New LFV results from e^+e^- colliders

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Outline

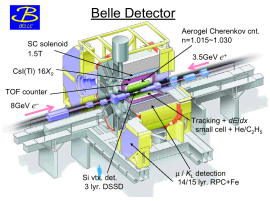
1. Motivation
2. Search for the $e^+e^- \to ll'$ decay
3. Lepton flavor violation in the τ lepton
4. Recent results on LFV B and D mesons decay

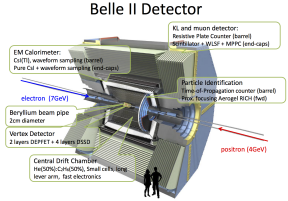
- Within the standard model (SM), the coupling strength between the families of leptons and gauge bosons are equal, known as the lepton flavor universality (LFU).
- Further, the lepton number is conserved within a family for an absolute zero mass neutrinos; $W \to l\bar{\nu}_{l'}$, $Z \to ll'$, or $\gamma \to ll'$ are not allowed.
- However, the observation of neutrino flavor oscillations suggests their non-zero and unequal masses.
- The branching fraction of the lepton flavor violating (LFV) $\mu \to e\gamma$ decay

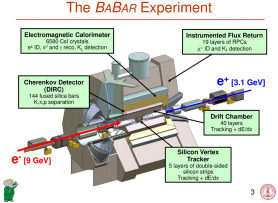
$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_i U^*_{\mu i} U_{ei} \frac{m^2_{\nu_i} - m^2_{\nu_1}}{M^2_W} \right| < 10^{-54}$$

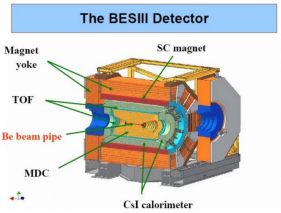
- Various physics models such as supersymmetry, two-Higgs doublet, fourth generation of quarks and leptons, etc., predict the BF of LFV decay modes, which can be observed in the high luminosity modern experiments. Any observation of such decay is a direct evidence for the new physics.

Search for the LFV at the e^+e^- collider experiments





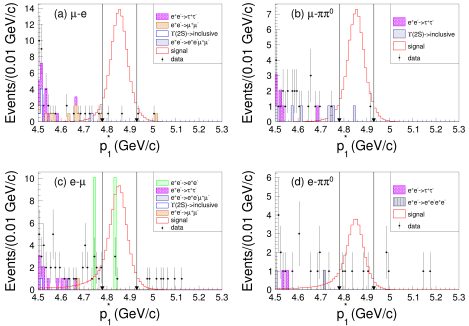




- The e^+e^- colliders at Belle, Belle II, BABAR, and BESIII experiments produce the $\Upsilon(nS)$ and $\psi(nS)$ resonances, τ and μ leptons, B and D mesons in a large abundance by tuning the center of mass (CM) energy.
- $\Upsilon(nS) \to l^+l'^-$ & $J/\psi \to l^+l'^-$ (including the radiative decays).
- $\tau^- \to l^-\gamma$, $e^-e^-e^+$, $e^-\mu^-e^+$, $e^-\mu^-\mu^+$, $\mu^-\mu^-\mu^+$, l^-h (hadrons), etc.
- $D \to Xl^\pm l'^\mp$ and $B \to Xl^\pm l'^\mp$.

$\Upsilon(2S) \to l^{\pm}\tau^{\mp}$ at Belle

- τ^- is reconstructed from $e^-\bar{\nu}_e\nu_\tau$, $\mu^-\bar{\nu}_\mu\nu_\tau$, and $\pi^-\pi^0\nu_\tau$.
- The signal region is defined based on the momentum of primary lepton in the e^+e^- system.
- Background is suppressed using multivariate analysis based on the FastBDT classifier.



