Searches for lepton flavor violation in meson decays at Belle

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Abstract

We report the results of recent searches on charged lepton flavor violation using the e^+e^- collision data collected by the Belle detector. In the first section, we present a search for the lepton-flavor-violating decays $B_s^0 \to \ell^\mp \tau^\pm$, where $\ell = e, \mu$, using 121 fb^{-1} data collected at the $\Upsilon(5S)$ resonance. We also search for the lepton-flavour-violating decays $B^+ \to K^+ \tau^\pm \ell^\mp$, with $\ell = (e, \mu)$, using 711fb^{-1} $\Upsilon(4S)$ data sample. Finally, we present a search for the charged lepton-flavor-violating decays $\Upsilon(1S) \to \ell^\pm \ell'^\mp$ and radiative charged lepton-flavour-violating decays $\Upsilon(1S) \to \gamma \ell^\pm \ell'^\mp$ $[\ell, \ell' = e, \mu, \tau]$ using 25fb^{-1} data recorded at $\Upsilon(2S)$ resonance. This search uses $\Upsilon(1S)$ mesons produced in $\Upsilon(2S) \to \pi^+ \pi^- \Upsilon(1S)$ transitions.

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1 Introduction

Recently, there has been a resurgence of interest in the study of leptoquark fields in light of discrepancies in semi-leptonic B-decays [1], which challenge the assumed Lepton Flavour Universality (LFU) of fundamental interactions. Although the SM gauge couplings do not discriminate between different generations of leptons, there are some new physics (NP) models such as leptoquarks model [2], Z' model [3], which predict the enhancement of the couplings with increasing lepton mass. Also, it has been pointed out that the violation of lepton flavor universality generically implies the violation of lepton flavor [4, 5]. Thus, one can constrain the parameters for the NP models, describing LFU violation, by studying the charge lepton flavor violation (CLFV).

The Wilson coefficients of the NP operators can be determined via fits to measurements of phenomena that involve CLFV interactions [6]. Several classes of operators, such as vector, axial-vector, and tensor operators involved in four-fermionic interactions, allow CLFV transitions. Precise measurement of two-body vector meson CLFV decays allows one to effectively probe the vector and tensor operators. Radiative lepton-flavor-violating (RLFV) transitions

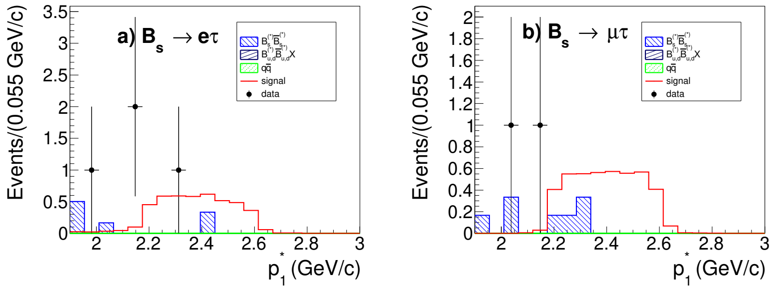

Figure 1: The p_1^* distribution of signal MC, generic MC, and data in (a) $B_s \to e^-\tau^+$ and (b) $B_s \to \mu^-\tau^+$ modes.

allow one to probe the operators which are not easily accessible in the two-body decays [6]. Using three-body vector meson RLFV decays, one can put constraints on the corresponding Wilson coefficients of axial-vector, scalar, and pseudoscalar operators.

We use e^+e^- collision data collected by the Belle detector at the KEKB asymmetric-energy collider [7] operating at a center-of-mass of energy (s) of 10.8 GeV. The Belle detector is a large-solid-angle spectrometer, which includes a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) comprised of 8736 CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5T magnetic field. An iron flux return located outside the coil is instrumented to detect K L 0 mesons and identify muons (KLM). The detector is described in detail elsewhere [8].

