Rare B Decay Analyses at Belle

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Outline

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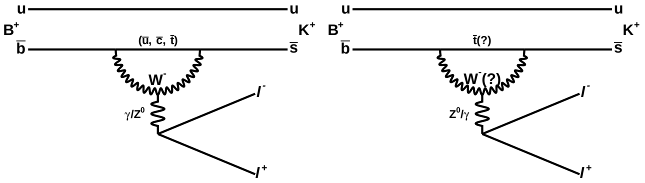
7. Summary

- The rare decay $B \to K^{(*)}\ell\ell$ involves $b \to s$ quark level transition, which are flavor changing neutral currents. 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})).
- They are very sensitive to new physics.
- The new physics can contribute by enhancing or suppressing the decay rates or modifying the angular distribution of the final state particles.

Introduction

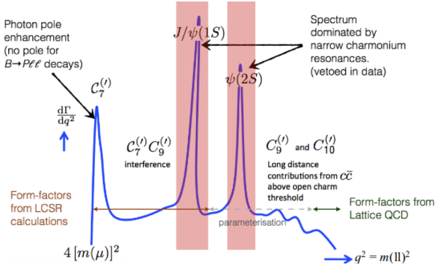
- The amplitude of a hadron decay process [arXiv:hep-ph/9806471] is described as:

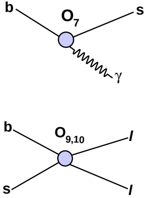
$$A(M \to F) = \langle F|\mathcal{H}_{eff}|M\rangle = \frac{G_F}{\sqrt{2}} \sum_i V^i_{CKM} C_i(\mu) \langle F|O_i(\mu)|M\rangle$$

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

$$\text{Wilson coefficients } C_i = \text{Perturbative short distance effects}$$
$$\text{Operators } O_i = \text{non-perturbative long distance effects.}$$
$$i = 7 : \text{ Photon penguin}$$
$$i = 9, 10 : \text{ Electoweak penguin}$$

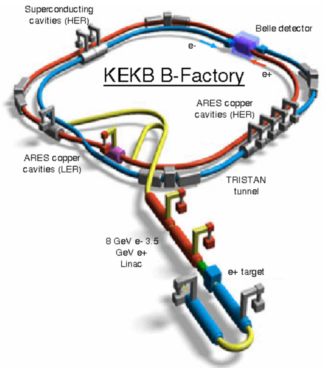
- NP can affect SM operator contributions (Wilson coefficients) and/or enter through new operators.

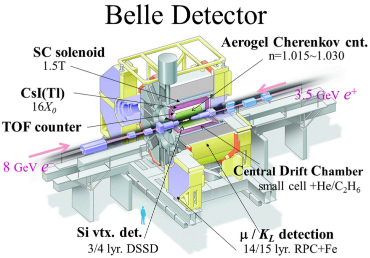




- Contribution of C_7, C_9 and C_{10} depends on q^2 (invariant mass square of two leptons).

Belle Experiment



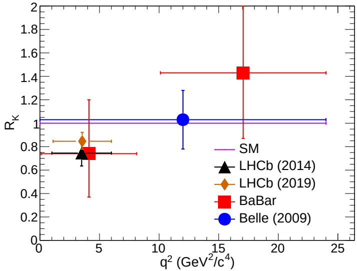


- The Belle experiment was located at the KEKB accelerator in Tsukuba, Japan.
- Data taking from 1999 to 2010.
- Data collected at $\Upsilon(4S)$: 711 fb^{-1} = 772 million $B\bar{B}$ pairs.

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

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

- SM prediction is very accurate. $R_K^{(SM)} = 1 \pm \mathcal{O}(10^{-2})$ [Eur. Phys. J. C76, 440 (2016)]
- 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 $3\mathrm{fb}^{-1}$ data sample (2011-12 data).
- LHCb [PRL 122, 191801 (2019)] 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 [PRL 103, 171801 (2009)] was consistent with unity for the whole q^2 region within the uncertainty limit, measured for a data sample of $605\mathrm{fb}^{-1}$.



Bin (GeV$^2/c^4$)	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

- We want to exploit maximum from the data already collected (711 fb^{-1}) and make the extrapolation to Belle II reliable.

