Search for charged-lepton flavor violation in $\Upsilon(2S) \to \ell^{\mp}\tau^{\pm}(\ell = e, \mu)$ decays at Belle

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Outline of the talk

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1. The Belle experiment

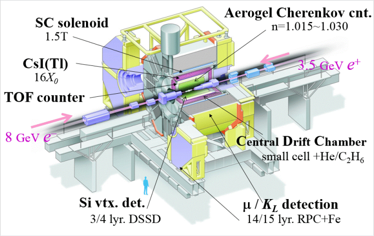
2. Motivation

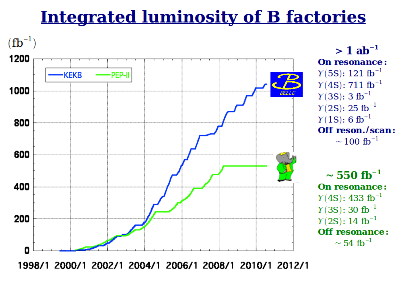
3. $\Upsilon(2S) \to \ell^{\mp}\tau^{\pm}(\ell = e, \mu)$ study at Belle.

4. Results

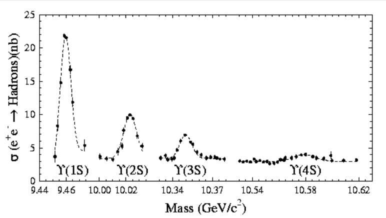
The Belle experiment

Well known to measure the CP-violation in the B-meson decays.





Measured by CUSB.



- KEKB: An asymmetric-energy $e^-(8\ \mathrm{GeV})e^+(3.5\ \mathrm{GeV})$ collider, collided at the center-of-mass energy of $10.58\ \mathrm{GeV}$.
- Belle detector was placed at the interaction point (IP) of KEKB.
- Collected most of the data at $\Upsilon(4S)$ resonance, however it also collected data at $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, and so on.

Motivation

- The lepton flavor conservation is an intrinsic property of the Standard Model (SM).
- The experimental evidence of lepton flavor violation has already been observed in neutrino oscillation.
- The transitions involving charged-lepton flavor violation (CLFV) are mediated by $W^{\pm}$ bosons and massive neutrinos to account for neutrino oscillation.
- In consequence, the CLFV transitions ⇒ significantly suppressed $\sim m_{\nu}^{2}/m_{W}^{2}$. For e.g., $\mathcal{B}(\mu \to e\gamma) \sim 10^{-54}$
- Several new physics models (for e.g. leptoquarks) predict the enhanced BF for such transitions ⇒ high luminosity experiments.
- With the current statistics, CLFV cannot be seen in $\Upsilon(4S)$; it decays immediately to pair of B mesons. So, CLFV in $\Upsilon(nS)$ (n=1,2,3) is a good probe for the physics beyond the SM.
- Any observation of CLFV ⇒ clearest evidence of the new physics.

CLFV in $\Upsilon(nS)$ decays

- BaBar, CLEO, and recently Belle searched for CLFV in $\Upsilon(nS) \to \ell\tau$ (n=1,2,3) decays.

Table: Experimental results on $\Upsilon(nS)$ CLFV transitions

Decay modes	Upper limits	Experiments	References
$B(\Upsilon(1S) \to \mu\tau)$	$< 6 \times 10^{-6}$	CLEO	PRL 101, 201601 (2008)
$B(\Upsilon(1S) \to e\tau)$	$< 2.7 \times 10^{-6}$	Belle	JHEP 05 2022, 095 (2022)
$B(\Upsilon(1S) \to \mu\tau)$	$< 2.7 \times 10^{-6}$	Belle	JHEP 05 2022, 095 (2022)
$B(\Upsilon(2S) \to \mu\tau)$	$< 14.4 \times 10^{-6}$	CLEO	PRL 101, 201601 (2008)
$B(\Upsilon(2S) \to e\tau)$	$< 3.2 \times 10^{-6}$	BaBar	PRL 104, 151802 (2010)
$B(\Upsilon(2S) \to \mu\tau)$	$< 3.3 \times 10^{-6}$	BaBar	PRL 104, 151802 (2010)
$B(\Upsilon(3S) \to \mu\tau)$	$< 26.3 \times 10^{-6}$	CLEO	PRL 101, 201601 (2008)
$B(\Upsilon(3S) \to e\tau)$	$< 4.2 \times 10^{-6}$	BaBar	PRL 104, 151802 (2010)
$B(\Upsilon(3S) \to \mu\tau)$	$< 3.1 \times 10^{-6}$	BaBar	PRL 104, 151802 (2010)

