to decay into both leptons and hadrons. Thus, many decay modes including new physics beyond the Standard Model are expected and studies of the τ lepton are crucial. Belle is the B factory experiment operating at the KEKB asymmetric-energy e^+e^- collider [1], working at the $\Upsilon(nS)$ $(n = 1, 2, 3, 4, 5)$ resonance and off-resonance, which is 60 MeV below the $\Upsilon(nS)$ threshold [2]. In Belle, the tau pairs are also produced via the $e^+e^- \to \tau^+\tau^-$ process and the total number of collected tau-pair events is 912×10^6. It represents the largest number of tau-pair events recorded by a single e^+e^- experiment.

In this proceeding, recent three studies via the τ lepton from Belle are summarized: search for dark leptophilic scalar, lepton flavor violation and measurement of electric dipole moment [3–5].

2. Search for a dark leptohilic scalar

Models that couple the dark sector to the SM via light leptophilic mediators are motivated to explain the anomaly of the muon anomalous magnetic moment and violation of lepton flavor universality [6]. They predict a dark leptophilic scalar (ϕ_L), which couples directly only to leptons [7, 8]. Since the strength of its coupling is proportional to the mass of the lepton, the dark scalar could be produced in association with $\tau^+\tau^-$ pair in e^+e^- annihilation, $e^+e^- \to \tau^+\tau^-\phi_L$. We search for the dark scalar over a wide mass range of 0.04 GeV< m_{ϕ_L} <6.5 GeV using 626 fb^{-1} of data.

We use $\phi_L \to e^+e^-$ channel only up to $m_{\phi_L} = 2m_\mu$, and $\phi_L \to \mu^+\mu^-$ channel for $m_{\phi_L} > 2m_\mu$. Figure 1 shows the distributions of di-lepton invariant mass. The signal distribution has narrow peak near the corresponding dark scalar mass, whereas the background distribution has broad structure except $J/\psi \to \mu^+\mu^-$ resonance. By comparing two distributions, we can distinguish signal and background events.

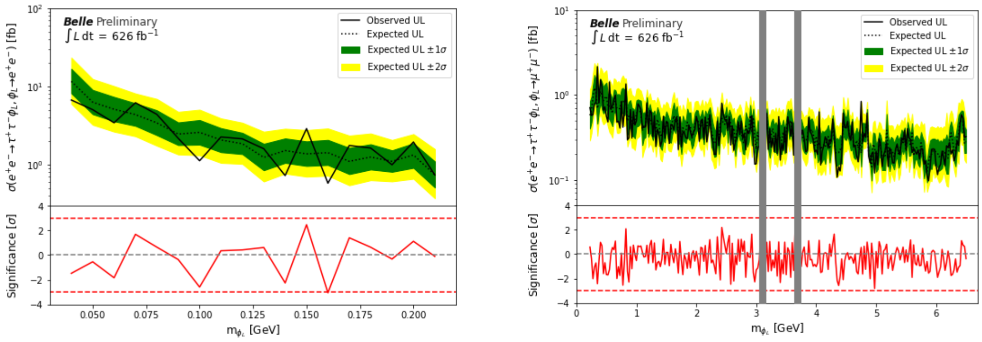


(a) $\phi_L \to e^+e^-$ channel (a) $\phi_L \to \mu^+\mu^-$ channel

Figure 1: Distribution of e^+e^- and $\mu^+\mu^-$ invariant mass. The signal sample in $\phi_L \to e^+e^-$ ($\phi_L \to \mu^+\mu^-$) channel is generated with $m_{\phi_L} = 100$ MeV (2.1 GeV)

.

We perform binned maximum likelihood fits to extract the signal events in the distributions. The results of the likelihood fits are consistent with the background predictions over all signal mass points. Figure 2 shows the upper limits on the cross-section at 90% confidence level (CL) as a function of the dark scalar mass. Figure 3 shows the observed upper limits at 90% CL on the coupling constant ξ as a function of the dark scalar mass. The exclusion limit is most stringent and comparable with that determined by the BaBar experiment [9]. In addition, we could exclude a wide range of parameter space of the model favored by the anomaly of the muon anomalous magnetic moment.



(a) $\phi_L \to e^+e^-$ channel (a) $\phi_L \to \mu^+\mu^-$ channel

Figure 2: Observed upper limits on the cross-section at 90% CL as a function of the dark scalar mass in $\phi_L \to e^+e^-$ (left) and $\phi_L \to \mu^+\mu^-$ channels.

