# Test of lepton family universality and search for lepton flavor, lepton and baryon number violating tau decays at Belle

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# Outline

## Test of lepton family universality

- Test of LFU $R_K$ in $B \to K\ell\ell$ decays [To be submitted to JHEP]

## Lepton flavor violation in $B$ decays

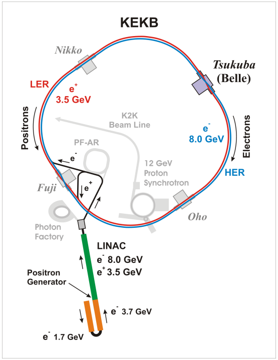
- LFV in $B \to K\ell\ell'$ [NEW] Belle preliminary [To be submitted to JHEP]

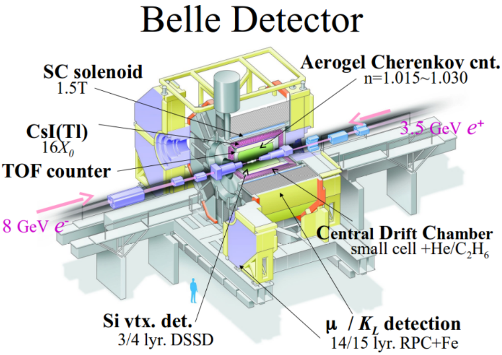
## Lepton flavor, lepton and baryon number violating $\tau$ decays

- Search for $\tau \to p\ell\ell'$ ($\ell^{(\prime)} = \mu$, $e$) decays [NEW] Belle preliminary

# KEKB and Belle detector

- KEKB: Mostly $e^+$ (3.5 GeV) and $e^-$ (8 GeV) mostly collide at center-of-mass energy 10.58 GeV.
- $\sigma(bb) \sim 1.1\text{nb}$ and $\sigma(\tau\tau) \sim 0.9\text{nb}$: So a $B$ factory as well as $\tau$ factory.

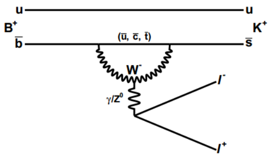


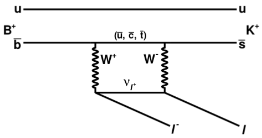

- Collected close to $1\text{ab}^{-1}$ data at different resonances and off-resonances.

# Introduction to lepton family universality

- In standard model (SM) the electroweak couplings of gauge bosons to leptons are independent of their flavor and the property is known as lepton universality.
- The decays $B \to K\ell\ell$, mediated by $b \to s\ell\ell$ quark-level transition, constitute a flavor-changing neutral current process.
- Such processes are forbidden at tree level in the SM but can proceed by loop level.
- To test lepton family universality, the ratio of branching fraction are determined.
- $R_K = \dfrac{\mathcal{B}(B \to K\mu\mu)}{\mathcal{B}(B \to Kee)}$
- Useful to explore new physics since the common experimantal systematic uncertainties, uncertainties on quark mixing matrix and meson form factors cancel out