2 Search for $B_s^0 \to \ell^\mp\tau^\pm$ with the semi-leptonic tagging method

In models with either scalar or vector leptoquarks, the largest prediction for the $B_s^0 \to \ell^-\tau^+$ branching fraction ranges from 10^{-10} to 10^{-5} [9, 10], depending on the assumed leptoquark mass. Previously, no experimental results for $B_s^0 \to e^\mp\tau^\pm$ have been reported while an upper limit $\mathcal{B}(B_s^0 \to \mu^\mp\tau^\pm) < 3.4 \times 10^{-5}$ at 90% confidence level (CL) [11] has been reported by LHCb. We search for $B_s^0 \to \ell^\mp\tau^\pm$ decays using 121 fb^{-1} of data at $\Upsilon(5S)$ resonance. Hereafter, B_s refers to either B_s^0 or $\bar{B}\,_s^0$, and the inclusion of charge-conjugated modes is implied. In this analysis, one B_s is reconstructed in a semileptonic decay mode $\bar{B}_s^0 \to D_s^+\ell^-(X)\overline{\nu}_\ell$ and used as a tag, where X stands for any particles such as π or $\pi\pi$, and the signal $B_s \to \ell^-\tau^+$ is searched for in the mode $\tau^+ \to \ell^+\overline{\nu}_\tau\nu_\ell$. We label the primary and secondary leptons from the τ decay on the signal side B_s as ℓ_1 and ℓ_2, and the lepton on the tag side as ℓ_3. We reconstruct D_s meson candidates with opposite charge to ℓ_3 from the following five decay modes: $D_s^+ \to \phi\pi^+$, $\overline{K}^{*0}K^+, \phi\rho^0\pi^+, K_s^0K^+$ and $\phi\rho^+$.

The background comes from the continuum $e^+e^- \to q\overline{q}$ process and $e^+e^- \to B_s^{(*)0}\overline{B}_s^{(*)0}, B^{(*)}\overline{B}^{(*)}X$. We form a single FastBDT [12] classifier trained using simulated samples to suppress the background events.

In the signal region, we find three events for $B_s \to e^-\tau^+$ and one event for $B_s \to \mu^-\tau^+$, as shown in Figure 1. The expected number of background events in the signal region, $N_{\rm bkg}$, is estimated from the number of events in the sideband.

To calculate this limit, we use the POLE program [13] with the relation $\mathcal{B} = (N_{\rm obs} - N_{\rm bkg})/(N_{\rm B_s} \times \epsilon_{\rm sig})$, where $N_{\rm obs}$ is the number of the observed events, $N_{\rm B_s}$ is the number of B_s mesons in the data $(16.6 \pm 2.7) \times 10^6$, and $\epsilon_{\rm sig}$ is the signal efficiency including the branching fraction of τ. Since the uncertainty in f_s is significant, we report the upper limit

Table 1: Efficiency (ϵ), expected background events (N_{bkg}^{exp}), observed events (N_{obs}) and the 90% CL upper limits on $\mathcal{B}$ and $f_s \times \mathcal{B}$.

	ϵ (%)	N_{bkg}^{exp}	N_{obs}	$\mathcal{B}$ ($\times 10^{-4}$)	$f_s \times \mathcal{B}$ ($\times 10^{-4}$)
$B_s \to e^- \tau^+$	0.0312 ± 0.0071	0.68 ± 0.69	3	< 14.1	< 5.5
$B_s \to \mu^- \tau^+$	0.0303 ± 0.0068	0.77 ± 0.78	1	< 7.3	< 2.9