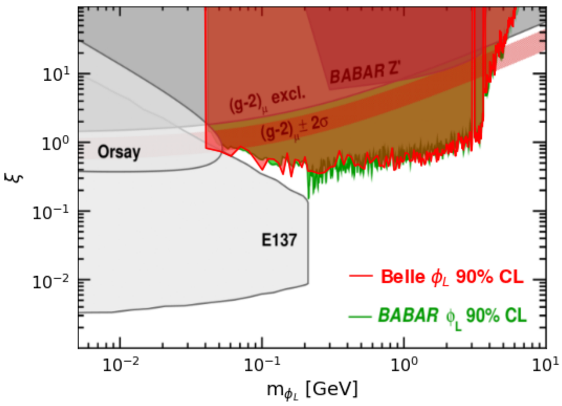


Figure 3: Observed upper limits at 90% CL on the coupling constant ξ as a function of the dark scalar mass.

3. Search for lepton flavor violation, $\tau^\pm \to \ell^\pm\gamma$

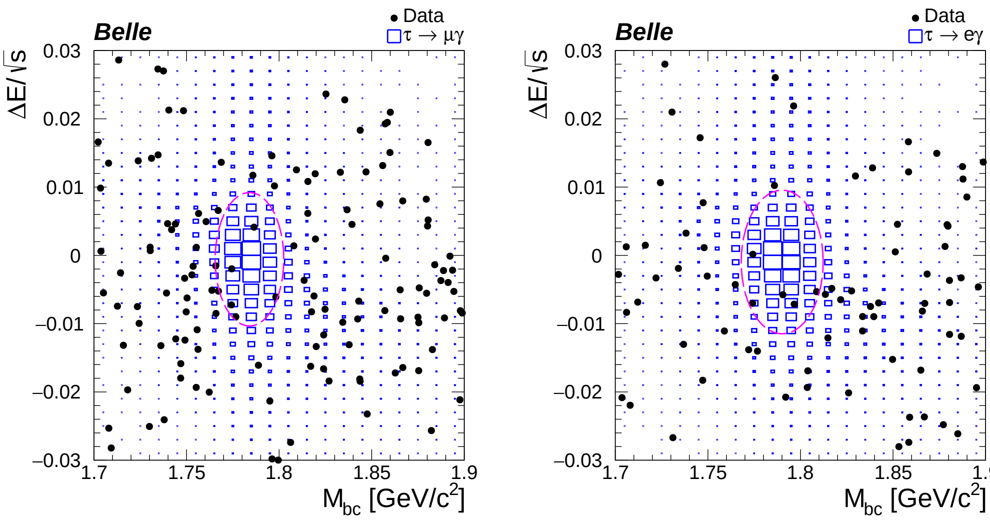
Radiative decays $\tau^\pm \to \ell^\pm\gamma$ ($\ell = e, \mu$) with charged lepton-flavor violation occur with a small probability, $O(10^{-40})$, via neutrino oscillations in the SM [10]. However, they have a sizeable probability in several theories beyond the Standard Model and the search is highly motivated. In order to increase search sensitivities, we use the full data collected by Belle, corresponding to 988 fb^{-1}.

Since the tau decays into a muon (electron) and a photon for the $\tau^\pm \to \mu^\pm\gamma$ ($\tau^\pm \to e^\pm\gamma$) search, the invariant mass and the total energy in the center-of-mass (CM) frame of $\ell\gamma$ pair are powerful variables to identify the signal events. The signal region is defined by two kinematic variables: the beam-energy-constrained mass, $M_{\rm bc}$, and the normalized energy difference, $\Delta E/\sqrt{s}$, given as

$$M_{\rm bc} = \sqrt{(E^{\rm CM}_{\rm beam})^2 - |\vec{p}^{\,\rm CM}_{\ell\gamma}|^2}, \tag{1}$$

$$\Delta E/\sqrt{s} = (E^{\rm CM}_{\ell\gamma} - \sqrt{s}/2)/\sqrt{s}, \tag{2}$$

where $E^{\rm CM}_{\rm beam} = \sqrt{s}/2$ and $\vec{p}^{\,\rm CM}_{\ell\gamma}$ is the sum of the lepton and photon momenta in the CM frame. Here, $\sqrt{s} \sim 10.57$ GeV is the beam energy in the CM frame. Figure 4 shows the two-dimensional distribution of $\Delta E/\sqrt{s}$ and $M_{\rm bc}$. The signal events have $M_{\rm bc} \sim m_\tau$ and $\Delta E/\sqrt{s} \sim 0$ and an elliptical region around their expected values is adopted as the signal region.