- No signal observed yet!

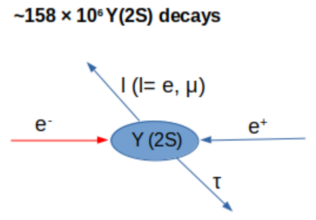
Table: Data sample and the number of $\Upsilon(nS)$ at B-factories and CLEO

Experiment	$\Upsilon(1S)$ data ($N_{\Upsilon(1S)}$)	$\Upsilon(2S)$ data ($N_{\Upsilon(2S)}$)	$\Upsilon(3S)$ data ($N_{\Upsilon(3S)}$)
CLEO	$1.1\ \mathrm{fb}^{-1}$ (20.8 M)	$1.3\ \mathrm{fb}^{-1}$ (9.3 M)	$1.4\ \mathrm{fb}^{-1}$ (5.9 M)
Belle	$6\ \mathrm{fb}^{-1}$ (119 M)	$25\ \mathrm{fb}^{-1}$ (158 M)	$3\ \mathrm{fb}^{-1}$ (11 M)
BaBar	-	$14\ \mathrm{fb}^{-1}$ (98.6 M)	$30\ \mathrm{fb}^{-1}$ (116.7 M)

$\Upsilon(2S) \to \ell^{\mp}\tau^{\pm} (\ell = e, \mu)$ decays at Belle

- We search for decays $\Upsilon(2S) \to \ell_1^{\mp}\tau^{\pm}$ with $\tau^+ \to \ell_2^+ \nu_{\ell_2} \overline{\nu}_\tau$ or $\tau^+ \to \pi^+\pi^0\overline{\nu}_\tau$. Charge conjugation is applied.
- We don't consider the combination of the same flavored ℓ_1 and ℓ_2. For e.g. $\Upsilon(2S) \to \mu^{\mp}\tau^{\pm}(\tau^+ \to \mu^+\nu_\mu\overline{\nu}_\tau)$ to avoid the background contribution from $e^+e^- \to \mu^+\mu^-$ events.
- We also don't use this mode, $\tau^+ \to \pi^+\overline{\nu}_\tau$ since π^+ can fake as μ/e and can contribute to the background.
- Reconstruct: $\Upsilon(2S)$ from ℓ_1 and τ; τ from ℓ_2 or $\pi^+\pi^0$. $\Upsilon(2S)$ cannot be fully reconstructed!

- Decay modes in study:
  - $\Upsilon(2S) \to \mu^{\mp}\tau^{\pm}(\tau^+ \to e^+\nu_e\bar{\nu}_\tau)$ $[\mu - e]$
  - $\Upsilon(2S) \to e^{\mp}\tau^{\pm}(\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau)$ $[e - \mu]$
  - $\Upsilon(2S) \to \mu^{\mp}\tau^{\pm}(\tau^+ \to \pi^+\pi^0\bar{\nu}_\tau)$ $[\mu - \pi\pi^0]$
  - $\Upsilon(2S) \to e^{\mp}\tau^{\pm}(\tau^+ \to \pi^+\pi^0\bar{\nu}_\tau)$ $[e - \pi\pi^0]$
- Trigger simulation is done to simulate the trigger effect.