- 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_{bc}, ΔE and background suppression variable to extract the signal yield.
- The R_K values are given in five q^2 bins and also the whole q^2 region.
- We calibrate the signal component with $B \to J/\psi K$ sample and continuum ($e^+e^- \to q\bar{q}$) background with off-resonance data sample (89 fb^{-1}).
- The leptonID systematics (major source) were improved significantly.

Particle Selection Criteria

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

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

- The requirement on kinematic variables are

$$5.20 < M_{\mathrm{bc}} < 5.30 \text{ GeV}/c^2 \text{ and } -0.1 < \Delta E < 0.25 \text{ GeV}$$

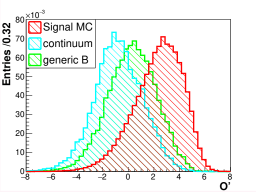
Background suppression and *NN* translation

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

Mode	Peaking source	Veto
$B^+ \to K^+\mu^+\mu^-$	$B^+ \to \bar{D}^0(\to K^+\pi^-)\pi^+$	$M_{K^+\mu^-} \notin [1.85 - 1.88]$
$B^+ \to K^+\mu^+\mu^-$	$B^+ \to J/\psi(\to \mu^+\mu^-)K^+$	$M_{K^+\mu^-} \notin [3.06 - 3.13]$

- Small contribution of $B \to K\pi\pi$ decay is studied with all intermediate resonances and fixed in the fit.
- 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

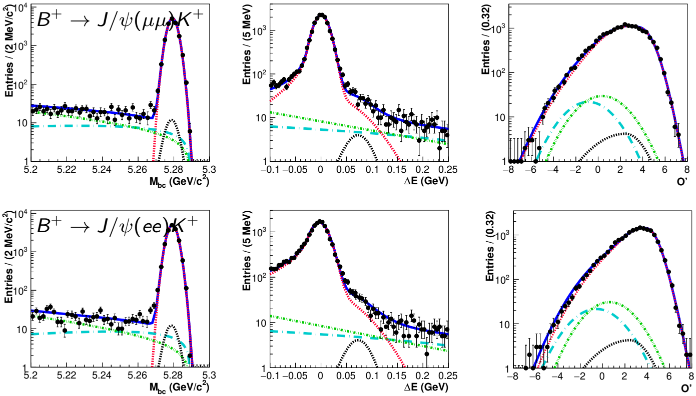
$$\mathcal{O}' = \log \frac{\mathcal{O} - \mathcal{O}_{\min}}{\mathcal{O}_{\max} - \mathcal{O}}$$



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

- The signal yield is extracted by performing extended maximum likelihood fit in 3-dimensions *i.e.*, $M_{\rm bc}$, ΔE and $\mathcal{O}'$.

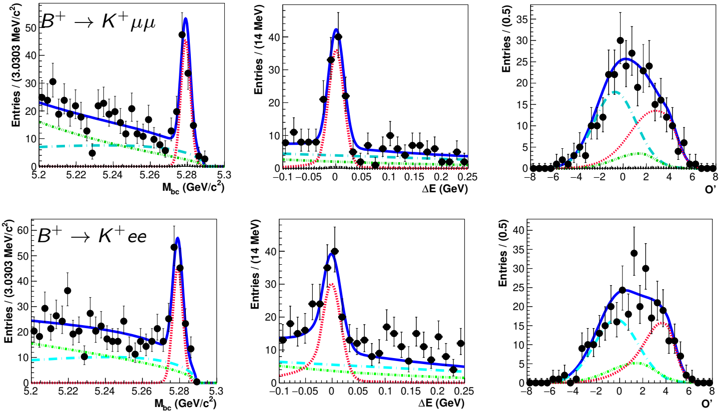
continuum, generic B, $[\pi^+ J/\psi]$, signal, total



Sample	$\mathcal{B}$ (10^{-3})	PDG (10^{-3})
$\mathcal{B}(\mathrm{B}^+ \to \mathrm{J}/\psi\mathrm{K}^+)$	$1.032 \pm 0.007 \pm 0.024$	1.006 ± 0.027
$\mathcal{B}(\mathrm{B}^0 \to \mathrm{J}/\psi\mathrm{K}^0)$	$0.902 \pm 0.010 \pm 0.026$	0.868 ± 0.030

- These are world's most precise measurements because of dramatic improvement in systematic uncertainties (especially leptonID systematic is $< 1\%$).
- $R_K(J/\psi) = 0.994 \pm 0.011 \pm 0.010$ is consistent with SM expectation.

