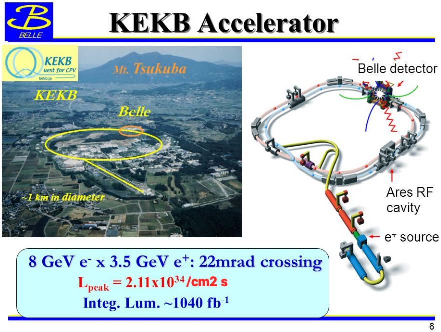
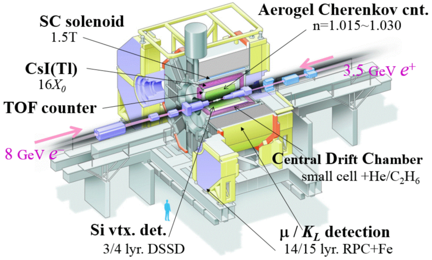
Lepton flavor universality at Belle and Belle II

Seema Choudhury
on behalf of the Belle & Belle II collaborations

8^{th} International Symposium on Symmetries in Subatomic Physics
29 August - 2 September, 2022
Vienna, Austria



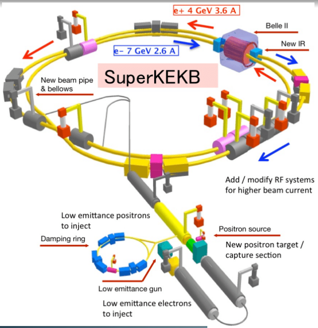


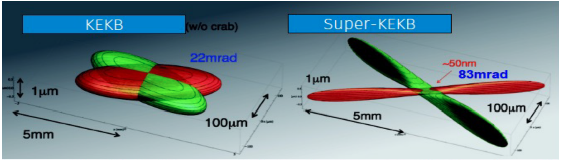
- Belle experiment is located at the KEKB accelerator in Tsukuba, Japan.
- Asymmetric e^+e^- collider with center-of-mass (CM) energy at $B\bar{B}$ threshold, 10.58 GeV.
- Data taking from 1999 to 2010.
- Data collected: 711 fb^{-1} = 772 million $B\bar{B}$ pairs.

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

SuperKEKB Accelerator

- Located at Tsukuba, Japan.
- Asymmetric e^+ (4 GeV) - e^- (7 GeV) collider with CM energy at $B\bar{B}$ threshold, 10.58 GeV.
- Aims to collect 50 ab^{-1} (50 $\times$ Belle) of data sample.
- Plan to deliver collision at a peak luminosity of 6.5×10^{35} cm^{-2}s^{-1} (30 times that of KEKB) by;
    - reducing beam size by 20 times.
    - increasing beam current by 1.5 times.





	Energy (GeV) LER/HER	β_y^* (mm) LER/HER	ε_x (nm) LER/HER	ξ_y LER/HER	φ (mrad)	I_{beam} (A) LER/HER	Luminosity (cm^{-2}s^{-1}) x 10^{34}
KEKB Achieved	3.5/8.0	5.9/5.9	18/24	0.13/0.09	11	1.6/1.2	2.11
SuperKEKB	4.0/7.0	0.27/0.3	3.2/2.4	0.09/0.09	41.5	2.8/2.0	65

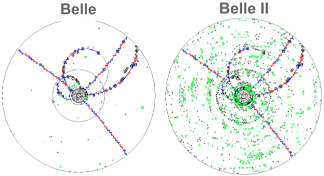
factor 20 factor 1.5

Factor ~30 in the luminosity

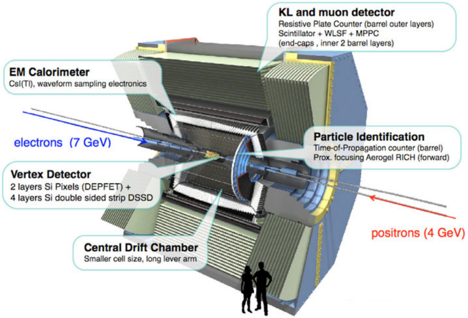
Belle II detector

- Designed to operate with a performance similar or better than Belle.
- New detector (only the structure, the superconducting magnets, the crystals of the calorimeter, and KLM RPCs are re-utilized).

