भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

BELLE

Measurement of Lepton Flavor Universality in B decays at Belle

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July 12 2019

Outline

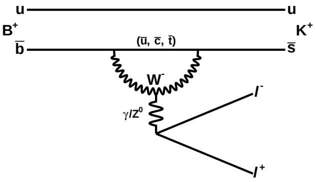
Test of LFU (R_K^*) in $B \to K^* \ell\ell$ decays [Belle, arXiv: 1904.02440]

Test of LFU (R_K) in $B \to K \ell\ell$ decays [New] [Conference paper to come] (Preliminary)

Isospin asymmetry (A_I) in $B \to K \ell\ell$ decays [New] [Conference paper to come] (Preliminary)

Introduction

- The rare decay $B \to K^{(*)}\ell\ell$ involves $b \to s$ quark level transition, which are flavor changing neutral currents (FCNCs). These processes occur through penguin loop and box diagrams in standard model (SM).



- Global analysis of B decays hints at lepton flavor non universality.
- These decays are highly suppressed and very small BR ($\mathcal{O}$ (10^{-7})).
- These decays are very sensitive to new physics (NP).

New physics can contribute by:

- enhancing or suppressing decay rates.
- modifying the angular distribution of the final state particles.

Introduction

- The amplitude of a hadron decay process [arXiv: hep-ph/9806471] is described as:

$$A(M \to F) = \langle F|\mathcal{H}_{eff}|M\rangle = \frac{G_F}{\sqrt{2}} \sum_i V^i_{CKM} C_i(\mu) \langle F|O_i(\mu)|M\rangle$$

CKM couplings | Wilson Coefficients (μ = scale) | Hadronic Matrix Elements

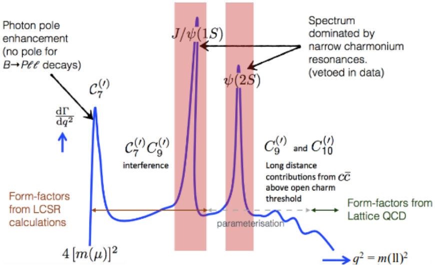
Wilson coefficients C_i = Perturbative short distance effects

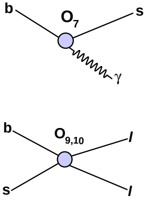
Operators O_i = non-perturbative long distance effects.

$i = 7$: Photon penguin

$i = 9, 10$: Electoweak penguin

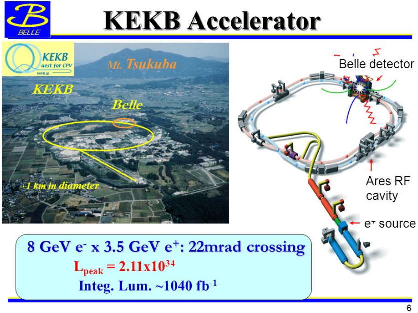
- NP can affect SM operator contributions (Wilson coefficients) and/or enter through new operators.

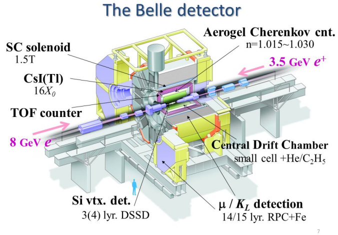




- Contribution of C_7, C_9 and C_{10} depends on q^2 (invariant mass square of two leptons).

Belle Experiment

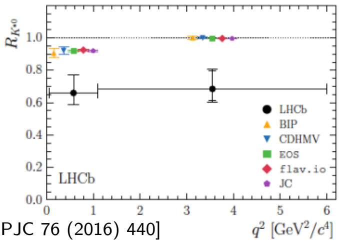


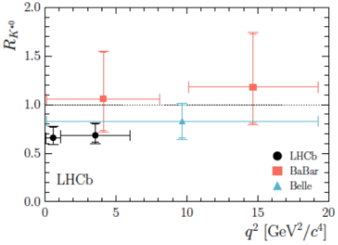


- The Belle experiment is located at the KEKB accelerator in Tsukuba, Japan.
- Data taking from 1999 to 2010.
- Data collected: 711 fb^{-1} = 772 million $B\bar{B}$ pairs.