- Extended maximum likelihood fit is performed in 3-dimensions *i.e.*, $M_{\rm bc}$, ΔE and $\mathcal{O}'$.
- $B \to J/\psi(\to \ell\ell)K$ 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$^2/c^4$.

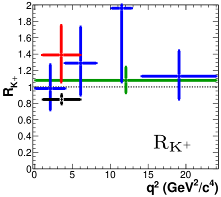


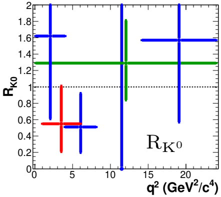
- 137 ± 14 and 138 ± 15 events in $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$ modes.
- $27.3^{+6.6}_{-5.8}$ and $21.8^{+7.0}_{-6.1}$ events in $B^0 \to K^0_S\mu^+\mu^-$ and $B^0 \to K^0_S e^+e^-$ modes.

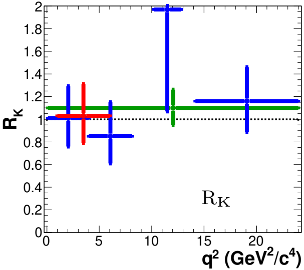
$$\mathcal{B}(\mathrm{B}^+ \to \mathrm{K}^+\ell\ell) = (5.99^{+0.45}_{-0.43} \pm 0.14) \times 10^{-7}$$
$$\mathcal{B}(\mathrm{B}^0 \to \mathrm{K}^0\ell\ell) = (3.51^{+0.69}_{-0.60} \pm 0.10) \times 10^{-7}.$$

R_{K^+}, R_{K^0} and R_K results from Belle [arXiv:1908.01848v2]

- $R_K(J/\psi)$ is $0.994 \pm 0.011 \pm 0.010$.
- R_{K^+}, R_{K^0} and R_K are measured 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.





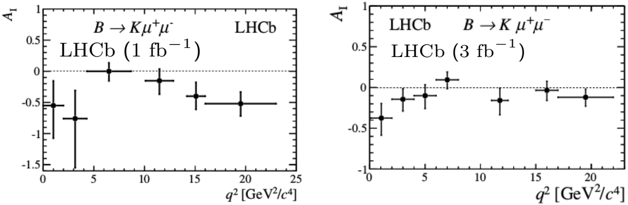


- The measurements are found to be consistent with SM prediction.
- The R_K^+ result of Belle for $q^2 \in [1.0, 6.0]$ GeV$^2/c^4$ bin is consitent with SM expectation within 1.1σ and deviates from LHCb [PRL 122, 191801 (2019)] by 1.6σ.

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

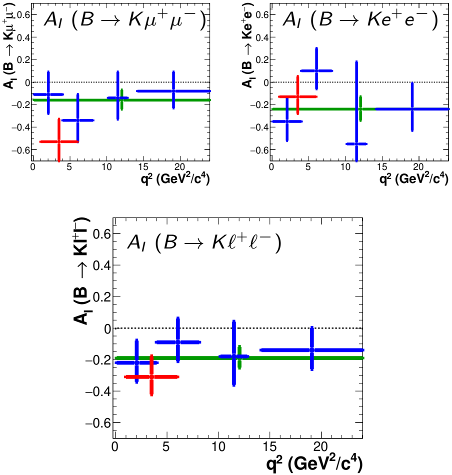
$$A_I = \frac{(\tau_{B^+}/\tau_{B^0}) \times \mathcal{B}(\mathrm{B}^0 \to \mathrm{K}^0\ell\ell) - \mathcal{B}(\mathrm{B}^+ \to \mathrm{K}^+\ell\ell)}{(\tau_{B^+}/\tau_{B^0}) \times \mathcal{B}(\mathrm{B}^0 \to \mathrm{K}^0\ell\ell) + \mathcal{B}(\mathrm{B}^+ \to \mathrm{K}^+\ell\ell)}$$