MC simulation

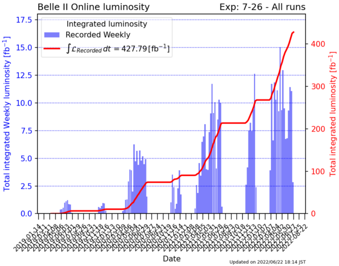


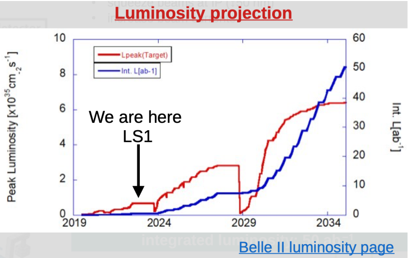
- Expect increased beam background ($\times 10 - 20$) at design luminosity
  - Upgraded trigger system and sub-detectors.



- improved vertex resolution ($2\times$ Belle) and K_S^0 reconstruction efficiency
- enhanced K/π separation
- new trigger lines for dark sector searches
- more efficient reconstruction and analysis tools

- Recorded integrated luminosity: 424 fb^{-1}, data taken between 2019–2022
  - $\sim$ 362 fb^{-1} taken at a CM energy of 10.58 GeV, corresponding to the mass of the $\Upsilon(4S)$
  - $\sim$ 42 fb^{-1} taken 60 MeV below the $\Upsilon(4S)$ peak, continuum background
  - $\sim$ 19 fb^{-1} taken around 10.75 GeV for exotic hadron searches
- World record instantaneous luminosity of $L = 4.71 \times 10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$ ($> 2\times$ KEKB record) on 22 June, 2022: Entering the regime of a "Super B factory".





- Shutdown (LS1) from summer 2022 for 15 months: improvement of machine and detector (beam pipe, pixel vertex detector, Time-Of-Propagation PMT)

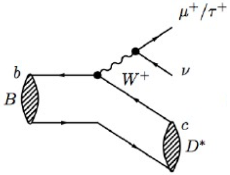
Outline

- **Belle**
  - LFU in $B^0 \to D^{*-}\ell^+\nu_\ell$
  - $\mathcal{R}(D)$ & $\mathcal{R}(D^*)$
  - R_K & R_{K^*}
  - LFU in $\Omega_c^0 \to \Omega^-\ell^+\nu_\ell$
- **Belle II**
  - Inclusive measurement of $R(X_{e/\mu})$
  - Measurement of $\mathcal{B}(B \to K^*\ell\ell)$
  - $R_K(J/\psi)$

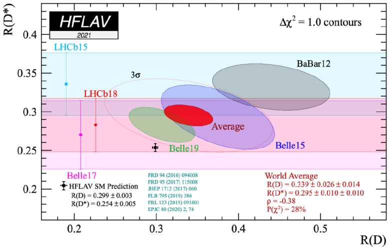
Results shown are with 711 fb^{-1} (920 fb^{-1} for $\Omega_c^0 \to \Omega^-\ell^+\nu_\ell$) and 190 fb^{-1} data sample of Belle and Belle II, respectively.

- B decays with $b \to c$ tree-level transition (thus, assumed to be unaffected by NP) are an important probe to test LFU
- Ratio of exclusive decays with τ lepton can be used to test SM

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$



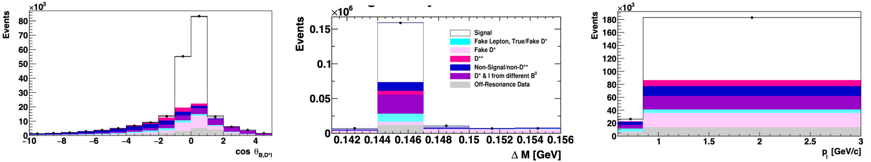
- Experimentally clean final state due to the entire decay chain being reconstructed



- Combined result from Belle [PRD 92, **072014** (2015), PRL 118, **211801** (2017), PRL **124** 161803 (2020)], BaBar [PRD 88, **072012** (2013)], and LHCb [PRL **115**, 111803 (2015), PRD **97**, 072013 (2018)] has a tension of 3.1σ with the SM
- Tension has decreased to 3.1σ from 3.8σ after recent measurement from Belle [PRL **124** 161803 (2020)]