$$e^+e^- \to \Upsilon(4S) \to B\bar{B}$$

- LHCb measurement of $R_{K^*} = \frac{BR(B \to K^* \mu^+ \mu^-)}{BR(B \to K^* e^+ e^-)}$ shows deviations from SM expectation.
  $R_{K^*}(0.045 < q^2 < 1.1 \text{ GeV}^2/c^4) = 0.66^{+0.11}_{-0.07} \pm 0.03$
  $R_{K^*}(1.1 < q^2 < 6 \text{ GeV}^2/c^4) = 0.69^{+0.11}_{-0.07} \pm 0.05$
- Compatibility with the SM estimated to be at the level of $2.1 - 2.3\sigma$ for low q^2 and $2.4 - 2.5\sigma$ at central q^2 for a data sample of 3fb^{-1}.
- Belle [605 fb^{-1}] measurement for whole q^2 region, $R_{K^*} = 0.83 \pm 0.17 \pm 0.08$, is consistent with SM prediction.
- BaBar measured for low and high q^2 bins and are consistent with SM with large uncertainty.





▲ BIP [EPJC 76 (2016) 440]
▼ CDHMV [JHEP 04 (2017) 016]
■ EOS [PRD 95 (2017) 035029]
♦ flav. io [EPJC 77 (2017) 377]
● JC [PRD 93 (2016) 014028]

● LHCb [JHEP 08(2017) 055]
■ BaBar [PRD 86 (2012) 032012]
▲ Belle [PRL 103 (2009) 171801]

Test of LFU (R_{K^*}) in $B \to K^* \ell\ell$ decays at Belle **[arXiv: 1904.02440]**

- R_{K^*} measurement with 711 fb^{-1} data sample for different q^2 bins.
- The channels reconstructed for analysis are

$$B^0 \to K^{*0}\mu^+\mu^-,\ B^+ \to K^{*+}\mu^+\mu^-$$
$$B^0 \to K^{*0}e^+e^-,\ B^+ \to K^{*+}e^+e^-$$

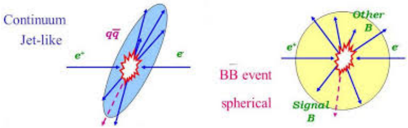
- K^* is reconstructed from:

$$K^{*0} \to K^+\pi^-$$
$$K^{*+} \to K^+\pi^0$$
$$K^{*+} \to K^0_S\pi^+$$

- Multivariate analysis technique (NN) is used to identify each particle type in the decay chain.
- Kinematic variables which distinguish signal from background are

$$M_{\rm bc} = \sqrt{E^2_{beam}/c^4 - |p_B|^2/c^4}$$
$$\Delta E = E_B - E_{beam}$$

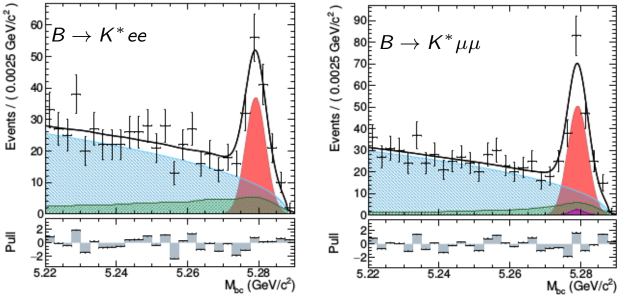
- Requirment on kinematic variables:
  $5.22 < M_{\rm bc} < 5.30$ GeV$/c^2$ and -0.10 $(-0.05) < \Delta E < 0.05$ GeV for ee$(\mu\mu)$
- Backgrounds:



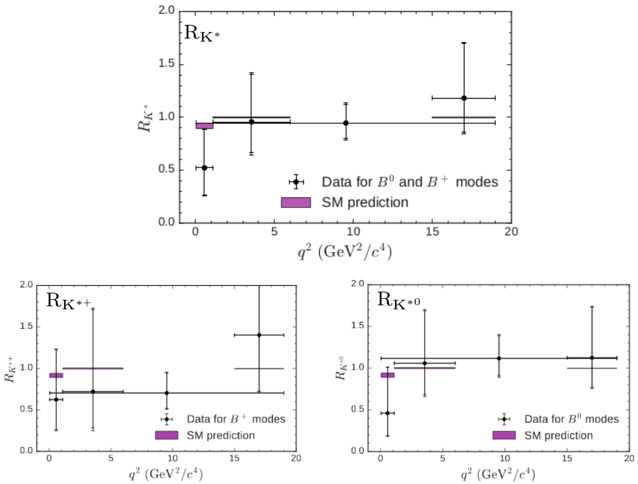
- NN is used to suppress the backgrounds.

R_K^* Data fit **[arXiv: 1904.02440]**

- Perfomed extended maximum likelihood fit in $M_{\rm bc}$ to extract the signal.
- Example fit for $q^2 > 0.045$ GeV$^2/c^4$.
- $103.0^{+13.4}_{-12.7}$ and $139.9^{+16.0}_{-15.4}$ events for electron and muon modes, respectively.



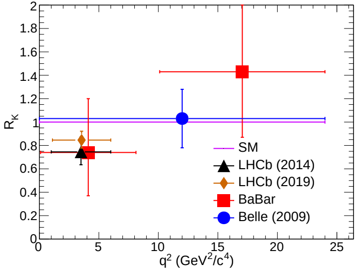
R_K^* Results [arXiv: 1904.02440]



- First measurement of $R_{K^{*+}}$.
- All results are found to be compatible with SM prediction.

Test of LFU (R_K) for $B \to K\ell\ell$

- SM prediction is very accurate. $R_K^{(SM)} = 1 \pm \mathcal{O}(10^{-2})$
- LHCb [PRL 113, 151601(2014)] shows deviation from SM
  $$R_K = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$
  in $q^2 = [1-6]$ GeV$^2/c^4$: 2.6σ tension for 3fb^{-1} data sample (2011-12 data).
- LHCb [arXiv: 1903.09252] shows $R_K([1.1-6]) = 0.846^{+0.016}_{-0.054}{}^{+0.060}_{-0.014}$, 2.5$\sigma$ deviation for 5 fb^{-1} data sample (2011 - 2016 data).
- The value of R_K for Belle [arXiv: 0904.0770] was consistent with unity within the uncertainty limit measured for a data sample of 605fb^{-1}.



Bin	R_K	Collaboration
$1 < q^2 < 6$	$0.745^{+0.090}_{-0.074} \pm 0.036$	LHCb (2014)
$1.1 < q^2 < 6$	$0.846^{+0.060+0.016}_{-0.054-0.014}$	LHCb (2019)
whole q^2	$1.03 \pm 0.19 \pm 0.06$	Belle
$0.10 < q^2 < 8.12$	$0.74^{+0.40}_{-0.31} \pm 0.06$	BaBar
$q^2 > 10.11$	$1.43^{+0.65}_{-0.44} \pm 0.12$	BaBar

Test of LFU (R_K) in $B \to K\ell\ell$ decays at Belle **[New]**

Introduction

- This measurement of R_K is with Belle full data sample of 711 fb^{-1}, while the previous measurement was with 605 fb^{-1}.
- We perform a multi-dimensional fit using $M_{\rm bc}$, ΔE and background suppression variable to extract the signal yield.
- We calibrate the signal component with $B \to KJ/\psi$ sample and continuum ($e^+e^- \to q\bar{q}$) background with off-resonance data sample.