$\Upsilon(2S) \to \ell^{\mp}\tau^{\pm} (\ell = e, \mu)$ decays at Belle

- Signal MC: 5 million signal MC events of $\Upsilon(2S) \to \ell^{\mp}\tau^{\pm}$, where τ can decay to anything are generated with EVTGEN.
- Background MC:
  - $e^+e^- \to e^+e^-$, $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to \tau^+\tau^-$
  - $e^+e^- \to e^+e^-\mu^+\mu^-$, $e^+e^- \to e^+e^-e^+e^-$
  - Inclusive $\Upsilon(2S)$ decays.
  - $e^+e^- \to q\bar{q}$ $(q = u, d, s, c)$ processes generated with an initial state radiation (ISR) photon.

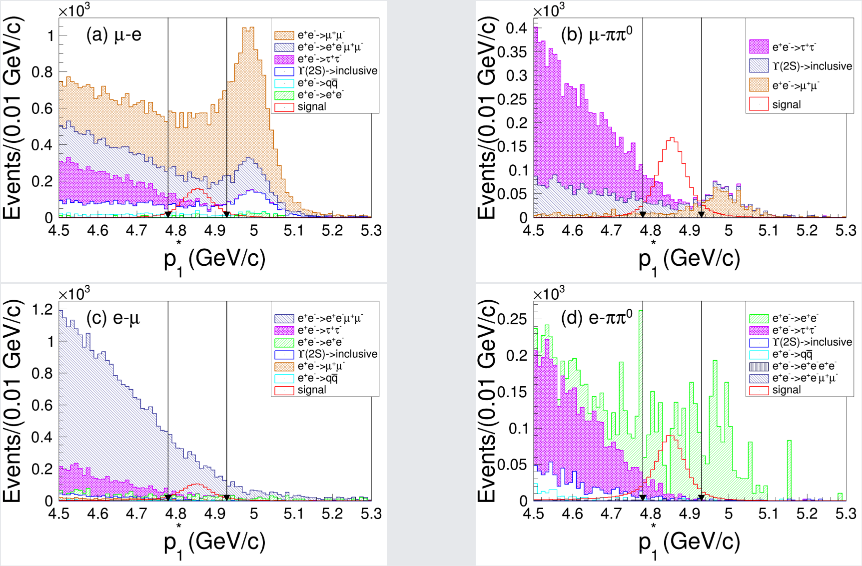
  Most of the background samples $\approx 25\ \mathrm{fb}^{-1}$.

Signal signature of $\Upsilon(2S) \to \ell_1^{\mp}\tau^{\pm}$ is a monochromatic momentum of primary lepton (p_1^*) with,

$$p_1^* = \sqrt{\frac{(m_{\Upsilon(2S)}^2 - m_{\ell_1}^2 - m_{\tau}^2)^2 - 4m_{\ell_1}^2 m_{\tau}^2}{4m_{\Upsilon(2S)}^2}};$$

peaks around $4.85\ \mathrm{GeV}/c$ in the c.m. frame.
Signal window: $4.78 < p_1^* < 4.93\ \mathrm{GeV}/c$ (2σ around the expected p_1^*).
Sideband region: $p_1^* \notin [4.7, 5.0]$.

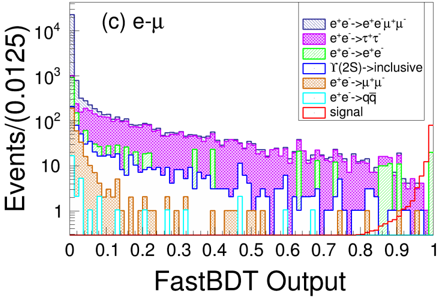
Distribution of p_1^* in MC

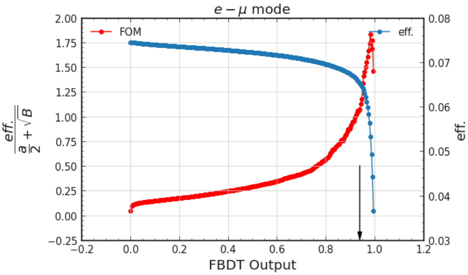


Huge background!