Measurement of LFU in $B^0 \to D^{*-}\ell\nu_\ell$ at Belle [PRD 100, 052007 (2019)]

- Measurement of LFU using exclusive semileptonic B decay, $B^0 \to D^{*-}(\overline{D}^0(K^-\pi^+)\pi^-)\ell\nu_\ell$
- Untagged approach (high efficiency but sizable background)
- D^* momentum in the CM frame $(p^*(D^*)) < 2.45$ GeV$/c$ to suppress fake D^*
- Signal yield is extracted with a 3-dimensional binned ML fit to $\cos\theta_{B,D^*\ell}$ $\left(\frac{2E^*_B E^*_{D^*\ell} - m^2_B - m^2_{D^*\ell}}{2|p^*_B||p^*_{D^*\ell}|}\right)$, $\Delta M = M(D^* - D^0)$, and lepton momentum (p_ℓ)



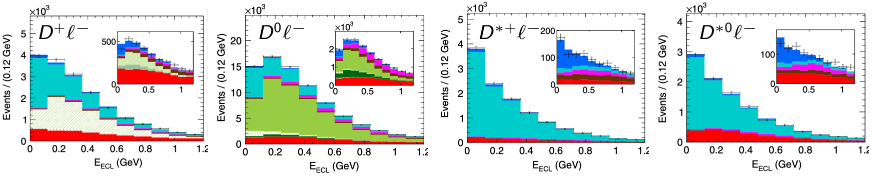
- Ratio of the branching fractions of modes with electrons and muons provides a test of LFU

$$\frac{\mathcal{B}(B^0 \to D^{*-}e^+\nu_e)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)} = 1.01 \pm 0.01 \pm 0.03$$

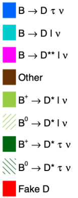
- Result is consistent with unity within the uncertainty
- Stringent test of LFU in B decays to date

Measurement of $\mathcal{R}(D)$ & $\mathcal{R}(D^*)$ at Belle **[PRL 124, 161803 (2020)]**

- Simultaneous measurement of $\mathcal{R}(D)$ & $\mathcal{R}(D^*)$ at Belle with semileptonic tagging method
- Exclusive semileptonic B decay analysis
  tag-side: $B^{0/\pm} \to D^{(*)}\ell^-\nu$
  signal side: signal channel $B^{0/\pm} \to D^{(*)}\tau^-(\ell^-\overline{\nu}\nu)\nu$ and normalization channel $B^{0/\pm} \to D^{(*)}\ell^-\nu$
- Signal is extracted by 2-dimensional binned extended ML fit to E_{ECL} and $\mathcal{O}_{\mathrm{cls}}$
  E_{ECL} : Sum of energies of neutral clusters in the ECL, not associated with any reconstructed particles
  $\mathcal{O}_{\mathrm{cls}}$: Background suppression classifier output

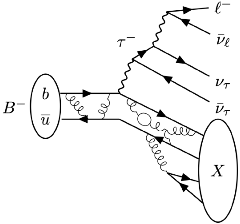


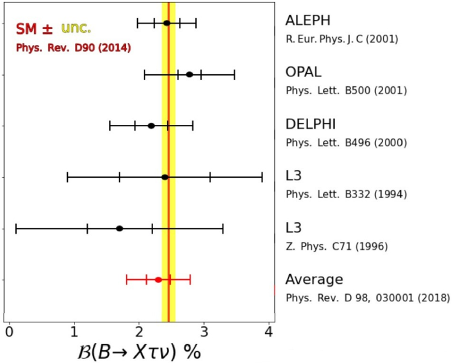
$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$



- Most precise measurements of $\mathcal{R}(D)$ & $\mathcal{R}(D^*)$
- Results are in agreement with the SM within 0.2σ and 1.1σ for $\mathcal{R}(D)$ & $\mathcal{R}(D^*)$
- Combination of $\mathcal{R}(D)$ & $\mathcal{R}(D^*)$ has a deviation of 0.8σ

