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Recent Belle II results related to B anomalies

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Semileptonic B-meson decays involving the quark transition $b \to cl\nu$ provide excellent sensitivity to probe potential lepton-flavour universality violation. This work introduces two recent measurements related to tests of light-lepton flavour universality using a data sample collected at the $\Upsilon(4S)$ resonance on the Belle II experiment corresponding to an integrated luminosity of 189 fb^{-1}. Measurement of the ratio of the branching fractions of inclusive $B \to Xe\nu_e$ and $B \to X\mu\nu_\mu$ decays and measurement of angular asymmetries of $B^0 \to D^{*-}l\nu$ decays agree well with standard model expectation.

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1. Introduction

The standard model (SM) of particle physics currently gives a thoroughly description of fundamental particles and their interactions. SM predicts that three charged leptons ($e^{\pm}$, $\mu^{\pm}$ and $\tau^{\pm}$) share the identical electroweak coupling, a symmetry known as lepton-flavour universality (LFU). A violation of this symmetry can shed light on new physics beyond SM. Various methods are proposed to test this symmetry, e.g. measuring the branching fraction and angular distribution of (semi-)leptonic decays involving different leptons. The ratio of these branching fractions is predicted close to unity and the their kinematics are predicted similarly in SM. An evidence for LFU violation in the rate of semileptonic decays to τ relative to the light leptons l ($l = e, \mu$) has been found in the combined results from *BABAR*, Belle and LHCb experiments [1–8]. To futher test the LFU, two measurements have been performed currently with ratio of branching fractions and angular asymmetries in beauty quark transition processes containing light leptons by Belle II experiment.

Belle II detector [9] is located around the SuperKEKB [10] which is a e^+e^- collider running at $\Upsilon(4S)$ energy and producing B-meson pairs without additional particles. Belle II detector is a nearly 4π magnetic spectrometer surrounded by subdetectors. The innermost subsystem consists of a silicon pixel detector surrounded by a double-sided silicon strip detector (SVD) which provides precise determination of particle-decay vertices, and a central drift chamber which determines the momentum and electric charge of charged-particles. A time-of-propagation counter (TOP) and a Cherenkov counter cover the barrel and forward endcap regions of the detector, are important for charged-particle identification (PID). An electromagnetic calorimeter (ECL), used to reconstruct photons and distinguish electrons, makes up the remaining volume inside a superconducting solenoid which provides a uniform 1.5 T magnetic field. A dedicated system to identify K_L^0 and muons is installed in the outermost layer.

The nearly hermetic structure of Belle II detector allows to reconstruct fully-inclusive final states and events with missing energy. In an $\Upsilon(4S)$ event, a B-meson (B_{tag}) is fully reconstructed through the full event interpretation (FEI) [11] algorithm which combines the measured particles to intermediate particles until they form a B-meson. The two measurements introduced in this paper use FEI with the probability of its corrected describing the true process exceeding 0.1%. With an identified B_{tag}, a signal B-meson is reconstructed inclusively or exclusively on the recoiling side. Leptons in the signal side can be identified by two approaches which have high efficiencies and low hadron-lepton fake rates. One is based on likelihood, in which the identification likelihood $\mathcal{L}_i$ for each charged-particle hypothesis i combines particle identification information from all subdetectors except SVD and TOP for $l = e^{\pm}$, and except SVD for $l = \mu^{\pm}$, then these $\mathcal{L}_i$ are combined to a global likelihood ratio $lID = \frac{\mathcal{L}_l}{\mathcal{L}_e+\mathcal{L}_\mu+\mathcal{L}_\pi+\mathcal{L}_K+\mathcal{L}_p+\mathcal{L}_d}$. Another is based on a multiclass boosted-decision-tree classifier [12] which exploits several observables with properties of the energy deposits in the ECL in combination with particle-identification likelihood defined analogously to $\mathcal{L}_i$. Besides, the four-momentum of electron is corrected by bremsstrahlung radiation effect. The two measurements use a data set corresponding to 189 fb^{-1} of electron-positron collisions at 10.58 GeV center of mass energy and 18 fb^{-1} of collisions 60 MeV below 10.58 GeV collected by the Belle II experiment between 2019 and 2021. Charge conjugation is implied throughout.

2. Test of light-lepton universality in the rates of inclusive semileptonic B-meson decays

The ratio of branching fraction of inclusive semileptonic B-meson decays, $R(X_{e/\mu}) = Br(B \rightarrow Xe\nu)/Br(B \rightarrow X\mu\nu)$, is measured in $B \rightarrow Xl\nu$ decays in which X denotes the generic hadronic final state of the semileptonic decay of any flavour of B-meson originating from $b \rightarrow cl\nu$ or, rarely, $b \rightarrow ul\nu$. This measurement was published recently in [13].