Background suppression

- We use the multi-variate analysis (MVA) to further suppress the background.
- Classifier: FastBDT (trained on MC-simulated events).
- Input variable are: $E_{\rm ECL}$, $E^*_{\rm vis}$, $M^{*2}_{\rm miss}$, $\cos\theta^*_{12}$, $\cos\theta^*_{\rm miss}$ based on energy of cluster, missing momentum, and the cosine angles.





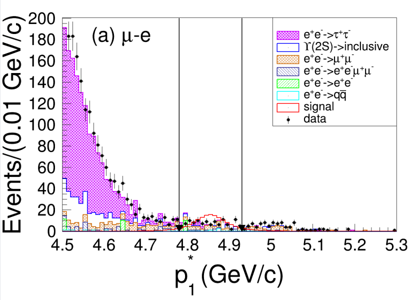
We choose $\mathcal{O}_{\rm FBDT} > 0.94$, which rejects more than 99% of the background events for all the modes while retaining 86%, 66%, 89%, and 66% of the signal events for the μ-e, μ-$\pi\pi^0$, e-μ, and e-$\pi\pi^0$ modes.

Background estimation

The expected number of background events ($N_{\mathrm{exp}}^{\mathrm{bkg}}$) is calulated from,

$$N_{\mathrm{exp}}^{\mathrm{bkg}} = N_{\mathrm{data}}^{\mathrm{SB}}(\mathrm{BDT}) \times \left(\frac{N_{\mathrm{MC}}}{N_{\mathrm{MC}}^{\mathrm{SB}}}\right)(\text{loose BDT})$$

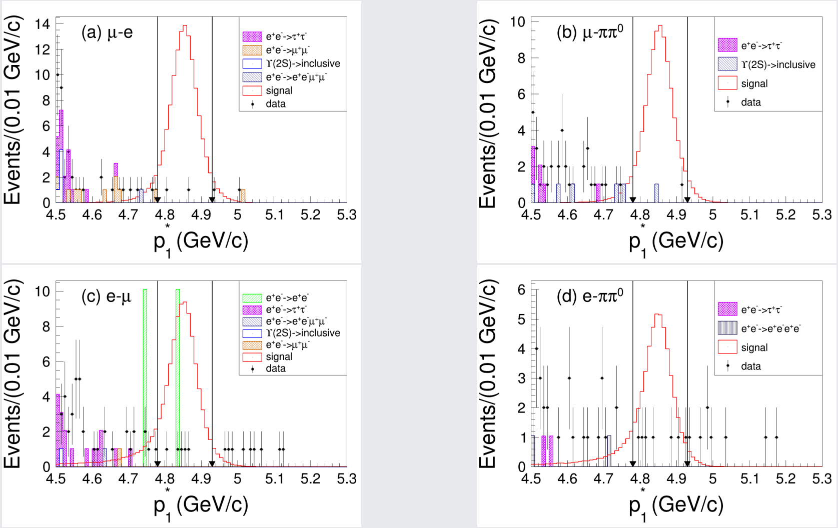
where,
$N_{\mathrm{data}}^{\mathrm{SB}}$- number of data events in the sideband region
$N_{\mathrm{MC}}^{\mathrm{SB}}$- numbers of MC events in the sideband region
N_{MC}- number of MC events in the signal region.



We estimate N_{exp}^{bkg} with $\mathcal{O}_{\mathrm{FBDT}} > 0.4$ as a nominal value and take the difference of the central value from $0.2 < \mathcal{O}_{\mathrm{FBDT}} < 0.4$ as a systematic error due to background estimation.