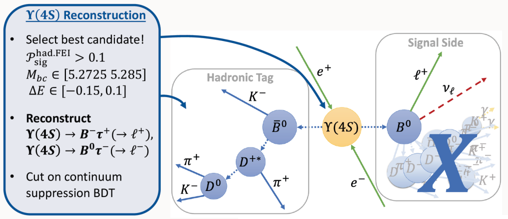
- $R(X) = \dfrac{\mathcal{B}(B \to X\tau\nu)}{\mathcal{B}(B \to X\ell\nu)}$ is the complimentary measurement to the $R_{D^{(*)}}$ via inclusive reconstruction for $b \to c$ transition.
- In the SM, $R(X) = 0.223 \pm 0.004$ [PRD **92**, 054018 (2015)]
- More challenging due to larger background from less constrained X system



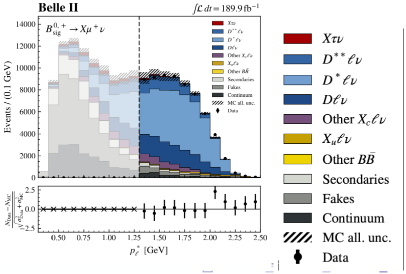


- Inclusive decay with τ lepton is challenging
- World average from LEP experiments, $\mathcal{B}(B \to X\tau\nu) = (2.41 \pm 0.23)\%$ is consistent with the SM $(2.45 \pm 0.10)\%$
- LFU can also be tested using light leptons $R(X_{e/\mu}) = \dfrac{\mathcal{B}(B \to Xe\nu)}{\mathcal{B}(B \to X\mu\nu)}$
- $R(X_{e/\mu})$ (SM) $= 1.006 \pm 0.001$ [EPJC **81**, 984 (2021)]

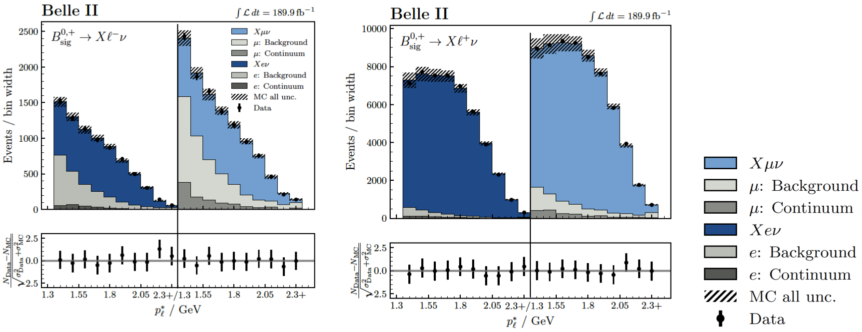
- Test LFU with inclusive measurement of $R(X_{e/\mu})$
- Analysis is performed on Belle II data sample of 189/fb with hadronic-B tagging (FEI)
- Constrain flavor and kinematics of the signal B meson by tagging the other B in its fully hadronic decays, *i.e.*, good purity at the cost of lower signal reconstruction efficiency.
- X system in signal side contains a large variety of different charged and neutral final-state particles



- lepton momentum in the CM frame of the signal B meson, p^*_ℓ is used to extract signal yield
- Require lepton to have high probability to be an electron or muon and $p^*_\ell > 1.3$ GeV$/c$ to suppress backgrounds from hadron faking leptons and secondary leptons from $b \to c \to (\ell, s)$ cascades and $B \to X\tau\nu$



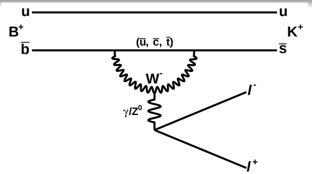
- Signal yields for $B \to X\mu\nu$ and $B \to Xe\nu$ are extracted in 10 bins of p^*_ℓ
- Simultaneous fit for μ and e channel: one-dimensional binned ML fit



- 48034 ± 286 and 58569 ± 429 signal events for $B \to Xe\nu$ and $B \to X\mu\nu$ channels.

$$R(X_{e/\mu}) = 1.033 \pm 0.010 \pm 0.020 \text{ for } p^*_\ell > 1.3 \text{ GeV}/c$$

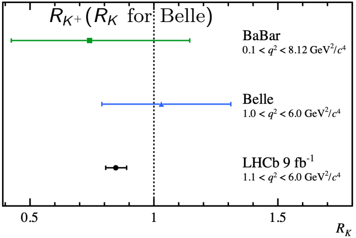
- First inclusive test of (e, μ) lepton flavor universality in semileptonic $B \to X\ell\nu$ decays
- Measurement in agreement with unity within 1.5σ
- World leading precision (2.2% combined uncertainty)
- Paved the path for inclusive $R(X_{\tau/\ell}) = R(X)$ measurement