The selected B_{tag} candidates are correctly reconstructed with 82% efficiency by FEI. After B_{tag} reconstruction, the signal-lepton candidate with momentum in the rest frame of the signal B meson $p_l^B > 1.3$ GeV/c is selected. With this requirement, most of the $B \rightarrow X\tau\nu$ events can be rejected and reduce events with hadrons misidentified as leptons (fakes) and events with correctly reconstructed lepton candidates originating mainly from decays of charmed hadrons (secondaries) and have low momentum. The lepton charge has the opposite flavour to the B_{tag} candidate. With requirement of transverse momentum p_T >0.4 GeV/c, muon candidates are identified by means of a likelihood-based ratio lID ($l = \mu$) with an average 90% efficiency for p >1.0 GeV/c and corresponding to an average muon misidentification probability for pions and kaons of 3%. With requirement of transverse momentum p_T >0.3 GeV/c, electron candidates are identified by means of multiclass boosted-decision-tree classifier with an average 80% efficiency for p >1.0 GeV/c and corresponding to an average hadron-misidentification probability of 0.01%. The lepton with the highest identification likelihood is selected when two or more signal lepton candidates from the same events pass corresponding selections. The rest of events are assigned as X system.

A boosted decision tree is trained to distinguish $B\bar{B}$ events and continuum events ($e^+e^- \rightarrow q\bar{q}$ where q indicates u, d, s, or c quarks). Approximately 55% continuum backgrounds are rejected while 97% of $B\bar{B}$ events are retained. After all selections and corrections, the signal efficiencies of electron and muon channel are determined to be $(1.77 \pm 0.04) \times 10^{-3}$ and $(2.14 \pm 0.06) \times 10^{-3}$, separately. An binned maximum likelihood simultaneous fit is applied to two channels with 10 p_l^B bins. Each channel has three components, the continuum component which yields are constraint by off-resonance data, the $B\bar{B}$ backgrounds component which mostly contains events with fakes and secondaries and the signal component, $B \rightarrow Xl\nu$, which has an unconstrained yields. In order to have a good constraint on the $B\bar{B}$ backgrounds, a same charge control channel containing events with two B mesons reconstructed with the same flavour is defined. Fitting simultaneously to the electron and muon control channels which enriched with fakes and secondaries with unconstrained $B\bar{B}$ backgrounds, the fitting results shown in left two plots of Fig. 1. The statistics uncertainty is incorporated into the likelihood definition via nuisance parameters in each p_l^B bin. The difference between results from fitting the simulated spectrum with statistical fluctuation only and that from fitting the simulated spectrum with this systematic source is regarded as each systematic uncertainty.

The signal yields are extracted by simultaneous binned maximum-likelihood fits to muon and electron channel of experimental p_l^B spectra in the opposite charged signal events, shown in Fig. 1 (right). Total 50960±290 and 61300±400 signal events are measured in electron and muon channel, respectively. The $R(X_{e/\mu})$ can be calculated by $R(X_{e/\mu}) = (N_e^{meas}/\epsilon_e)/(N_\mu^{meas}/\epsilon_\mu)$, where N_l^{meas} are the measured signal yields from the fitting to opposite charged signal sample and ϵ_l are the selected efficiencies of electron and muon channels, separately. This ratio is measured to be $R(X_{e/\mu}) = 1.007 \pm 0.009(\text{stat.}) \pm 0.019(\text{syst.})$, in which the second and third terms are statistic