- The SM prediction for A_I is $\mathcal{O}(1\%)$ [JHEP 01, 074 (2003), JHEP 02, 010 (2013), PRD D88, 094004 (2013)].
- BaBar [PRL 102, 091803(2009)] has reported 3.2 σ in $B \to K\ell\ell$ for low q^2 bin using 384 million $B\bar{B}$ pairs.
- Belle [PRL 103, 171801 (2009)] measurement with 657 million $B\bar{B}$ pairs, shows a deviation of 1.75σ from null value.
- LHCb [JHEP 07, 133 (2012)] shows 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 [JHEP 06, 133 (2014)] shows $A_I(B \to K\mu\mu)$ with 3 fb^{-1} data sample and found negative asymmetry but the results are more consistent with SM expectation.



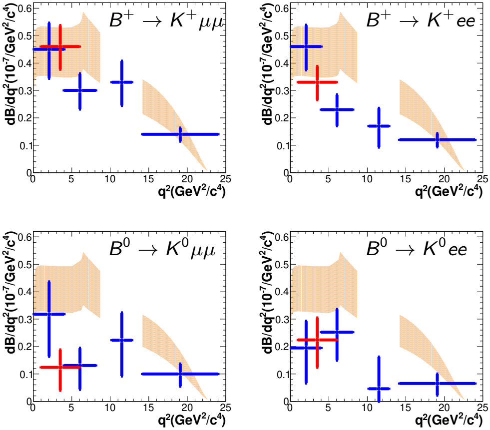
A_I results from Belle [arXiv:1908.01848v2]

- The $A_I(B \to J/\psi K)$ is $-0.002 \pm 0.006 \pm 0.014$.
- A_I is measured for $B \to K\mu^+\mu^-$, $B \to Ke^+e^-$ and $B \to K\ell^+\ell^-$ in [0.1 , 4.0], [4.0 , 8.12], [1.0 , 6.0], [10.2, 12.8], > 14.18, and > 0.1 q^2 bins.



- The A_I values for all bins show negative asymmetry.
- The isospin asymmetry is found for $B \to K\mu^+\mu^-$ at a level of 2.6σ for the bin of $1 < q^2 < 6$ GeV$^2/c^4$.

- dB/dq^2 is measured for $B^+ \to K^+\ell^+\ell^-$ and $B^0 \to K^0\ell^+\ell^-$ in [0.1 , 4.0], [4.0 , 8.12], [1.0 , 6.0], [10.2, 12.8], and > 14.18 bins.
- The theoretical predictions is from the light-cone sum rule and lattice QCD calculations [JHEP 07, 067 (2011), JHEP 01, 107 (2012)].



- The dB/dq^2 results for $B^+ \to K^+\mu^+\mu^-$ is consistent with SM prediction for almost all q^2 bins, where LHCb [JHEP 06, 133 (2014)] seems to have lower values.

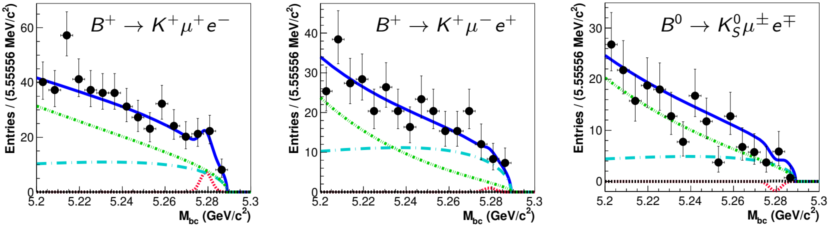
Introduction to LFV $B \to K\ell\ell'$ decays

- In many theoretical models [PRL 114, 091801 (2015)], LFV accompanies LFU violation.
- With neutrino mixing, LFV is possible at rates far below the current experimental sensitivity[Nucl. Phys.B853, 80 (2011)].
- In case of signal, this will signify physics beyond SM.
- The most stringent upper limits on $B^+ \to K^+\mu^+e^-$ and $B^+ \to K^+\mu^-e^+$ modes are 6.4×10^{-9} and 7.0×10^{-9} at 90% CL and set by LHCb [PRL 123, 241802 (2019)].
- The $B^0 \to K^0\mu^\pm e^\mp$ decays were seached by BaBar [PRD 73, 092001 (2006)] and 90% CL upper limit on BR is 2.7×10^{-7}.