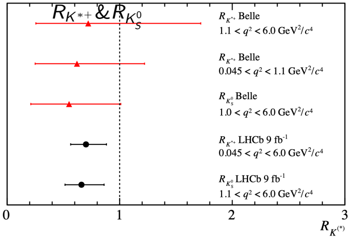


- B decays with rare $b \to s$ loop-level transitions are an important probe to test LFU
- LFU ratio is named as R_K and R_{K^*} for $B \to K\ell\ell$ and $B \to K^*\ell\ell$

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}$$

- According to SM this ratio should be 1 [EPJC **76**, 440 (2016)], as the coupling of lepton to gauge boson is independent of flavor.





- LHCb [arXiv:2103.11769] $R_{K^+} = 0.846^{+0.044}_{-0.041}$ for $1.1 < q^2 < 6.0$ GeV$^2/c^4$ has a deviation of 3.1σ from SM prediction with 9 fb^{-1} data sample, where $q^2 = M^2_{\ell\ell}$.
- $R_{K^{*+}}$ and $R_{K^0_S}$ results from LHCb [PRL **128**, 191802 (2022)] are individually consistent with the SM at the 1.4σ and 1.5σ level
- $B \to J/\psi K^{(*)}$ can be used to cross-check the ratio, which is compatible with the SM prediction of unity.

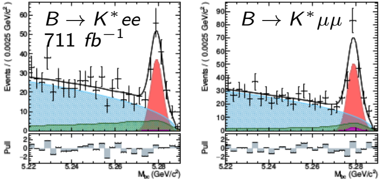
Measurement of R_{K^*} at Belle [PRL 126, 161801 (2021)]

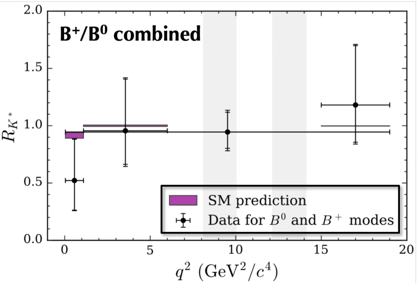
- R_{K^*} tests the lepton-flavor-universality in $B \to K^* \ell^+ \ell^-$.
- Reconstructed 4 decay modes;
  $B^+ \to K^{*+}(K^+\pi^0, K^0_S\pi^+)\ell^+\ell^-$
  $B^0 \to K^{*0}(K^+\pi^-, K^0_S\pi^0)\ell^+\ell^-$.
- Kinematic variables to distinguish signal from background;

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

- Continuum and $B\overline{B}$ backgrounds are suppressed using Neural Networks.
- Performed 1D unbinned extended ML fit to extract the signal yield.
- $103^{+13.4}_{-12.7}$ and $139.9^{+16.0}_{-15.4}$ events for electron and muon modes.
- $R_{K^{*+}}$, $R_{K^{*0}}$ and R_{K^*} are measured for both low and high q^2 bins.
- Results consistent with the SM predictions.
- First result for $R_{K^{*+}}$ measurement.

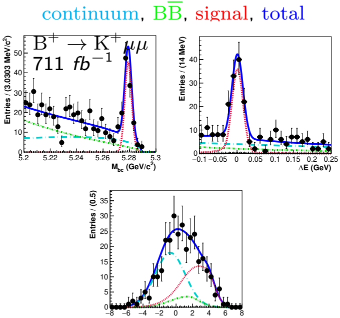
combinatorial, signal, charmonium, peaking, total