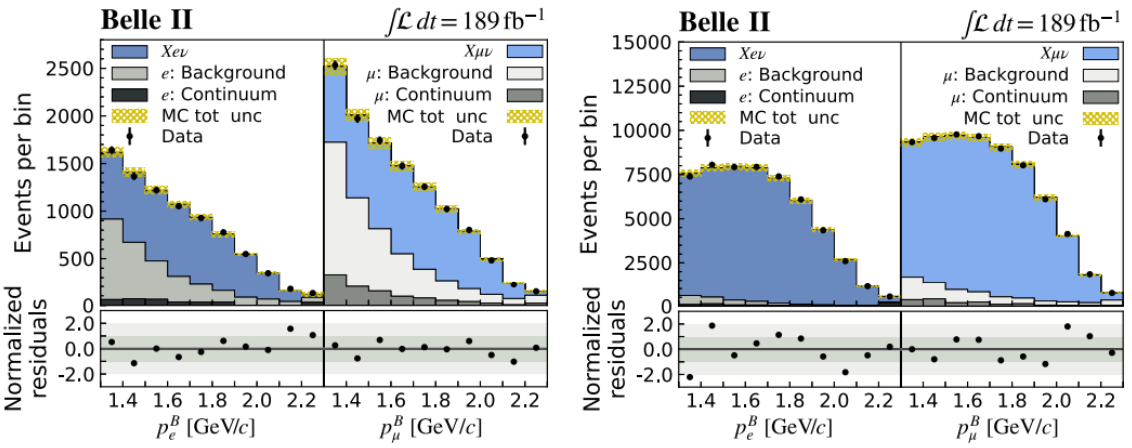

Figure 1: Fit to same-charge control channel (left) and opposite-charge signal channel (right) in the 10 bins of lepton momentum p_l^B. The continuum background which constrained by the off-resonance data is depicted in dark grey category, the $B\bar{B}$ background mostly containing fake and secondaries is depicted in light grey category, the $B \to Xl\nu$ signal is depicted in blue category and the dots with error bars are data.

and systematic uncertainties. A fiducial measurement is provided by constraining the generated B−frame lepton momentum above 1.3 GeV$/c$ when calculating ϵ_l to reduce the model dependence, $R(X_{e/\mu}|p_l^B > 1.3\ \mathrm{GeV}/c) = 1.005 \pm 0.009(\mathrm{stat.}) \pm 0.019(\mathrm{syst.})$.

3. Tests of light-lepton universality in angular asymmetries of $B^0 \to D^{*-} l\nu$ decays

Measuring angular asymmetries is a very promising method to test potential violation of LFU. Belle II preform comprehensive tests of light-lepton flavour universality in the angular distributions of semileptonic neutral B-meson decays involving an charged spin-1 charmed mesons [17].

The semileptonic decay of $B^0 \to D^{*-} l\nu$ can be characterized by a squared invariant mass of $l\nu$ system, $q^2 = (p_B - p_{D^*})^2$, and in term of three helicity angles θ_l, θ_V and χ, where θ_l is angle between the direction of the charged lepton in the virtual W frame and the W in the B^0 frame, θ_V is the angle between the $\bar{D}^0$ direction in the D^{*-} frame and the D^{*-} in the B^0 frame, and χ id the angle between the decay planes formed by the virtual W and the D^{*-} in the B^0 frame.

Five asymmetric observables A_{FB}, S_3, S_5, S_7 and S_9 [18] can be redefined in terms of one-dimensional integrals

$$A \equiv \frac{\int_0^1 \frac{d\Gamma}{dx}dx - \int_{-1}^0 \frac{d\Gamma}{dx}dx}{\Gamma} \tag{1}$$

with $x = \cos\theta_\mathrm{l}$ for A_{FB}, $x = \cos 2\chi$ for S_3, $x = \cos\chi\cos\theta_V$ for S_5, $x = \sin\chi\cos\theta_V$ for S_7 and $x = \sin 2\chi$ for S_9. The A_{FB} measures the tendency for the flight of charged lepton to the direction of virtual W. The S_3 and S_9 are sensitive to the alignment of the lepton and D^* momentum, while S_5 and S_7 measure the orientation of the D with respect to the D^*. Then the five asymmetry measurements are translated into measuring the events N_x^+ with positive category ($x \in [0, 1]$), and events with N_x^- negative category ($x \in [-1, 0)$)

$$A = \frac{N_x(x > 0) - N_x(x < 0)}{N_x(x > 0) + N_x(x < 0)} \tag{2}$$

for each asymmetric observable in each lepton channel. The differences which are sensitive to LFU violation between the angular asymmetries of electrons and muons can be obtained by $\Delta A \equiv A(B \to D^* \mu\nu) - A(B \to D^* e\nu)$. The squared invariant mass of $l\nu$ system is possible to be translated into a recoiling parameter

$$w \equiv \frac{m_{B^0}^2 + m_{D^*}^2 - q^2}{2m_B m_{D^*}} \tag{3}$$

where m_{B^0} and m_{D^*} are masses of B^0 and D^{*-} in PDG [19]. To optimise the sensitivity to the extensions of the SM [18], the five asymmetries are measured in three w range, the full phase space region ($w_{\text{incl.}}$), the low w region ($w_{\text{low}} \in (1, 1.275)$) and high w region ($w_{\text{high}} \in (1.275, 1.503)$).