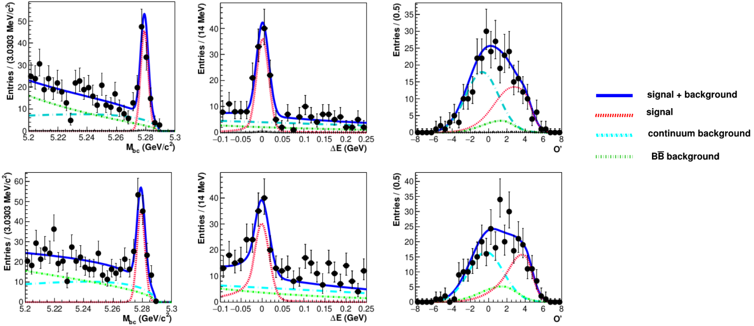

Penguin diagram, $B \to K\ell\ell$




Box diagram, $B \to K\ell\ell$

# Signal extraction

- Following channels are studied: $B^+ \to K^+ e^+ e^-$, $B^+ \to K^+ \mu^+ \mu^-$, $B^0 \to K_s^0 e^+ e^-$, $B^0 \to K_s^0 \mu^+ \mu^-$ using 711 $\mathrm{fb}^{-1}$ $\Upsilon(4S)$ data $\to 772 \times 10^6 B\bar{B}$ events.
- Signal yield is extracted by performing an extended maximum-likelihood fit to $M_{bc} = \sqrt{E_{\mathrm{beam}}^2 - |p_B^2|}$ , $\Delta E = E_B - E_{\mathrm{beam}}$ and NN output (background suppression variable).

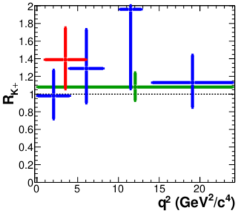



Top: $B^+ \to K^+ \mu^+ \mu^-$, bottom: $B^+ \to K^+ e^+ e^-$

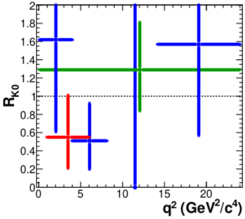
- $137 \pm 14$ and $138 \pm 15$ events in $B^+ \to K^+ \mu^+ \mu^-$ and $B^+ \to K^+ e^+ e^-$ modes.
- $27.3^{+6.6}_{-5.8}$ and $21.8^{+7.0}_{-6.1}$ events in $B^0 \to K_s^0 \mu^+ \mu^-$ and $B^0 \to K_s^0 e^+ e^-$ modes.

# Recent $R_K$ results

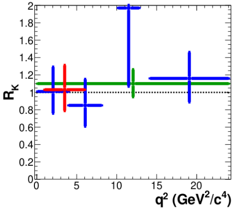
- $R_K$ study is done for [0.1, 4.0], [4.0, 8.12], [1.0, 6.0], [10.2, 12.8], >14.18 and > 0.1 $q^2$ bins.
- $R_K$ is taken as the weighted average of $R_{K^0}$ and $R_{K^+}$.




$R_{K^+}$




$R_{K^0}$

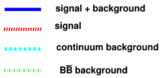



$R_K$

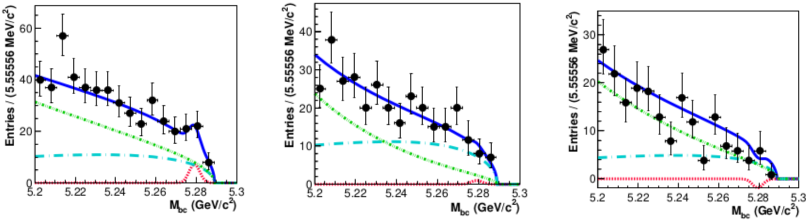
- $R_{K^+}$ results for [1.0, 6.0] is higher than the LHCb result by $1.6\sigma$.
- All measurements from Belle are consistent with SM.

# Search for lepton flavor violation in $B$ decays

- In many theoretical models, LFV accompanies LFU violation [Phys. Rev. Lett. 114, 091801 (2015)].
- Following channels are studied: $B^+ \to K^+\mu^+e^-$, $B^+ \to K^+\mu^-e^+$ and $B^0 \to K^0_s\mu^\pm e^\mp$ using 711 $\mathrm{fb}^{-1}$ $\Upsilon(4S)$ data $\to 772 \times 10^6 B\bar{B}$ events