Particle Selection Criteria

- The decay mode reconstructed are $B^+ \to K^+\ell\ell$ and $B^0 \to K^0_S\ell\ell$, where $\ell\ell = \mu\mu$ or ee.
- $K^\pm$, $\mu^\pm$ and $e^\pm$ particles satisfying PID are selected from tracks near IP. K^0_S are selected using K^0_S displaced vertex properties and with a mass window, 3σ about K^0_S nominal mass.
- The requirement on kinematic variables are

$$5.2 < M_{\rm bc} < 5.29\ \text{GeV}/c^2 \text{ and } -0.1 < \Delta E < 0.25\ \text{GeV}$$

Test of LFU (R_K) in $B \to K\ell\ell$ decays at Belle **[New]**

Background suppression and *NN* translation

- The irreducible peaking background coming from $B \to KJ/\psi(\to \ell\ell)$ and $B \to K\psi(2S)(\to \ell\ell)$ are removed by q^2 veto.
- The peaking background are reduced by applying invariant mass veto.

Mode	Peaking source	Veto
$B^+ \to K^+\mu^+\mu^-$	$B^+ \to \bar{D}^0(\to K^+\pi^-)\pi^+$	$M_{K^+\mu^-} \notin [1.8489 - 1.8810]$
$B^+ \to K^+\mu^+\mu^-$	$B^+ \to K^+J/\psi(\to \mu^+\mu^-)$	$M_{K^+\mu^-} \notin [3.06 - 3.13]$

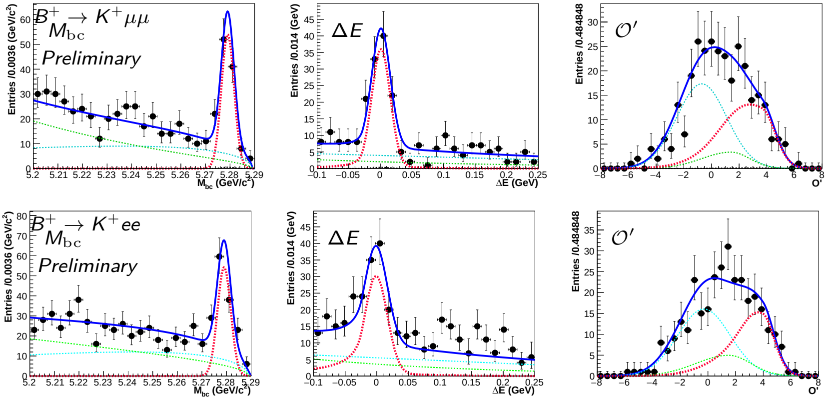
- B to charmless decays have negligible contribution in all modes.
- The *NN* is trained with some event shape, vertex quality and kinematic variables to suppress the background from continuum and generic B decays.
- The *NN* output ($\mathcal{O}$) is translated to $\mathcal{O}'$ using the formula

$$\mathcal{O}' = \log \frac{\mathcal{O} - \mathcal{O}_{\min}}{\mathcal{O}_{\max} - \mathcal{O}}$$

- $NN_{min} = -0.6$ reduces background $\sim 75\%$, with signal efficiency loss of $4 - 5\%$.

Fit results for $B \to K\ell\ell$ [New]

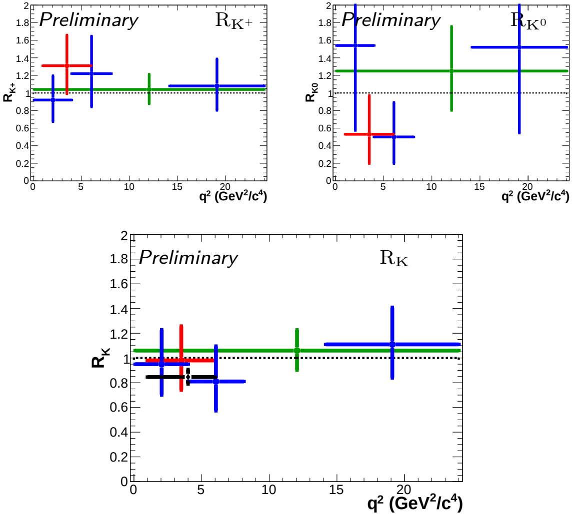
- Extended maximum likelihood fit is performed in 3-dimensions *i.e.*, $M_{\rm bc}$, ΔE and $\mathcal{O}'$.
- $B \to KJ/\psi(\to \ell\ell)$ is used as a control sample to calibrate the signal PDF of $B \to K\ell\ell$.
- Example fit of $B^+ \to K^+\mu\mu$ and $B^+ \to K^+e^+e^-$ for $q^2 > 0.1$ GeV$^2/c^4$.