- The $B \to K\ell\ell'$ analysis is done in the similar way as $B \to K\ell\ell$ decays.
- Peaking backgrounds:
  - Background from $B \to J/\psi(\to ee)K$:

Mode	description	Veto (GeV/c^2)
$B^+ \to K^+\mu^+e^-$	e is misidentified as K and K as μ	$M_{K^+e^-} \in (2.95, 3.11)$
$B^+ \to K^+\mu^+e^-$	e is misidentified as μ	$M_{\mu^+e^-} \in (3.02, 3.12)$
$B^+ \to K^+\mu^-e^+$	e is misidentified as μ	$M_{\mu^+e^-} \in (3.02, 3.12)$
$B^0 \to K^0_S\mu^\pm e^\mp$	e is misidentified as μ	$M_{\mu^+e^-} \in (3.04, 3.12)$

  - A tiny contribution from $B^+ \to \bar{D}^0(K^+\pi^-)\pi^+$ is removed by $M_{K^+\mu^-} \in (1.85, 1.88)$ GeV/c^2.
  - Small contribution of $B \to K\pi\pi$ decay is studied with all intermediate resonances and fixed in the fit.
- The signal yield is extracted by performing maximum likelihood fit in 3-dimensions, $M_{\rm bc}$, ΔE and $\mathcal{O}'$.



- There are $11.6^{+6.1}_{-5.5}$, $1.7^{+3.6}_{-2.2}$ and $-3.3^{+4.0}_{-2.8}$ signal events for $B^+ \to K^+\mu^+e^-$, $B^+ \to K^+\mu^-e^+$ and $B^0 \to K^0_S\mu^\pm e^\mp$ modes, respectively.
- The significance of signal yield for $B^+ \to K^+\mu^+e^-$ channel is 3.2σ considering statistical and systematic uncertainties.
- The excess in $B^+ \to K^+\mu^+e^-$ is driven by one golden event.

Mode	ε (%)	$N_{\rm sig}$	$N_{\rm sig}^{\rm UL}$	$\mathcal{B}^{(\rm UL)}$ (10^{-8})
$B^+ \to K^+\mu^+e^-$	29.4	$11.6^{+6.1}_{-5.5}$	19.9	8.5
$B^+ \to K^+\mu^-e^+$	31.2	$1.7^{+3.6}_{-2.2}$	7.5	3.0
$B^0 \to K^0\mu^\pm e^\mp$	20.9	$-3.3^{+4.0}_{-2.8}$	3.0	3.8

- The existing limit on the neutral decay mode is improved by an order of magnitude.

Summary

- $\mathcal{B}(\mathrm{B}^+ \to \mathrm{J}/\psi \mathrm{K}^+)$ and $\mathcal{B}(\mathrm{B}^0 \to \mathrm{J}/\psi \mathrm{K}^0)$ are most precise measurements to date.
- $R_K(J/\psi)$ and $A_I(B \to J/\psi K)$ are consistent with SM expectations.

- The R_K values for different q^2 bins are consistent with SM predictions.
- Our result of R_{K^+} for $1.0 < q^2 < 6.0$ GeV$^2/c^4$ deviates from LHCb result by 1.6σ.

- The A_I values for almost all the bins show a negative asymmetry.
- A_I shows 2.6σ deviation for $B \to K\mu\mu$ mode in $1 < q^2 < 6$ GeV$^2/c^4$ bin.

- The dB/dq^2 results for $B^+ \to K^+\mu^+\mu^-$ is consistent with SM prediction for all q^2 bins, where LHCb seems to have lower values.
- The values for neutral B are lower than theoretical prediction.

- The upper limit on BR for $B^+ \to K^+\mu^\pm e^\mp$ modes are $\mathcal{O}(10^{-8})$.
- We improves the exising upper limit on $B^0 \to K^0\mu^\pm e^\mp$ mode by an order of magnitude, *i.e.*, 3.8×10^{-8}.

- We extracted the most from Belle data sample and pass the relay to Belle II.