Belle preliminary

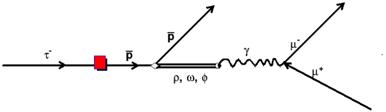



$B^+ \to K^+\mu^+e^-$ $B^+ \to K^+\mu^-e^+$ $B^0 \to K^0_s\mu^\pm e^\mp$

- The upper limits are $\mathcal{B}(B^+ \to K^+\mu^+e^-) < 8.5 \times 10^{-8}$, $\mathcal{B}(B^+ \to K^+\mu^-e^+) < 3.0 \times 10^{-8}$ and $\mathcal{B}(B^0 \to K^0_s\mu^\pm e^\mp) < 1.9 \times 10^{-8}$ 90% confidence level (CL).
- As $3.2\sigma$ evidence for signal is found for $B^+ \to K^+\mu^+e^-$, we also quote the branching fraction : $(4.98^{+2.62}_{-2.36} \pm 0.13) \times 10^{-8}$.

# Introduction to lepton flavor, lepton and baryon number violation

- Sakharov formulated three conditions to explain matter-antimatter asymmetry in the universe [JETP Lett. 5, 24-27, 1967]
  1. Baryon number violation 2. C-symmetry and CP-symmetry violation 3. Interaction out of thermal equilibrium
- Searching for six decay channels $\tau^- \to p\mu^-\mu^-$, $\bar{p}\mu^+\mu^-$, $pe^-e^-$ , $\bar{p}e^+e^-$, $\bar{p}e^+\mu^-$ and $\bar{p}e^-\mu^+$ using the data recorded by Belle
- Any observation of lepton flavor, lepton and baryon number violation would be a clear sign for new physics
- A diagram for $\tau^- \to \bar{p}\mu^+\mu^-$ possible in a new physics scenario proposed by Fuentes-Martin et al. [JHEP 1501,134 (2015)], shown in right



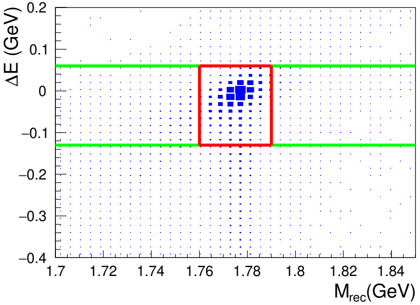

- LHCb set $\mathcal{B}(\tau^- \to p\mu^-\mu^-) < 4.4 \times 10^{-7}$ and $\mathcal{B}(\tau^- \to \bar{p}\mu^+\mu^-) < 3.3 \times 10^{-7}$ at 90% confidence level using 1 $\mathrm{fb}^{-1}$ pp collision data [Phys. Lett. B 724 (2013)]

# Data and reconstruction

- $711\,\mathrm{fb}^{-1}$ ($89.4\,\mathrm{fb}^{-1}$) data recorded at ($60\,\mathrm{MeV}$ below) the $\Upsilon(4S)$ resonance and a sample of $121\,\mathrm{fb}^{-1}$ collected near the $\Upsilon(5S)$ peak are used in the analysis.

We reconstruct $\tau \to p\ell\ell'$ ($\ell^{(')} = \mu,\, e$)

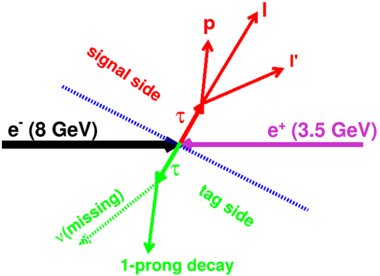
- Variables to identify signal:
  $M_{\mathrm{rec}} = \sqrt{E^2_{p\ell\ell'} - \vec{p}^{\,2}_{p\ell\ell'}}$,
  $\Delta E = E^{\mathrm{CM}}_{p\ell\ell'} - E^{\mathrm{CM}}_{\mathrm{beam}}$
- Red box denotes the signal region.
- The sideband is the $\Delta E$–$M_{\mathrm{rec}}$ region outside the red box; we use it to check the overall data - MC agreement for different variables.
- The $\Delta E$ strip, indicated by the region between two green lines excluding the red box is used to calculate the expected background yield in the signal region.