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

R_K, R_{K^+} and R_{K^0} results from Belle **[New]**

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

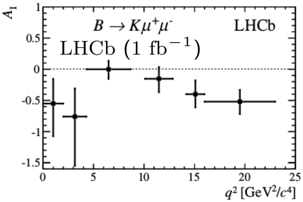


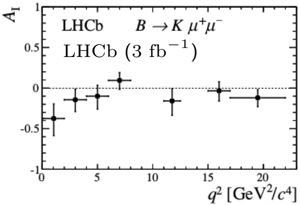
- The measurements are found to be consistent with SM prediction as well as LHCb result.

Isospin Asymmetry (A_I) in $B \to K\ell\ell$ decays

$$A_I = \frac{(\tau_{B^+}/\tau_{B^0}) \times \mathcal{B}(\mathrm{B}^0 \to \mathrm{K}^0\ell\ell) - \mathcal{B}(\mathrm{B}^+ \to \mathrm{K}^+\ell\ell)}{(\tau_{B^+}/\tau_{B^0}) \times \mathcal{B}(\mathrm{B}^0 \to \mathrm{K}^0\ell\ell) + \mathcal{B}(\mathrm{B}^+ \to \mathrm{K}^+\ell\ell)}$$

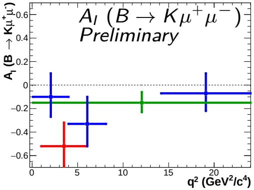
- BaBar [arXiv:0807.4119] has reported 3.2 σ in $B \to K\ell\ell$ for low q^2 bin using 384 million $B\bar{B}$ pairs.
- Belle [arXiv: 0904.0770] measurent with 657 million $B\bar{B}$ pairs, show no significant deviation from null value, $\sigma = 1.75$.
- LHCb [arXiv: 1205.3422] show deviation in $A_I(B \to K\mu\mu)$ measured for 1 fb^{-1} data sample, the deviation below $q^2 < 4.3$ GeV$^2/c^4$ and above $q^2 > 16$ GeV$^2/c^4$ bin more significant. The significance of the deviation from zero integrated across q^2 is 4.4 σ.
- LHCb [arXiv: 1403.8044] again show $A_I(B \to K\mu\mu)$ with 3 fb^{-1} data sample and found negative asymmetry but the results are more consistent with SM expectation.

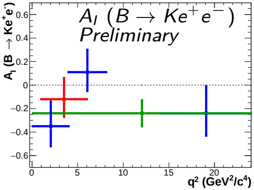


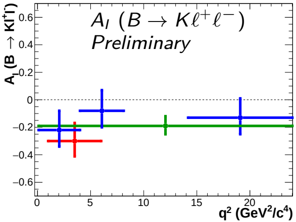


A_I results from Belle **[New]**

- A_I is measured for $B \to K\mu^+\mu^-$, $B \to Ke^+e^-$ and $B \to K\ell^+\ell^-$ for [0.1 , 4.0], [4.0 , 8.12], [1.0 , 6.0], $>$ 14.18 and $>$ 0.1 q^2 bins.
- $A_I(B \to K\ell^+\ell^-)$ as weighted average of $A_I(B \to K\mu^+\mu^-)$ and $A_I(B \to Ke^+e^-)$.







- The isospin asymmetry is found for $B \to K\mu^+\mu^-$ at a level of $\sim 2.7\sigma$ for the bin of $1 < q^2 < 6$ GeV$^2/c^4$ and this deviation is $\sim 2.5\sigma$ for $B \to K\ell^+\ell^+$.

Conclusion

- The LFU ratio is measured for several q^2 bins, including the bin of $1 < q^2 < 6$ GeV$^2/c^4$.
- The new results of R_K with Belle full data sample of 711 fb^{-1} are consistent with SM prediction as well as LHCb result.
- R_{K^*} measurement for different q^2 bins are compatible with SM prediction for Belle full data sample.