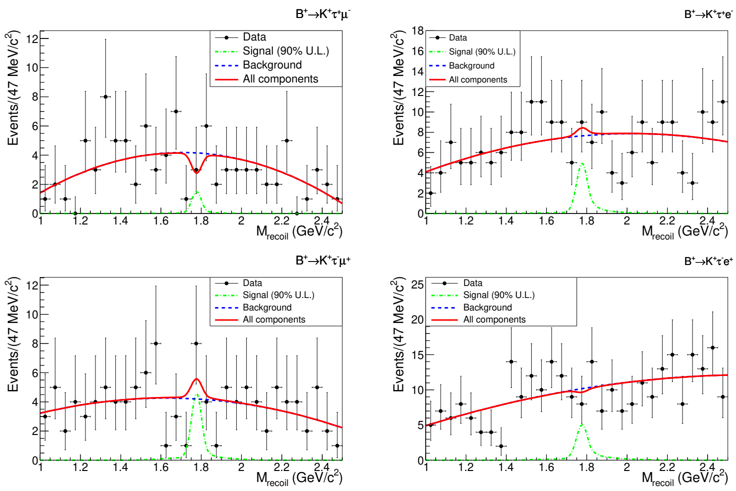

Figure 2: Observed M_{recoil} distributions for the four $B \to K\tau\ell$ modes, along with projections of the fit result. The dash-dotted green curve shows the signal PDF, with a normalization corresponding to the upper limit at 90% CL.

not only on the branching fraction but also on $f_s \times \mathcal{B}(B_s \to \ell^- \tau^+)$. Table 1 summarizes the results, including the upper limit. We report the first result on $B_s \to e^- \tau^+$ decay.

3 Search for the lepton flavor violating decays $B^+ \to K^+ \tau^\pm \ell^\mp (\ell = e, \mu)$

Upper limits on the branching fractions for $B^+ \to K^+ \tau^\pm \ell^\mp$ decays have been previously set at the 90% CL using hadronic B-tagging by the BaBar collaboration between 1.5×10^{-5} and 4.5×10^{-5} [14]; the LHCb collaboration has studied a single mode, using B^+ mesons from $B_{s2}^{*0} \to B^+ K^-$ decays, setting a limit $\mathcal{B}(B^+ \to K^+ \tau^+ \mu^-) < 3.9 \times 10^{-5}$ at the 90% CL [15].

$B^+ \to K^+ \tau^+ \mu^-$ and $B^+ \to K^+ \tau^+ e^-$ defined as $OS_{\mu,e}$ modes because the kaon and the primary lepton have opposite charge, and $B^+ \to K^+ \tau^- \mu^+$ and $B^+ \to K^+ \tau^- e^+$, defined as $SS_{\mu,e}$ modes. In all cases, we require that the τ decays to $\tau \to e \nu \overline{\nu}$, $\tau \to \mu \nu \overline{\nu}$, or $\tau \to \pi \nu$.

For the OS configurations, where the primary lepton charge is opposite to the B_{sig} charge, the dominant background comes from semileptonic D decays: $B^+ \to \overline{D}^0 (\to K^+ \ell^- \overline{\nu}_\ell) X^+$. On the other hand, for the SS configurations the primary lepton and the B_{sig} have the same charge and the semileptonic B^+ decays like $B^+ \to \overline{D}^0 (\to K^+ X^-) X \ell^+ \nu_\ell$ provide the three charged particles for the B_{sig} candidates. Two classifiers are trained for the background suppression. The first one is optimized to reduce the $B\overline{B}$ background events. After the cut on the first BDT output, a large fraction of the surviving background is coming from $q\overline{q}$ ($q = u, d, s, c$) events; for this reason a second BDT classifier is trained on these events.

Table 2: Efficiencies, fit yields, and branching fraction upper limits at the 90% CL for PHSP (and NP) case.

Mode	ε (%)	$\varepsilon^{\mathrm{NP}}$ (%)	N_{sig}	$\mathcal{B}^{\mathrm{UL}}$ (10^{-5})
$B^+ \to K^+\tau^+\mu^-$	0.064	0.058	-2.1 ± 2.9	0.59 (0.65)
$B^+ \to K^+\tau^+e^-$	0.084	0.074	1.5 ± 5.5	1.51 (1.71)
$B^+ \to K^+\tau^-\mu^+$	0.046	0.038	2.3 ± 4.1	2.45 (2.97)
$B^+ \to K^+\tau^-e^+$	0.079	0.058	-1.1 ± 7.4	1.53 (2.08)

The signal yields for $B \to K\tau\ell$ decays are obtained by performing unbinned extended maximum-likelihood fits to the M_{recoil} distributions. The yields and background shape parameters are floated while the parameters describing the signal PDF are fixed from the Monte Carlo (MC) simulation. The M_{recoil} distributions for LFV $B \to K\tau\ell$ decays along with projections of the fit result are shown in Fig. 2. The fitted signal yields listed in Table 2 are consistent with zero for all four modes.