Backup slides

Bin	R_{K^+}	R_{K^0}	R_K
$[0.1, 4.0]$	$0.98^{+0.29}_{-0.26} \pm 0.02$	$1.62^{+1.31}_{-1.01} \pm 0.02$	$1.01^{+-0.28}_{-0.25} \pm 0.02$
$[4.0, 8.12]$	$1.29^{+0.44}_{-0.39} \pm 0.02$	$0.51^{+0.41}_{-0.31} \pm 0.01$	$0.85^{+0.30}_{-0.24} \pm 0.01$
$[1.0, 6.0]$	$1.39^{+0.36}_{-0.33} \pm 0.02$	$0.55^{+0.46}_{-0.34} \pm 0.01$	$1.03^{+0.28}_{-0.24} \pm 0.01$
$[10.2, 12.8]$	$1.96^{+1.03}_{0.89} \pm 0.02$	$5.18^{+17.69}_{-14.32} \pm 0.06$	$1.97^{+1.03}_{-0.89} \pm 0.02$
> 14.18	$1.13^{+0.31}_{-0.28} \pm 0.01$	$1.57^{+1.28}_{1.00} \pm 0.02$	$1.16^{+0.30}_{-0.27} \pm 0.01$
$q^2 > 0.1$	$1.08^{+0.16}_{-0.15} \pm 0.02$	$1.29^{+0.52}_{-0.45} \pm 0.01$	$1.10^{+0.16}_{-0.15} \pm 0.02$

Bin	$A_I(B \to K\mu\mu)$	$A_I(B \to Kee)$	$A_I(B \to K\ell\ell)$
$[0.1, 4.0]$	$-0.11^{+0.20}_{-0.17} \pm 0.01$	$-0.35^{+0.21}_{-0.17} \pm 0.01$	$-0.22^{+0.14}_{-0.12} \pm 0.01$
$[4.0, 8.12]$	$-0.34^{+0.23}_{-0.19} \pm 0.01$	$0.10^{+0.20}_{-0.16} \pm 0.01$	$-0.09^{+0.15}_{-0.12} \pm 0.01$
$[1.0, 6.0]$	$-0.53^{+0.20}_{-0.17} \pm 0.02$	$-0.13^{+0.18}_{-0.15} \pm 0.01$	$-0.31^{+0.13}_{-0.11} \pm 0.01$
$[10.2, 12.8]$	$-0.14^{+0.24}_{-0.19} \pm 0.01$	$-0.55^{+0.73}_{-0.60} \pm 0.01$	$-0.18^{+0.22}_{-0.18} \pm 0.01$
> 14.18	$-0.08^{+0.17}_{-0.15} \pm 0.01$	$-0.24^{+0.23}_{-0.19} \pm 0.01$	$-0.14^{+0.14}_{-0.12} \pm 0.01$
$q^2 > 0.1$	$-0.16^{+0.09}_{-0.10} \pm 0.01$	$-0.24^{+0.11}_{-0.10} \pm 0.01$	$-0.19^{+0.07}_{-0.06} \pm 0.01$

Systematics in $B \to J/\psi K$

Table: Relative systematic uncertainties (%) for $\mathcal{B}(B \to J/\psi K)$, $R_K(J/\psi)$, and absolute uncertainty for $A_I(B \to J/\psi K)$.

Sources	$B^+ \to J/\psi K^+$	$B^0 \to J/\psi K_s^0$	$R_{K^+}(J/\psi)$	$R_{K^0}(J/\psi)$	$A_I(J/\psi K)$
Lepton identification	± 0.68	± 0.68	± 0.97	± 0.97	–
Kaon identification	± 0.80	–	–	–	± 0.007
K_S^0 identification	–	± 1.57	–	–	± 0.002
Track reconstruction	± 1.05	± 1.40	–	–	± 0.002
Efficiency calculation	± 0.14	± 0.18	± 0.20	± 0.25	± 0.001
Number of $B\bar{B}$ pairs	± 1.40	± 1.40	–	–	–
$f^{+-(00)}$	± 1.20	± 1.20	–	–	± 0.012
$\mathcal{O}_{\min}$	± 0.16	± 0.28	± 0.24	± 0.39	± 0.001
PDF shape parameters	$^{+0.15}_{-0.20}$	$^{+0.05}_{-0.10}$	$^{+0.22}_{-0.31}$	$^{+0.10}_{-0.20}$	± 0.002
Total	± 2.38	± 2.90	$^{+1.05}_{-1.07}$	$^{+1.08}_{-1.09}$	± 0.014