- A_I shows $\sim 2.7\sigma$ deviation for $B \to K\mu\mu$ mode of $1 < q^2 < 6$ GeV$^2/c^4$ bin.

- More results to come from Belle and Belle II.

R_K and A_I

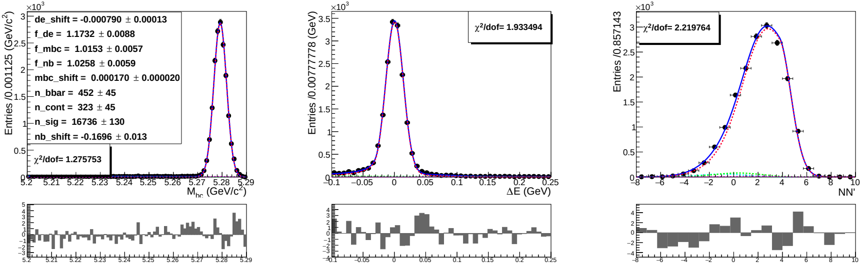
Table: R_{K^+}, R_{K^0} and R_K for different q^2 bins.

Bin	R_{K^+}	R_{K^0}	R_K
$0.1 < q^2 < 4$	$0.92^{+0.27}_{-0.24} \pm 0.05$	$1.5^{+1.2}_{-1.0} \pm 0.1$	$0.95^{+0.27}_{-0.24} \pm 0.06$
$4 < q^2 < 8.12$	$1.22^{+0.42}_{-0.37} \pm 0.07$	$0.50^{+0.39}_{-0.30} \pm 0.03$	$0.81^{+0.28}_{-0.23} \pm 0.05$
$1 < q^2 < 6$	$1.31^{+0.34}_{-0.31} \pm 0.07$	$0.53^{+0.44}_{-0.33} \pm 0.03$	$0.98^{+0.27}_{-0.23} \pm 0.06$
$q^2 > 14.18$	$1.08^{+0.30}_{-0.27} \pm 0.06$	$1.52^{+1.23}_{-0.97} \pm 0.10$	$1.11^{+0.29}_{-0.26} \pm 0.07$
whole q^2	$1.04^{+0.16}_{-0.15} \pm 0.06$	$1.25^{+0.50}_{-0.44} \pm 0.08$	$1.06^{+0.15}_{-0.14} \pm 0.07$

Table: $A_I(B \to K\mu\mu)$, $A_I(B \to Kee)$ and $A_I(B \to K\ell\ell)$ for different q^2 bins.

Bin	$A_I(B \to K\mu\mu)$	$A_I(B \to Kee)$	$A_I(B \to K\ell\ell)$
$0.1 < q^2 < 4$	$-0.10^{+0.20}_{-0.17} \pm 0.01$	$-0.35^{+0.21}_{-0.17} \pm 0.01$	$-0.22^{+0.14}_{-0.12} \pm 0.01$
$4 < q^2 < 8.12$	$-0.33^{+0.23}_{-0.19} \pm 0.01$	$0.11^{+0.19}_{-0.16} \pm 0.01$	$-0.08^{+0.15}_{-0.12} \pm 0.01$
$1 < q^2 < 6$	$-0.52^{+0.20}_{-0.17} \pm 0.02$	$-0.12^{+0.18}_{-0.15} \pm 0.01$	$-0.30^{+0.13}_{-0.11} \pm 0.01$
$q^2 > 14.18$	$-0.07^{+0.17}_{-0.15} \pm 0.01$	$-0.24^{+0.23}_{-0.19} \pm 0.01$	$-0.13^{+0.14}_{-0.12} \pm 0.01$
whole q^2	$-0.15^{+0.09}_{-0.08} \pm 0.01$	$-0.24 \pm 0.11 \pm 0.01$	$-0.19^{+0.07}_{-0.06} \pm 0.01$

$R_K(J/\psi)$



Condition	R_K
$R_K(B^+ \to K^+ J/\psi)$	0.992 ± 0.011
$R_K(B^0 \to K^0_S J/\psi)$	1.048 ± 0.020