Using a frequentist method, we calculate the upper limit (UL) for these modes at the 90% CL. The upper limit on the branching fraction is then derived using the formula: $\mathcal{B}^{\mathrm{UL}} = \frac{\mathcal{N}^{\mathrm{UL}}_{\mathrm{sig}}}{\mathcal{N}_{\mathcal{B}\overline{\mathcal{B}}} \times \in \times \{^{+-} \times \varepsilon}$, where $N_{B\overline{B}}$ is the number of $B\overline{B}$ pairs $= (772 \pm 11) \times 10^6$, f^{+-} is the branching fraction $\mathcal{B}(\Upsilon(4S) \to B^+B^-)$ for charged B decays (using 0.514 ± 0.006 [16]), and ε is the signal reconstruction efficiency. By default, ε is obtained with signal phase space MC [17] samples, while we also consider a NP model with a combination of the effective operators $\mathcal{O}_{S,P}$ by reweighting the $q^2 = m^2_{\tau\ell}$ distribution which gives the smallest efficiency.

4 Search for charged lepton flavor violating decays of $\Upsilon(1S)$

$\Upsilon(1S) \to \mu^\pm\tau^\mp$ decay has been studied by the CLEO collaboration [18], and no $\Upsilon(1S) \to e^\pm\mu^\mp$ and $\Upsilon(1S) \to e^\pm\tau^\mp$ results are available. To suppress the background from QED processes, we use 25 fb^{-1} of data accumulated by the Belle experiment at $\Upsilon(2S)$ resonance, corresponding to 28 million $\Upsilon(1S)$ produced in $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ decays. Currently, there are no existing results available for the $\Upsilon(nS) \to \gamma\ell^\pm\ell'^\mp$ decays. We perform the first search for RLFV in $\Upsilon(1S) \to \gamma\ell^\pm\ell'^\mp$ decays using the $\Upsilon(2S)$ data sample.

For $\Upsilon(1S) \to e^\pm\mu^\mp$ decays, we extract the signal yield from a UML fit to the $\Delta M = M_{\pi\pi e\mu} - M_{e\mu}$ variable. We perform an UML fit to the mass difference $\Delta M = M_{\pi\pi\gamma e\mu} - M_{\gamma e\mu}$. A sum of two Gaussians sharing a common mean has been used as the signal PDF with a 1st-order Chebyshev polynomial to fit the background. We show the fitted ΔM distributions in Fig. 3.

For $\Upsilon(1S) \to \ell^\pm\tau^\mp$ decays, we extract the signal from an UML fit to the recoil mass of $\pi\pi\ell$ ($M^{\mathrm{recoil}}_{\pi\pi\ell}$), where $\ell = \mu, e$. Dominant backgrounds come from $\Upsilon(1S) \to \tau^+\tau^-$ and $\Upsilon(1S) \to \ell^\pm\ell'^\mp$ decays. Yields of these backgrounds are floated to fit the data. To extract the signal for $\Upsilon(1S) \to \gamma\ell^\pm\tau^\mp$ decays, we fit recoil mass of $\pi\pi\gamma\ell$ ($M^{\mathrm{recoil}}_{\pi\pi\ell\gamma}$). Fitted distributions are shown in Fig. 3. Obtained signal yields for LFV modes are consistent with 0. In the absence of significant signal events, we obtain the UL of signal yield in a frequentist approach. One can estimate UL of branching fraction: $\mathcal{B}[\Upsilon(1S) \to \ell^\pm\ell'^\mp] < \frac{N^{\mathrm{UL}}_{\mathrm{sig}}}{N_{\Upsilon(2S)} \times \mathcal{B}[\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)] \times \epsilon}$, where $N^{\mathrm{UL}}_{\mathrm{sig}}$ is the UL on the signal yield after including systematic uncertainty. Obtained results are summarized in Tab. 3.

