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Recent Anomalies in the Semi-leptonic *B*-meson Decays

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ABSTRACT

We review the experimental measurements of the 'anomalies' in the semileptonic decays of B mesons. The $R_{K^{(*)}}$ anomalies in $B \to K^{(*)} \ell^+ \ell^-$ measured by LHCb and an anomaly in the angular distribution of $B \to K^* \ell^+ \ell^-$ measured by LHCb and Belle are described. The $R_{D^{(*)}}$ anomalies in $B \to D^{(*)} \tau^- \bar{\nu}$ measured by BaBar, Belle, and LHCb are also discussed. Both anomalies are related to lepton flavor universality of the Standard Model.

INTRODUCTION

A B meson consists of a b quark, the second most massive of all quarks, and a lighter anti-quark, $\bar{q}$, where $q = u$, d, s or c [1]. Since b is much heavier than its partner q, the decay of B mesons is usually determined by the decay of b as a quark. The dominant majority of B decays occur through the quark-level process $b \to cW^*$[2]. In the case where the virtual W^* decays to a pair of leptons, $\ell^- \bar{\nu}$, the quark-level process becomes $b \to c\ell^- \bar{\nu}$ and such decays are called 'semi-leptonic' because part of the final-state particles are leptons.

Another class of semi-leptonic decays is the electroweak penguin-diagram process such as $b \to s\ell^+ s\ell^-$. This decay is a flavor-changing neutral-current (FCNC) process that is forbidden in the Standard Model (SM) at the tree level, but is allowed to occur via loop-diagram processes. Since the penguin loop may contain any unknown particles from new physics (NP), it can be a great probe to search for NP.

In the SM, the leptons are grouped into three generations, e, μ, τ and their weak-isospin doublet partner neutrinos. The SM coupling of W to leptons is universal over the three generations, which is often called *lepton flavor universality* (LFU). This universality has been stringently tested in weak decays of kaons as well as in τ lepton decays. Therefore, a violation of LFU can be clear evidence for the existence of NP beyond the SM.

Recently, however, there have been hints of violations of LFU in the semi-leptonic decays of B mesons, both in tree-level semi-tauonic decays $B \to D^{(*)} \tau^- \bar{\nu}$ and in penguin decays $B \to K^{(*)} \ell^+ \ell^-$. Such results have been obtained by three different experiments: the BaBar and Belle experiments using e^+e^- collisions at SLAC (Stanford, USA) and KEK (Tsukuba, Japan), respectively, and the LHCb experiment using pp collisions at CERN (Geneva, Switzerland). In another article by H. M. Lee of this issue, the theoretical interpretations of such results are explained in detail. In this article, we describe the experimental methods and analysis techniques for such measurements along with research prospects in the near future.

ANOMALY IN $B \to K^{(*)} \ell^+ \ell^-$

The most obvious observable to measure in $B \to K^{(*)} \ell^+ \ell^-$ decays is the branching fraction $\mathcal{B}$, both the total (integrated over q^2) and the differential distribution as a function of q^2, which is the square of the invariant mass of $\ell^+ \ell^-$. But due to relatively large theory error related to hadronization of the s quark, these measurements have not provided a significant test of the SM.