(a) $\tau^\pm \to \mu^\pm\gamma$ (b) $\tau^\pm \to e^\pm\gamma$

Figure 4: Two-dimensional distributions of $\Delta E/\sqrt{s}$ and $M_{\rm bc}$ for (a) $\tau^\pm \to \mu^\pm\gamma$ and (b) $\tau^\pm \to e^\pm\gamma$ events. Black points are data, blue squares are $\tau^\pm \to \ell^\pm\gamma$ signal MC events, and magenta ellipses show the signal region used in this analysis.

We perform an unbinned maximum likelihood fit to extract the signal events in the signal region. The results of the likelihood fit are $N_{\rm sig} = -0.3^{+1.8}_{-1.3}$, $N_{\rm bkg} = 5.3^{+3.2}_{-2.3}$ for $\tau^\pm \to \mu^\pm\gamma$, and $N_{\rm sig} = -0.5^{+4.4}_{-3.6}$, $N_{\rm bkg} = 5.5^{+5.2}_{-4.1}$ for $\tau^\pm \to e^\pm\gamma$ and are consistent with background predictions. Here, $N_{\rm sig}$ ($N_{\rm bkg}$) is the number of signal (background) events obtained from the likelihood fit. The observed upper limits on the branching fractions at 90% CL are

$$\mathcal{B}(\tau^\pm \to \mu^\pm\gamma) < 4.2 \times 10^{-8}, \tag{3}$$
$$\mathcal{B}(\tau^\pm \to e^\pm\gamma) < 5.6 \times 10^{-8}. \tag{4}$$

Our expected limits are 1.6–1.8 times more stringent compared to the previous Belle results [12]. In addition, the observed limit on the $\tau^\pm \to \mu^\pm\gamma$ decay is the most stringent to date.

PoS(ICHEP2022)721

4. Measurement of electric dipole moment of the tau lepton

The electric dipole moment (EDM) of the tau lepton is a fundamental parameter related to a violation of time-reversal (T) or charge-conjugation-parity (CP) at the $\gamma\tau\tau$ vertex. CP violation arises due to an irreducible phase in the CKM matrix, to which corresponds an unobservably EDM value of the tau lepton, predicted to be $d_\tau \sim O(10^{-37})$ $e$cm. However, several theories beyond the Standard Model indicate the EDM values at an observable level in experiments, so an observation of the EDM values would be a clear signature of new physics. We updated the search for the EDM using 833 fb^{-1} of data.

Considering the EDM term, the squared spin-density matrix ($\chi_{\rm prod}$) in the $e^+e^- \to \tau^+\tau^-$ process is written by

$$\chi_{\rm prod} = \chi_{\rm SM} + {\rm Re}(d_\tau)\chi_{\rm Re} + {\rm Im}(d_\tau)\chi_{\rm Im} + \text{ (higher-order EDM term)}, \tag{5}$$

where $\chi_{\rm SM}$ is the SM term, and $\chi_{\rm Re}$ ($\chi_{\rm Im}$) is the interference term between the SM and the EDM for real (imaginary) part of d_τ. The intereference terms are proportional to CP spin-momentum correlation. We extract ${\rm Re}(d_\tau)$ and ${\rm Im}(d_\tau)$ using spin information obtained from the momenta of the decay particles.

In order to measure d_τ efficiently, we use optimal observable method [13]. The optimal observables are defined as

$$O_{\rm Re} = \frac{\chi_{\rm Re}}{\chi_{\rm SM}}, \quad O_{\rm Im} = \frac{\chi_{\rm Im}}{\chi_{\rm SM}}. \tag{6}$$

The mean values of the observables, $\langle O_{\rm Re}\rangle$ and $\langle O_{\rm Im}\rangle$ have linear relation to ${\rm Re}(d_\tau)$ and ${\rm Im}(d_\tau)$, respectively as shown in Figure 5. Figure 6 shows the distribution of optimal observables using $\tau^\pm \to \rho^\pm\nu$ events. We take the average of the distributions and extract the EDM values in Figure 5.