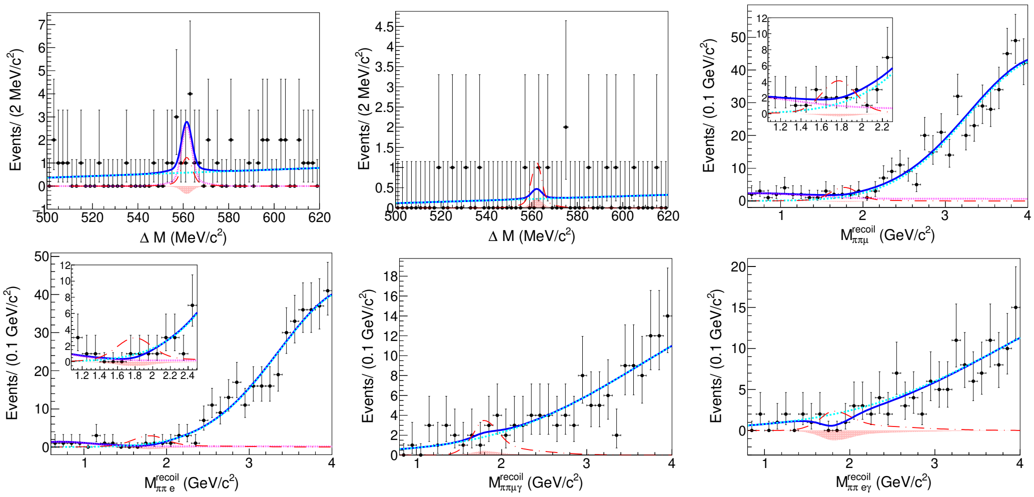

Figure 3: ΔM fit to $\Upsilon(2S)$ data for the $\Upsilon(1S) \to e^{\pm}\mu^{\mp}$ (top left) $\Upsilon(1S) \to \gamma e^{\pm}\mu^{\mp}$ (top middle) decays. UML fit to $M^{\rm recoil}_{\pi\pi\ell\gamma}$ for $\Upsilon(1S) \to \mu^{\pm}\tau^{\mp}$ (top right), $\Upsilon(1S) \to e^{\pm}\tau^{\mp}$ (bottom left), $\Upsilon(1S) \to \gamma\mu^{\pm}\tau^{\mp}$ (bottom middle), and $\Upsilon(1S) \to \gamma e^{\pm}\tau^{\mp}$ (bottom right) decays.

Table 3: Results of searches for CLFV in $\Upsilon(1S)$ decays. Here, $N^{\rm fit}_{\rm sig}$ is the fitted signal yield. $N^{\rm UL}_{\rm sig}$ and $\mathcal{B}^{\rm UL}$ are, respectively, the upper limits of signal yield and branching fraction at 90% CL.

Decay	ϵ (%)	$N^{\rm fit}_{\rm sig}$	$N^{\rm UL}_{\rm sig}$	$\mathcal{B}^{\rm UL}$	PDG result
$\Upsilon(1S) \to e^{\pm}\mu^{\mp}$	32.5	-1.3 ± 3.7	3.6	3.9×10^{-7}	–
$\Upsilon(1S) \to \mu^{\pm}\tau^{\mp}$	8.8	-1.5 ± 4.3	6.8	2.7×10^{-6}	6.0×10^{-6}
$\Upsilon(1S) \to e^{\pm}\tau^{\mp}$	7.1	-3.5 ± 2.7	5.3	2.7×10^{-6}	–
$\Upsilon(1S) \to \gamma e^{\pm}\mu^{\mp}$	24.6	$+0.8 \pm 1.5$	2.9	4.2×10^{-7}	–
$\Upsilon(1S) \to \gamma\mu^{\pm}\tau^{\mp}$	5.8	$+2.1 \pm 5.9$	10.0	6.1×10^{-6}	–
$\Upsilon(1S) \to \gamma e^{\pm}\tau^{\mp}$	5.0	-9.5 ± 6.3	9.1	6.5×10^{-6}	–

5 Conclusion

We have searched for charged lepton flavor violations in several decay modes. Apart from $B^0_s \to \mu^{\pm}\tau^{\mp}$ decay, obtained upper limits of branching fractions are the most stringent to date.

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