Modes	$\epsilon_{\rm sig}$ (%)	$N_{\rm exp}^{\rm bkg}$	$N_{\rm obs}$	$\mathcal{B}$ @ 90% CL
$\Upsilon(2S) \to \mu^{\mp}\tau^{\pm}$	11.0 ± 0.8	3.6 ± 1.2	3	$< 0.26 \times 10^{-6}$
$\Upsilon(2S) \to e^{\mp}\tau^{\pm}$	7.3 ± 0.9	4.6 ± 2.1	9	$< 1.02 \times 10^{-6}$

Reference: [arXiv:2309.02739]

Most stringent limit to date improving the previous bound on $\mathcal{B}(\Upsilon(2S) \to \mu^{\pm}\tau^{\mp})$ and $\mathcal{B}(\Upsilon(2S) \to e^{\pm}\tau^{\mp})$ by a factor of 13 and 3, respectively.

Similar results from Belle, BABAR, and BESIII Collaboration

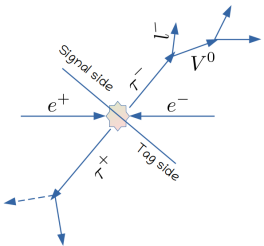
Collaboration	Data Sample	Decay mode	UL at 90%CL	References
Belle	158×10^6 $\Upsilon(2S)$	$\mathcal{B}(\Upsilon(1S)\to e^\pm\mu^\mp)$	3.9×10^{-7}	JHEP 05 (2022) 095
		$\mathcal{B}(\Upsilon(1S)\to \mu^\pm\tau^\mp)$	2.7×10^{-6}	
		$\mathcal{B}(\Upsilon(1S)\to e^\pm\tau^\mp)$	2.7×10^{-6}	
		$\mathcal{B}(\Upsilon(1S)\to \gamma e^\pm\mu^\mp)$	4.2×10^{-7}	
		$\mathcal{B}(\Upsilon(1S)\to \gamma \mu^\pm\tau^\mp)$	6.1×10^{-6}	
		$\mathcal{B}(\Upsilon(1S)\to \gamma e^\pm\tau^\mp)$	6.5×10^{-6}	
BABAR	118×10^6 $\Upsilon(3S)$	$\mathcal{B}(\Upsilon(3S)\to e^\pm\mu^\mp)$	3.6×10^{-7}	PRL 128, 091804
BESIII	9×10^9 J/ψ	$\mathcal{B}(J/\psi\to e^\pm\mu^\mp)$	4.5×10^{-9}	arXiv:2206.13956v2[1]
	10×10^9 J/ψ	$\mathcal{B}(J/\psi\to e^\pm\tau^\mp)$	7.5×10^{-9}	PRD 103, 112007

- These results can provide constraints on the new physics models based on supersymmetry, GUT, two Higgs doublet model, etc., in the references of [1].

Search for the $\tau^{\pm} \to l^{\pm} V^0$ decay at Belle and Belle II

- The leptoquark model accomodating the anomalies in leptonic B decays predict the branching fraction of the order of $\mathcal{O}(10^{-11})$ – $\mathcal{O}(10^{-8})$ [PRD 104, 055017], [JHEP 08, 050].

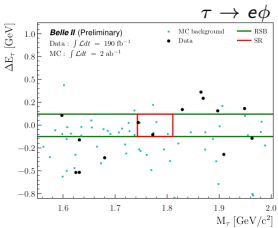
- A signal $\tau^{\pm}$ is reconstructed from the $l^{\pm}$ and V^0 daughters, where $V^0 \in [\rho\ (\rho \to \pi^+\pi^-),\ \phi\ (\phi \to K^+K^-),\ \omega\ (\omega \to \pi^+\pi^-\pi^0),\ K^{*0}\ (K^{*0} \to K^+\pi^-)]$.
- The signal extraction $\implies$ M_τ and the energy difference $\Delta E = E^*_\tau - \sqrt{s}/2$.
- No tagging of other τ in the Belle II analysis [2305.04759].

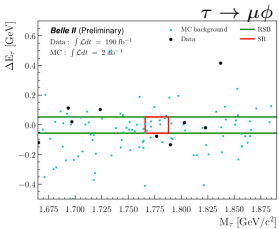


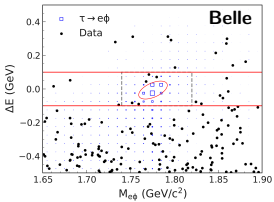
c.m. frame

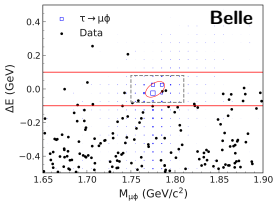
- Backgrounds from $\tau^+\tau^-$ generic decay, low multiplicity (four leptons in the final state) events, and $e^+e^- \to q\bar{q}$ (continuum) are studied using the MC simulated and side band data.