For $\Upsilon(2S) \to \mu^{\mp}\tau^{\pm}$, $N_{\mathrm{exp}}^{\mathrm{bkg}} = 3.9 \pm 1.8$
For $\Upsilon(2S) \to e^{\mp}\tau^{\pm}$, $N_{\mathrm{exp}}^{\mathrm{bkg}} = 5.9 \pm 2.6$

Distribution of p_1^* in MC and data with $\mathcal{O}_{\mathrm{FBDT}} > 0.94$



For $\Upsilon(2S) \to \mu^{\mp}\tau^{\pm}$, $N_{\mathrm{obs}} = 3$ which is consistent with the expectation.

For $\Upsilon(2S) \to e^{\mp}\tau^{\pm}$, $N_{\mathrm{obs}} = 12$ which is larger than the expectation; the probability of obtaining 12 or more events with $N_{\mathrm{exp}}^{\mathrm{bkg}} = 5.9 \pm 2.6$ is 8%.

Systematic Uncertainties

Table: Summary of systematic uncertainties.

Source	Systematic uncertainty (%)	
	$\Upsilon(2S) \to \mu^{\mp}\tau^{\pm}$	$\Upsilon(2S) \to e^{\mp}\tau^{\pm}$
Number of $\Upsilon(2S)$	2.3	2.3
Tracking	0.7	0.7
Particle identification and π^0 reconstruction	3.4	3.3
τ branching fraction	0.2	0.2
MVA selection	5.1	5.0
Trigger	2.3	11.9
Total	7.0	13.5

Results

We use the Feldman-Cousins method to set the upper limits on $\mathcal{B}$ @ 90% CL.

$$\mathcal{B} = \frac{N_{\rm obs} - N_{\rm exp}^{\rm bkg}}{\epsilon_{\rm sig} \times N_{\Upsilon(2S)}}$$

$\epsilon_{\rm sig}$- signal reconstruction efficiency.
$N_{\Upsilon(2S)}$- number of $\Upsilon(2S)$. $= (157.8 \pm 3.6) \times 10^6$.

Recent results from Belle, arxiv:2309.02739.

Modes	$\epsilon_{\rm sig}$ (%)	$N_{\rm exp}^{\rm bkg}$	$N_{\rm obs}$	$\mathcal{B}$ @ 90% CL
$\Upsilon(2S) \to \mu^{\mp}\tau^{\pm}$	12.3 ± 0.8	3.9 ± 1.8	3	$< 0.23 \times 10^{-6}$
$\Upsilon(2S) \to e^{\mp}\tau^{\pm}$	8.1 ± 1.1	5.9 ± 2.6	12	$< 1.12 \times 10^{-6}$

- $\mathcal{B}(\Upsilon(2S) \to \mu^{\mp}\tau^{\pm}) < 0.23 \times 10^{-6}$ @ 90% CL.
  $\mathcal{B}(\Upsilon(2S) \to e^{\mp}\tau^{\pm}) < 1.12 \times 10^{-6}$ @ 90% CL.
- We obtain 14 times better results for $\Upsilon(2S) \to \mu^{\mp}\tau^{\pm}$ and 3 times for $\Upsilon(2S) \to e^{\mp}\tau^{\pm}$ from the previous results from the BaBar collaboration.
- Recently published! JHEP02(2024)187

Thank You!

Back Up

Selections applied

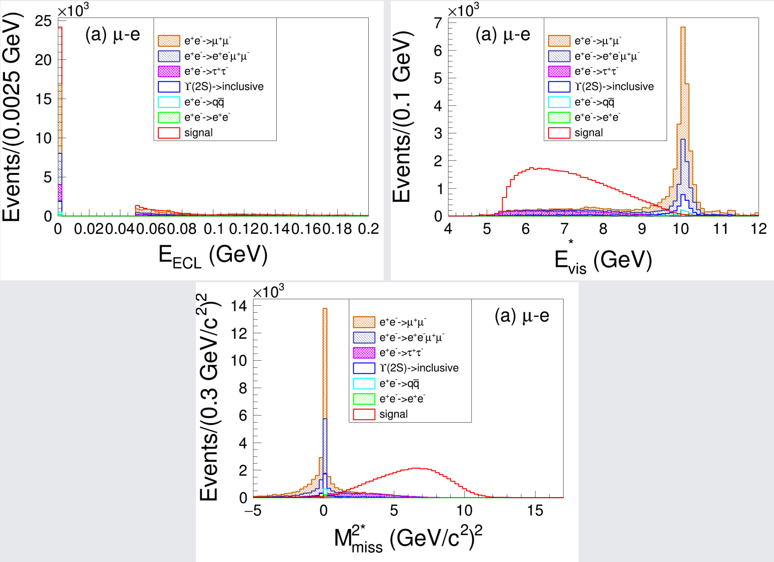
Table: Lists of all selection criteria corresponding to the variable for each mode.