$\Delta E$-$M_{\mathrm{rec}}$ distribution for $\tau^- \to \bar{p}e^-e^+$ in signal MC

# Selection criteria

- Select events with $17^\circ < \theta < 150^\circ$, where $\theta$ is the polar angle relative to the z axis.
- Impact parameters: $|dr| < 0.5$ cm and $|dz| < 3$ cm
- Transverse momentum $p_{\rm T} > 0.1$ GeV and energy of $\gamma$, $E_\gamma > 0.1$ GeV
- 3-1 event topolgy is used to select the $\tau\tau$ events.

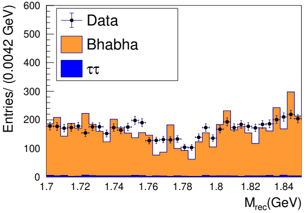



- Particle identification to identify final state charged tracks
- Thrust>0.9, $\cos\theta^{\rm CM}_{\rm tag-miss} > 0$ and $5^\circ < \theta_{\rm miss} < 175^\circ$
- For $\tau^- \to \overline{p}e^-e^+$, $\tau^- \to pe^-e^-$, $\tau^- \to \overline{p}e^+\mu^-$ and $\tau^- \to p\mu^-\mu^-$ channels, gamma conversion veto >0.2 GeV (on oppositely-charged track pairs assuming electron mass hypothesis) applied.
- In addition $E_{\rm ECL} < 10$ GeV applied for $\tau^- \to \overline{p}e^-e^+$, $\tau^- \to pe^-e^-$ channels to reject the remaining two-photon and radiative Bhabha backgrounds.

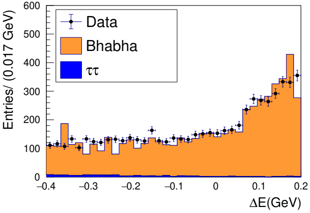
# Sideband study

- Sideband shape is shown in the case of $\tau^- \to \bar{p}e^+e^-$ channel without conversion veto.

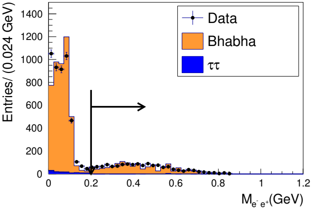
Belle preliminary



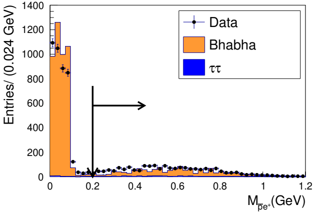

$M_{\rm rec}$ sideband




$\Delta E$ sideband




$M_{e^-e^+}$



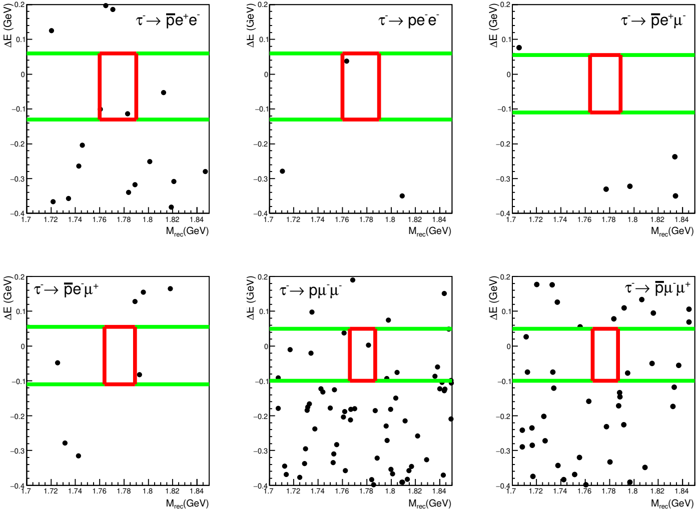

$M_{\bar{p}e^+}$

- $M_{e^-e^+}$ and $M_{\bar{p}e^+}$ are obtained assuming electron mass hypothesis.