Results on LFV $\tau^{\pm} \to l^{\pm} V^0$ decay







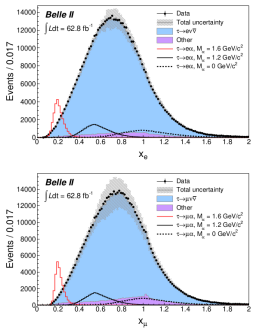


Collaboration	Data Sample	Decay mode	UL at 90%CL	References
Belle	980 fb^{-1}	$\tau \to \mu\phi$	2.3×10^{-8}	JHEP 06 (2023) 118
		$\tau \to e\phi$	2.0×10^{-8}	
Belle II	190 fb^{-1}	$\tau \to \mu\phi$	9.7×10^{-8}	2305.04759
		$\tau \to e\phi$	23×10^{-8}	

- The Belle collaboration set an upper limit on the $\tau \to l$ (ρ, ϕ, ω, K^{*0}, $\bar{K}^{*0}$) decays in the range of $(1.7 - 4.3) \times 10^{-8}$ at 90% CL.

Search for the LFV invisible decay of τ at Belle II: $\tau^{\pm} \to l^{\pm}\alpha$

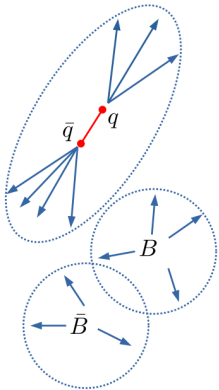
- Studying the LFV $\tau^{\pm} \to l^{\pm}\alpha$ decay is a good hunt for the axion like particles, where α is a spin-0 boson.
- $\tau_{\text{tag}} : \tau^- \to h^+h^-h^-\nu_\tau$ decays.
- Signal extraction: $x_l = \frac{E_l^*}{m_\tau c^2}$, where E_l^* is the energy of charged lepton in the pseudo rest frame of τ.
- Backgrounds: $e^+e^- \to q\bar{q}$, $l^+l^-\gamma$, $e^+e^-l^+l^-$, & $e^+e^-h^+h^-$.
- $\frac{\mathcal{B}(\tau^- \to l^-\alpha)}{\mathcal{B}(\tau^- \to l^-\bar{\nu}_\mu\nu_\tau)}$ for a range of $m_\alpha \in (0.0 - 1.6)$ GeV/c^2 are:



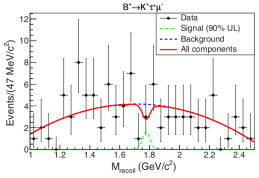
Collaboration	Data Sample	Leptonic mode	UL at 90%CL	References
Belle II	62.8 fb^{-1}	μ	$(0.7 - 12.2) \times 10^{-3}$	PRL 130, 18, 181803
		e	$(1.1 - 9.7) \times 10^{-3}$	
ARGUS	—	μ	$(3 - 34) \times 10^{-3}$	Z.P.C 68 (1995) 25-28
		e	$(6 - 36) \times 10^{-3}$	

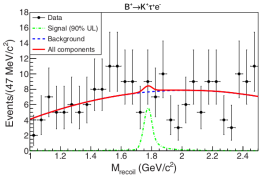
Search for the LFV $B^+ \to K^+\tau^\pm l^\mp$ decay at Belle

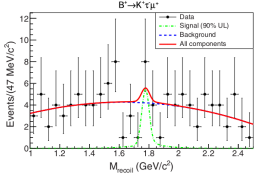
- The leptoquark models predict the $\mathcal{B}(B^+ \to K^+\tau^\pm\mu^\mp)$ via a vector mediator (U_1) with the SM quantum numbers of $(3,1)_{\frac{2}{3}}$ to be $> 0.7 \times 10^{-7}$ [PRD 104, 055017].
- Signal mode: $B^\pm \to K^\pm\tau(\tau \to l\nu\nu \text{ or } \pi\nu)l(e,\mu)$
- Accompanying B (B_{tag}) is reconstructed using Full Event Interpretation (FEI).
- The BDT classifier based on the event topology of the B_{sig} and the number of unused ECL clusters rejects the combinatorial B background.
- Another BDT classifier based on the difference in event topology suppresses the continuum background.
- Signal extraction: $M_{\text{recoil}} = m_B^2 + m_{Kl}^2 - 2(\frac{E^*_{\text{beam}}E^*_{Kl}}{c^4} + \frac{p^*_{B_{\text{tag}}}p^*_{Kl}\cos\theta}{c^2})$