FEI is applied to fully reconstruct one tagged B^0, $B^0 \to D^{*-} l\nu$ is reconstructed through $D^{*-} \to \bar{D}^0 \pi^-$ in the recoiling side. Lepton candidates in the signal side are required to have a lab-frame momentum above 0.4 GeV and identified by means of ratio lID ($l = e^+, \mu^+$) over 0.9 with an average 86% (89%) identification efficiency and hadron misidentification rates of less than 1% (3%) for e^+ (μ^+). π^0 candidates are reconstructed by $\pi^0 \to \gamma\gamma$ with the invariant mass of two photons constrained to [0.120, 0.145] GeV/c^2. K_S^0 candidates are reconstructed by $K_S^0 \to \pi^+\pi^-$ with the mass of two charged pions constrained to [0.468, 0.528] GeV/c^2. A D-meson reconstructed with clean and abundant decay channels combines with a slow π to reconstruct a D^*. If more than one candidates pass the selection, the one closest to expectation in the difference of D^* and D mass, $|M(D^*) - M(D)|$, is retained.

To extract the number of signal yields $N_x^{\pm}$ of each asymmetry, A binned maximum-likelihood fits to distribution of M_{miss}^2 of signal candidates in each positive/negative category, each w range and each lepton channel. The fit observable, $M_{\text{miss}}^2 = p_{\text{miss}}^2 = (p_{\Upsilon(4S)} - p_{B_{\text{tag}}} - p_{D^{*-}} - p_l)^2$, is the squared difference between the sum of the four-momentum of the tagged B meson, $p_{B_{\text{tag}}}$ and sum of the four-momentum of reconstructed particles, $p_{D^{*-}} + p_l$. The main background events come mostly from $B \to D^{**} l\nu$ which mimic the signal candidates if there are tracks or neutral particles missed from B^0-meson. The M_{miss}^2 distribution peaks around zero in the correctly reconstructed signal events, while not peaks around zero in the main background, $B \to D^{**} l\nu$. The fitted yields $N_x^{\pm}$ of each w range are corrected by selection and detector acceptance losses using efficiency estimates from simulation. And the migration effect of candidates between the positive and negative categories and different w bins is corrected.

The measurement differences of asymmetries and SM expectation of lepton channels and asymmetry differences among electron and muon channels shown in Fig. 2. The size of the simulated samples, which limits the precision of the efficiency and bin-migration corrections, contribute the largest systematic uncertainty. Uncertainties from lepton identification cancel mostly in the asymmetry.

4. Conclusion

In the measurement of $R(X_{e/\mu})$, branching fraction and form factor uncertainty cancel dramatically and the largest uncertainty is from lepton identification efficiencies and mis-identification probabilities. This result is the most precise branching fraction-based test of the light-lepton flavour universality in the semileptonic B-meson decays and is consistent with the SM prediction

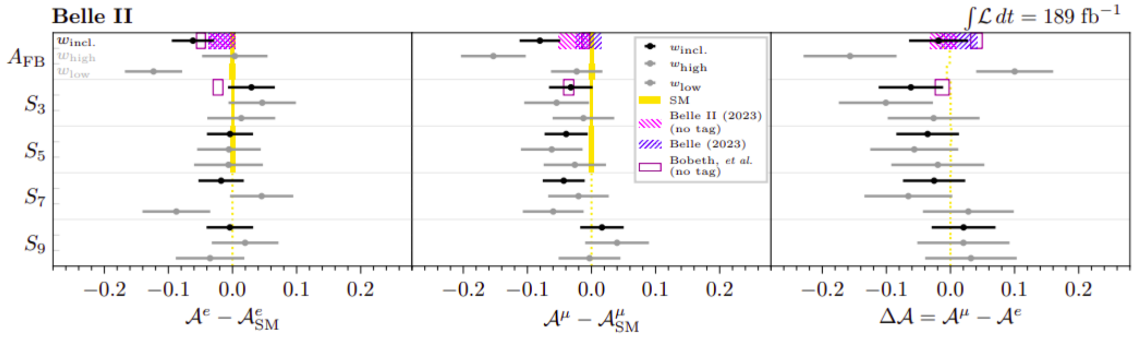

Figure 2: Differences of measured asymmetries and SM expectations in electron channel(left), muon channel(middle) and differences of measured electron and muon channel (right). Differences depicted by points with error bars, one-standard-deviation bands from Belle [16] and preliminary Belle II [?] measurements depicted by hatched boxes, calculations from [22] depicted by the empty boxes and the SM expectations depicted by the solid boxes.

which is 1.006 ± 0.001 [14]. In addition, this result is compatible with the Belle measurements in $B \to D^* l\nu$ [15, 16].

Currently, the measurements of angular asymmetries are the first comprehensive tests of LU in the angular distributions of semileptonic B-meson decays. And the results are in consistent with the SM expectations [20] and provide no evidence for violation of LU. Compared with Belle measurement [16], Belle II measurements [21] and an calculation [22], results in [22**?**] derive from analyses without explicit reconstruction of the tag B, while results in [22] are obtained in a slightly reduced w range, which makes them not strictly comparable to the others.

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