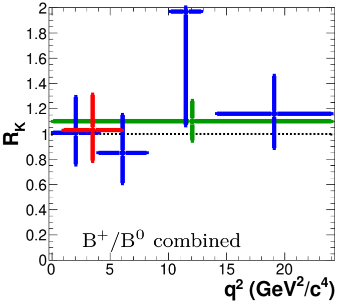




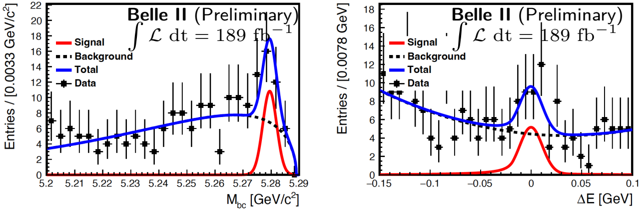
- R_K tests the lepton-flavor-universality in $B \to K\ell\ell$.
- Decay modes reconstructed, $B^+ \to K^+\ell\ell$ and $B^0 \to K^0_S\ell\ell$.
- Background from continuum and $B\overline{B}$ are suppressed using a Neural Network having event shape, vertex quality, and kinematic variables.
- Performed 3D unbinned ML fit in $M_{\rm bc}$, ΔE, and modified NN output (O') to extract the signal yield.
- Control mode is consistent with expectation; $R_{K^+}(J/\psi) = 0.994 \pm 0.011 \pm 0.010$ $R_{K^0}(J/\psi) = 0.993 \pm 0.015 \pm 0.010$
- 137 ± 14, 138 ± 15, $27.3^{+6.6}_{-5.8}$, and $21.8^{+7.0}_{-6.1}$ signal events for $B^+ \to K^+\mu\mu$, $B^+ \to K^+ee$, $B^0 \to K^0_S\mu\mu$, and $B^0 \to K^0_S ee$.
- R_{K^+}, R_{K^0}, R_K are measured in different q^2 bins.

  $q^2 \in$ [0.1 , 4.0], [4.0 , 8.12], [1.0 , 6.0], [10.2, 12.8], $>$ 14.18, and $>$ 0.1 GeV$^2/c^4$
- R_K values for various q^2 bins agree with the SM prediction.





- Decay modes reconstructed: $B^0 \to K^{*0}(K^+\pi^-)\ell\ell$ and $B^+ \to K^{*+}(K^+\pi^0, K^0_S\pi^+)\ell\ell$
- Background from continuum and $B\overline{B}$ is suppressed using a BDT having event shape, vertex quality, and kinematic variables.
- Performed 2D unbinned ML fit in $M_{\rm bc}$ and ΔE to extract the signal yield.

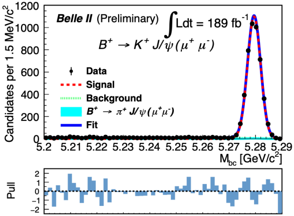


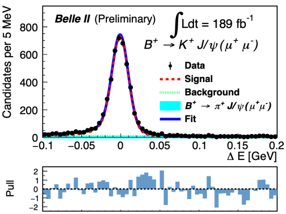
- Branching fraction are measured for the entire range of the dilepton mass, excluding the very low mass region to suppress the $B \to K^*\gamma(\to e^+e^-)$ background and regions compatible with decays of charmonium resonances

$$\mathcal{B}(B \to K^*(892)\mu^+\mu^-) = (1.19 \pm 0.31^{+0.08}_{-0.07}) \times 10^{-6},$$
$$\mathcal{B}(B \to K^*(892)e^+e^-) = (1.42 \pm 0.48 \pm 0.09) \times 10^{-6},$$
$$\mathcal{B}(B \to K^*(892)\ell^+\ell^-) = (1.25 \pm 0.30^{+0.08}_{-0.07}) \times 10^{-6},$$

- Results are compatible with world averages within the uncertainties.
- Observation of these decays is the first step towards LFU test (R_{K^*}).

- Decay channels: $B^+ \to J/\psi(\ell\ell)K^+$ and $B^0 \to J/\psi(\ell\ell)K^0$
- Important channels to test our analysis method
- Signal yield is extracted by a 2D unbinned ML fit in $M_{\rm bc}$ and ΔE.





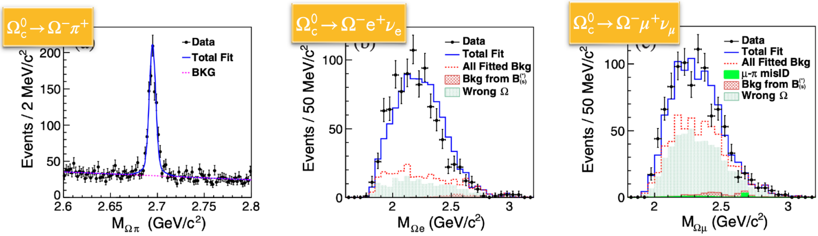
- Signal purity is $90 - 95\%$.

$$R_{K^+}(J/\psi) = 1.009 \pm 0.022 \pm 0.008$$
$$R_{K^0}(J/\psi) = 1.042 \pm 0.042 \pm 0.008$$

- Results are statistically dominated and in agreement with results from Belle and LHCb.
- Systematics uncertainties have been reduced compared to most precise measurements from Belle [JHEP **03**, 105 (2021)].