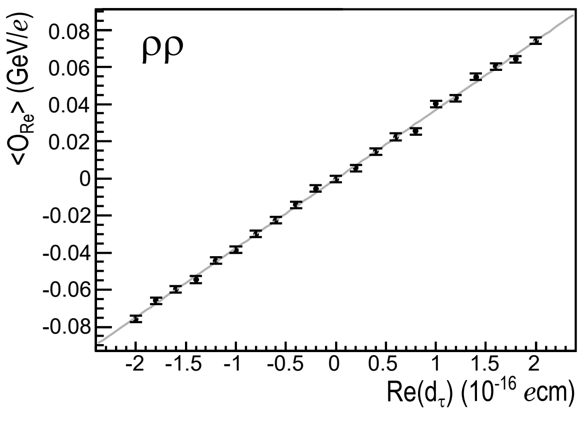
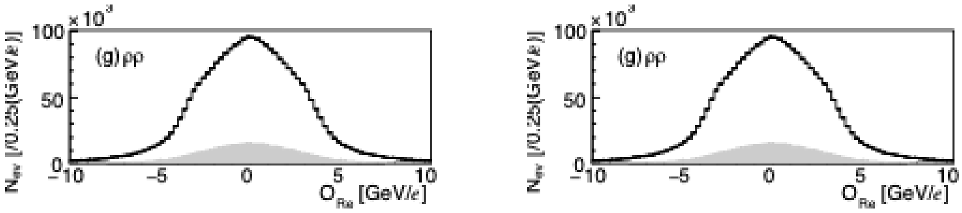


Figure 5: Relation of ${\rm Re}(d_\tau)$ and $\langle O_{\rm Re}\rangle$ for the $\tau^\pm \to \rho^\pm\nu$ mode obtained from the MC simulation.

We calculate EDM values for 8 decay modes such as $e^+e^- \to (e\nu\bar{\nu})(\pi\nu)$ and $e^+e^- \to (\mu\nu\bar{\nu})(\pi\nu)$, exclusively. The final EDM values are obtained by taking weighted average of each



(a) O_{Re} (b) O_{Im}

Figure 6: Distribution of optimal observable for $\tau \to \rho\nu$ decay mode.

decay mode:

$$\mathrm{Re}(d_\tau) = (-0.62 \pm 0.63) \times 10^{-17}\ e\mathrm{cm}, \quad (7)$$

$$\mathrm{Im}(d_\tau) = (-0.40 \pm 0.32) \times 10^{-17}\ e\mathrm{cm}. \quad (8)$$

We also set the upper limits on the EDM values at 95% CL:

$$-1.85 \times 10^{-17} < \mathrm{Re}(d_\tau) < 0.61 \times 10^{-17}\ e\mathrm{cm}, \quad (9)$$

$$-1.03 \times 10^{-17} < \mathrm{Im}(d_\tau) < 0.23 \times 10^{-17}\ e\mathrm{cm}. \quad (10)$$

The sensitivity for $\mathrm{Re}(d_\tau)$ and $\mathrm{Im}(d_\tau)$ has improved by about a factor of three compared to the previous Belle analysis [14].

References

[1] S. Kurokawa and E. Kikutani, Nucl. Instrum. Meth. Phys. Res., Sect. A **499**, 1 (2003).

[2] J. Brodzicka *et al.* (Belle Collaboration), Prog. Theor. Exp. Phys. **2012**, 2050 (2012).

[3] The Belle Collaboration, arXiv:2207.07476 [hep-ex]

[4] K. Uno *et al.* (Belle Collaboration), J. High Energ. Phys. **2021**, 19 (2021).

[5] K. Inami *et al.* (Belle Collaboration), J. High Energ. Phys. **2022**, 110 (2022).

[6] B. Abi *et al.* (Muon g-2 collaboration), Phys. Rev. Lett. **126**, 141801 (2021).

[7] P. J. Fox and E. Poppitz, Phys. Rev. D **79**, 083528 (2009),

[8] C.-Y. Chen, H. Davoudiasl, W. J. Marciano, and C. Zhang, Phys. Rev. D **93**, 035006 (2016),

[9] J. P. Lees et al. (BaBar collaboration), Phys. Rev. Lett. **125**, 181801 (2020).

[10] X.-Y. Pham, Eur. Phys. J. C **8**, 3 (1999)

[11] S. Brandt, C. Peyrou, R. Sosnowski, and A. Wroblewski, Phys. Lett. **12**, 57 (1964); E. Farhi, Phys. Rev. Lett. **39**, 1587 (1977).

[12] K. Hayasaka *et al.* (Belle Collaboration), Phys. Lett. B **666**, 16 (2008).

[13] D. Atwood and A. Soni, Phys. Rev. D **45**, 2405 (1992).

[14] K. Inami *et al.* (Belle Collaboration), Phys. Lett. B **551**, 16 (2003).