Variables	μ-e	e-μ	μ-$\pi\pi^0$	e-$\pi\pi^0$
Impact parameters	$\lvert dr \rvert < 2.0$ cm $\lvert dz \rvert < 5.0$ cm			
PID	e(μ)ID> 0.8 πID> 0.6			
p_1^*	> 4.5 GeV/c			
E_γ	-		$> 50/100/150$ MeV	
$M^*_{\pi^0}$	-		$0.125 < M^*_{\pi^0} < 0.145$ GeV/c^2	
p_2^*	> 0.5 GeV/c		-	
$p^*_{\pi^+}$	-		$0.3 < p^*_{\pi^+} < 4.0$ GeV/c	
$p^*_{\pi^0}$	-		> 0.4 GeV/c	
$M^*_{\pi^+\pi^0}$	-		$0.5 < M^*_{\pi^+\pi^0} < 1.0$ GeV/c^2	
E^*_{vis}	< 9.8 GeV (e-mode only)			

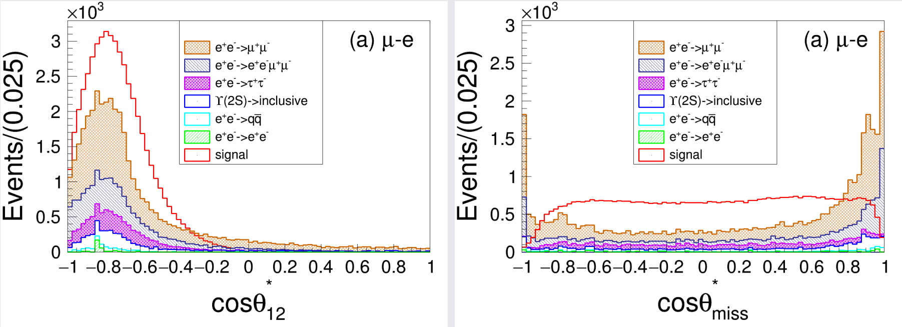
Table: Decay modes chosen for τ with their branching fractions (B.F.).

τ decay modes	B.F. (in %)
$\tau^+ \to e^+ \nu_e \bar{\nu}_\tau$	17.82 ± 0.04
$\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$	17.39 ± 0.04
$\tau^+ \to \pi^+ \pi^0 \bar{\nu}_\tau$	25.49 ± 0.09

Distributions



Distributions



- Distinguishing variables used to classify signal and background events are:
    - E_{ECL} - It is the sum of the energy of neutral ECL clusters that are related to the particles in the rest of the event in the lab frame.
    - E^*_{vis} - It is the sum of the energy of all neutral clusters and charged tracks in the c.m. frame.
    - M^{*2}_{miss} - It is the invariant mass squared of the missing momentum in the c.m. frame.
    - $\cos\theta^*_{12}$ - It is the cosine of the angle between p^*_1 and p^*_2 for μ-e and e-μ modes or between p^*_1 and $p^*_{\pi+} + p^*_{\pi^0}$ for μ-$\pi\pi^0$ and e-$\pi\pi^0$ modes in the c.m. frame.
    - $\cos\theta^*_{\mathrm{miss}}$ - It is the cosine of the polar angle of the missing momentum in the c.m. frame.