# Results

- Number of observed events are consistent with the background prediction.

Belle preliminary



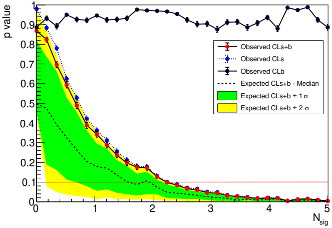
# Limits

- Upper limit (UL) on the signal yield is set using the Feldman-Cousins [G. J. Feldman and R. D. Cousins, Phys. Rev. D 57, 3873 (1998)] method.
- For $\tau^- \to \overline{p} e^- \mu^+$:
  No event in the signal region
  Expected background in the signal region $= 0.40 \pm 0.63$
  UL on the signal yield $= 2.2$ at 90% CL.
- Upper limit on

$$\mathcal{B}(\tau^- \to \overline{p} e^- \mu^+) < \frac{N_{\rm sig}^{\rm UL}}{2N_{\tau\tau}\epsilon},$$

$N_{\tau\tau} = 841 \times 10^6$ $\tau\tau$ pairs, $\epsilon = 6.9\%$, signal efficiency

$< 1.9 \times 10^{-8}$ at 90% CL.




Scan result for upperlimit, $\tau^- \to \overline{p} e^- \mu^+$

| All channels | $\epsilon$ (%) | $N_{\rm BG}$ | $N_{\rm obs}$ | $N_{\rm sig}^{\rm UL}$ | $\mathcal{B}$ ($\times 10^{-8}$) |
|---|---|---|---|---|---|
| $\tau^- \to \overline{p} e^+ e^-$ | 7.8 | $0.50 \pm 0.71$ | 1 | 3.3 | $< 2.5$ |
| $\tau^- \to p e^- e^-$ | 8.0 | $0.21 \pm 0.46$ | 1 | 3.8 | $< 2.8$ |
| $\tau^- \to \overline{p} e^+ \mu^-$ | 6.5 | $0.20 \pm 0.44$ | 0 | 2.3 | $< 2.1$ |
| $\tau^- \to \overline{p} e^- \mu^+$ | 6.9 | $0.40 \pm 0.63$ | 0 | 2.2 | $< 1.9$ |
| $\tau^- \to p \mu^- \mu^-$ | 4.6 | $1.30 \pm 1.14$ | 1 | 3.0 | $< 3.9$ |
| $\tau^- \to \overline{p} \mu^- \mu^+$ | 5.0 | $1.14 \pm 1.07$ | 0 | 2.3 | $< 2.7$ |

# Summary

- $R_K$ is measured for several $q^2$ bins.
- All measurements are compatible with the SM predictions.
- $R_{K^+}$ results for [1.0, 6.0] is higher than the LHCb result by $1.6\sigma$.
- More precision measurements can be done at Belle II.

- Limits on LFV $B$ decays are set in order of $10^{-8}$ at 90% CL. For neutral mode, Belle results improve than BaBar result by an order of magnitude.

- LHCb set $\mathcal{B}(\tau^- \to p\mu^-\mu^-) < 4.4 \times 10^{-7}$ and $\mathcal{B}(\tau^- \to \overline{p}\mu^+\mu^-) < 3.3 \times 10^{-7}$ at 90% CL using $1\ \mathrm{fb}^{-1}$ pp collision data.
- Our limit for $\mathcal{B}(\tau^- \to p\mu^-\mu^-) < 3.9 \times 10^{-8}$ and $\mathcal{B}(\tau^- \to \overline{p}\mu^-\mu^+) < 2.7 \times 10^{-8}$ improve by an order of magnitude using $841 \times 10^6$ $\tau^+\tau^-$ events.
- Also set the world's first limit on other four channels.

- More improved results are expected from Belle II.

THANK YOU