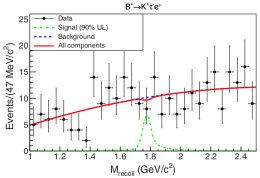


Results on LFV $B^+ \to K^+\tau^\pm l^\mp$ decay









Decay mode	BF UL (10^{-5}) at 90% CL	
	Belle	BABAR
$B^+ \to K^+\tau^+\mu^-$	0.59	4.8
$B^+ \to K^+\tau^-\mu^+$	2.45	
$B^+ \to K^+\tau^+e^-$	1.51	3.0
$B^+ \to K^+\tau^-e^+$	1.53	
$\#B\bar{B}$ pairs (10^6)	772	472
References	1	2

References

1 PRL 130, 261802 (2023)

2 PRD 86, 012004 (2012)

Search for the LFV D^0 decays at BABAR

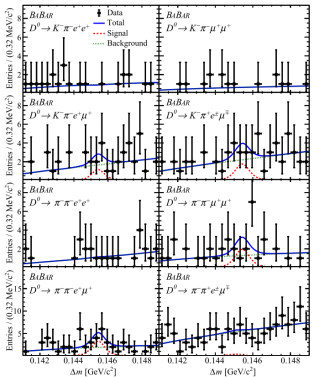
- Within the SM, the BF for the decay $D^0 \to X^0 e^{\pm}\mu^{\mp}$ is suppressed $\sim \mathcal{O}(10^{-50})$.
- For certain leptoquark coupling, the new physics models predicts the BF of the order of $\mathcal{O}(10^{-6}) - \mathcal{O}(10^{-5})$.
- The BABAR collaboration has reported the UL on three and four body LFV decays of D^0 mesons; Ref. [PRD 101, 112003] & [PRL 124, 071802].
- The signal reconstruction:
  - $D^0 \to X^0 e^{\pm}\mu^{\mp}$ for three body
  - $D^0 \to h^{\pm} h'^{\mp} e^{\pm}\mu^{\mp}$ for four body
- Considered neutral mesons: $X^0 \in (\pi^0, K^0_s, \bar{K}^{*0}, \rho^0, \omega, \eta)$.
- The background from $e^+e^- \to c\bar{c}$ events is suppressed using BDT classifier with the input variables based on the topology of D^0_{sig} mesons.

Signal Extraction : $\Delta m = m_{D^{*+}} - m_{D^0}$

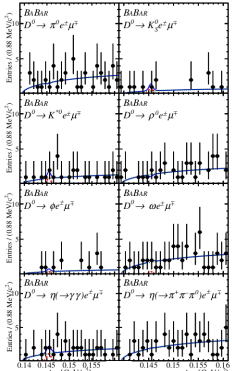
Results on LFV D^0 decays

- The signal events are found to be compatible with zero.
- Using 468 fb^{-1} of e^+e^- collision data at or close to $\Upsilon(4S)$ data

Decay mode	BF UL (10^{-7}) at 90% CL
Three body	5.0–22.5
Four body	1.0–30.6



Four-body



Three-body

- The reported ULs on the BF of three and four body decay can provide the bounds on the leptoquark couplings!!!

Summary

- We presented the recent results on the LFV decay modes at e^+e^- collider experiments: (a) Belle, (b) Belle II, (c) BABAR, and (d) BESIII.
- New physics models such as the supersymmetry, two-Higgs doublet model, leptoquark model, etc. predict the branching fractions for LFV decay modes, which are accessible to the high luminosity modern experiments.
- So far, no signal for the LFV decay could be observed.
- Hope to find out in the near future at Belle II and BESIII experiments... if nature allows!!!

Thank you for your attention.