Measurement of $R(\Omega)$ at Belle [PRD 105, L091101 (2022)]

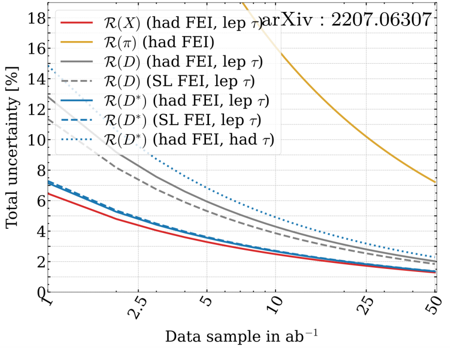
- LFU in Ω_c^0 is probed for the first time with $\Omega_c^0 \to \Omega^- \ell^+ \nu_\ell$
- Ω_c^0 are reconstructed in the process; $e^+e^- \to c\bar{c} \to \Omega_c^0 +$ anything
- Used 89.5, 711, and 121.1 fb^{-1} data collected at the CM energies of 10.52, 10.58, and 10.86 GeV.
- Ω_c^0 signals are extracted by binned ML fits to the invariant mass ($M_{\Omega\ell}$) spectra.

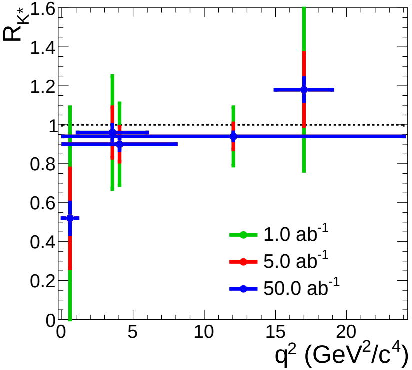


- Significances of the $\Omega_c^0 \to \Omega^- \ell^+ \nu_\ell$ are both larger than 10σ, $\Omega_c^0 \to \Omega^- \mu^+ \nu_\mu$ decay is seen for first time in Belle.
- 865.3 ± 35.3, 707.6 ± 37.7, and 367.9 ± 31.4 signal events for $\Omega_c^0 \to \Omega^- \pi^+$, $\Omega_c^0 \to \Omega^- e^+ \nu_\ell$, $\Omega_c^0 \to \Omega^- \mu^+ \nu_\ell$
- Ω_c^0 semileptonic decay branching fraction ratio;

$$R(\Omega) = \frac{\mathcal{B}(\Omega_c^0 \to \Omega^- e^+ \nu_e)}{\mathcal{B}(\Omega_c^0 \to \Omega^- \mu^+ \nu_\mu)} = 1.02 \pm 0.10 \pm 0.02$$

- $\mathcal{B}(\Omega_c^0 \to \Omega^- e^+ \nu_e)/\mathcal{B}(\Omega_c^0 \to \Omega^- \mu^+ \nu_\mu)$ agrees with the expected LFU value 1.03 ± 0.06 [arXiv:2108.06110].





- $R(X)$ (and in general inclusive processes) is unique to Belle II
- Currently estimated precision on $R(X)$ to be $\sim 17\%$ (stat+syst)
- Few ab^{-1} of data will be sufficient to clarify whether the anomaly on $\mathcal{R}(D) - \mathcal{R}(D^*)$ has a statistical or systematic origin

- Belle II can perform R_K and R_{K^*} measurements for low as well as high q^2 bins.
- Belle II will provide an independent measurement to confirm the tension with few ab^{-1} of data
- R_{K^+} and R_{K^*} statistical sensitivity will be $< 2\%$ for entire q^2 region and $\sim 3\%$ for $q^2 \in [1-6]\ \mathrm{GeV}^2/c^4$

Conclusions

- Belle II has now collected $\sim 424\ \mathrm{fb}^{-1}$ of data sample (comparable to size of that of BaBar) and can be combined with that of Belle ($711\ \mathrm{fb}^{-1}$)
- Flavor physics in e^+e^- collisions offers an extremely rich physics program with many opportunities to probe New Physics
- Access to charged and neutral B with equal efficiency
- Equal sensitivity for muon and electron channels
- Access to inclusive decay modes in addition to exclusive modes
- Untagged (high statistics) *vs* tagged (high purity) analysis
- Long way to go! A beginning has been made!

No sign of LFU violation so far from Belle or Belle II

An exciting era of discoveries and precision measurements !!!

$\mathcal{R}(D)$-$\mathcal{R}(D^*)$ systematics

TABLE I. Systematic uncertainties contributing to the $\mathcal{R}(D^{(*)})$ results, together with their correlation.

Source	$\Delta\mathcal{R}(D)(\%)$	$\Delta\mathcal{R}(D^*)(\%)$	Correlation
D^{**} composition	0.76	1.41	−0.41
PDF shapes	4.39	2.25	−0.55
Feed-down factors	1.69	0.44	0.53
Efficiency factors	1.93	4.12	−0.57
Fake $D^{(*)}$ calibration	0.19	0.11	−0.76
B_{tag} calibration	0.07	0.05	−0.76
Lepton efficiency and fake rate	0.36	0.33	−0.83
Slow pion efficiency	0.08	0.08	−0.98
B decay form factors	0.55	0.28	−0.60
Luminosity, f^{+-}, f^{00}, and $\mathcal{B}(\Upsilon(4S))$	0.10	0.04	−0.58
$\mathcal{B}(B \to D^{(*)}\ell\nu)$	0.05	0.02	−0.69
$\mathcal{B}(D)$	0.35	0.13	−0.65
$\mathcal{B}(D^*)$	0.04	0.02	−0.51
$\mathcal{B}(\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau)$	0.15	0.14	−0.11
Total	5.21	4.94	−0.52

R_K systematics

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

Source	$\mathcal{B}(B \to K J/\psi)$				R_K	
	K^+ e^+e^-	K^+ $\mu^+\mu^-$	K_S^0 e^+e^-	K_S^0 $\mu^+\mu^-$	K^+	K^0
Number of $B\overline{B}$ events	1.5	1.5	1.5	1.5	–	–
PDF shape	0.2	0.2	0.2	0.2	0.2	0.2
Electron identification	0.6	–	0.6	–	0.6	0.6
Muon identification	–	0.4	–	0.4	0.4	0.4
Kaon identification	0.2	0.2	–	–	–	–
K_S^0 reconstruction	–	–	3.0	3.0	–	–
Tracking efficiency	0.9	0.9	1.2	1.2	–	–
Simulation sample size	0.1	0.1	0.1	0.1	0.1	0.1
$\Upsilon(4S)$ branching fraction	2.6	2.6	2.6	2.6	–	–
(τ_{B^+}/τ_{B^0})	–	–	–	–	–	–
Total	3.2	3.2	4.4	4.4	0.8	0.8

$R(X_{e/\mu})$ systematics

	e channel	μ channel	Combination
M_X scaling	7.8 % (21.2 %)	12.5 % (20.5 %)	8.7 % (26.8 %)
PID	1.8 % (1.2 %)	7.1 % (6.6 %)	2.1 % (1.6 %)
Tracking eff.	2.9 % (2.8 %)	5.1 % (3.4 %)	3.4 % (4.0 %)
$X_c\ell\nu$ BRs	6.6 % (15.2 %)	11.1 % (15.9 %)	7.5 % (19.9 %)
$X_c\ell\nu$ FFs	4.5 % (7.1 %)	7.2 % (6.8 %)	5.0 % (8.9 %)
Statistical	10.8 % (40.3 %)	19.4 % (48.9 %)	9.4 % (31.3 %)
Total	17.0 % (100 %)	27.7 % (100 %)	16.8 % (100 %)

- Dominate systematic comes from $X_c\ell\nu$ BRs because of discrepancy between the inclusive semileptonic B meson width and sum of exclusively measured BRs. This difference is usually filled by $D^*\pi\pi$ and $D^*\eta$ modes and are scaled to inclusive B meson width. As this is speculative, they are assigned with 100% uncertainty, this become one of the leading systematic uncertatinty.