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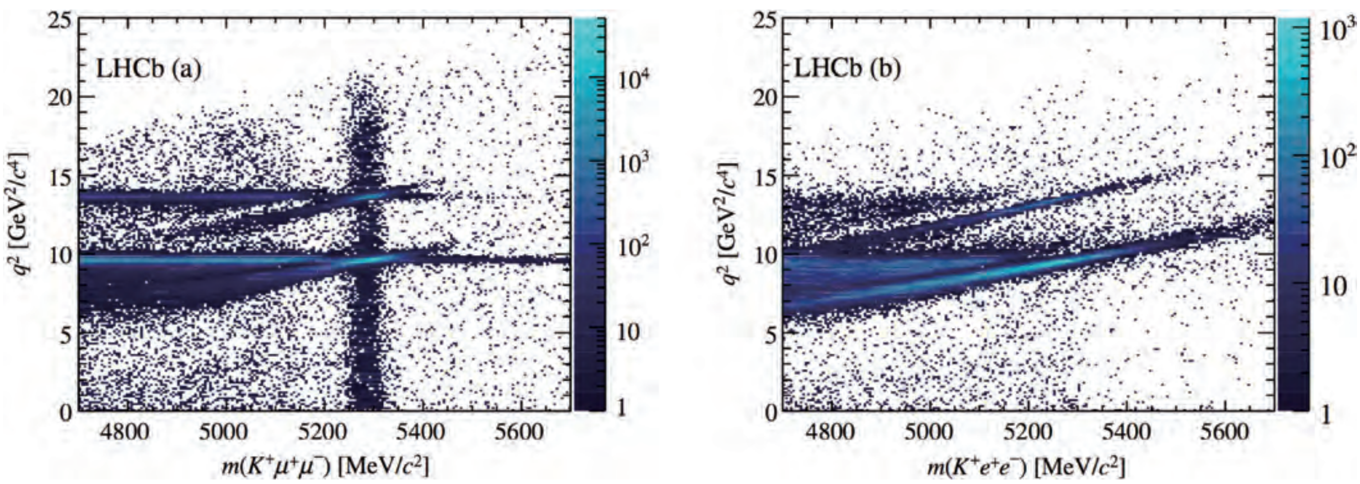

Fig. 1: Distribution of the observables, m($K^-\ell^+\ell^-$) (x-axis) and q^2(y-axis) for $B^+ \to K^+\mu^+\mu^-$ (left) and $K^+e^+e^-$ (right) by LHCb, taken from Ref. [4].

In the SM, it is expected that the ratio

$$R_{K^{(*)}} \equiv \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

is very close to unity, due to LFU. On the other hand, in NP models where LFU might be violated, the $R_{K^{(*)}}$ can have values different from unity. For instance, if a charged Higgs appears in the loop, its coupling to electrons is different from that to muons.

The LHCb collaboration has measured both R_K and R_{K^*} in $B^+ \to K^+\ell^+\ell^-$ and $B^0 \to K^{*0}\ell^+\ell^-$, respectively. Figure 1 shows the observables for $B^+ \to K^+\mu^+\mu^-$ (left) and $K^+e^+e^-$ (right) [4]. In both plots, the horizontal axis corresponds to the invariant mass of the B candidates that peak at $m_{\mathrm{B}} = 5.28\mathrm{GeV}/c^2$ and the vertical axis for the q^2. By comparing $B^+ \to K^+\mu^+\mu^-$ and $K^+e^+e^-$, they obtained $R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$.

Figure 2 shows the invariant mass of the B^0 candidates for $B^0 \to K^{*0}\mu^+\mu^-$ (left) and $K^{*0}e^+e^-$ (right) [5]. It is evident that the yield of $K^{*0}\mu^+\mu^-$ is much larger than that of $K^{*0}e^+e^-$. But it is mainly because of the low efficiency of identifying electrons with LHCb. After correcting for efficiencies, and comparing the results of $B^0 \to K^{*0}\mu^+\mu^-$ and $K^{*0}e^+e^-$, the researchers obtained $R_{K^*} = 0.69^{+0.11}_{-0.07} \pm 0.05$ for $1.1 < q^2 < 6.0$ GeV^2/c^4.

The internal structure of the $B \to K^*\ell^+\ell^-$ decays can be described with four variables, q^2 and three angles θ_K, θ_ℓ and ϕ, where θ_K is the helicity angle of t he subdecay $K^* \to K\pi$, θ_ℓ, for $\ell^+\ell^-$, and ϕ is the angle between the decay planes of K^* and the $\ell^+\ell^-$ system. The differential decay width $d\Gamma(B \to K^*\ell^+\ell^-)/dq^2 d\cos\theta_K d\cos\theta_\ell d\phi$ is expressed as a linear combination of various angular dependences, with each amplitude being a function of q^2 only. By analyzing the four-dimensional distributions,

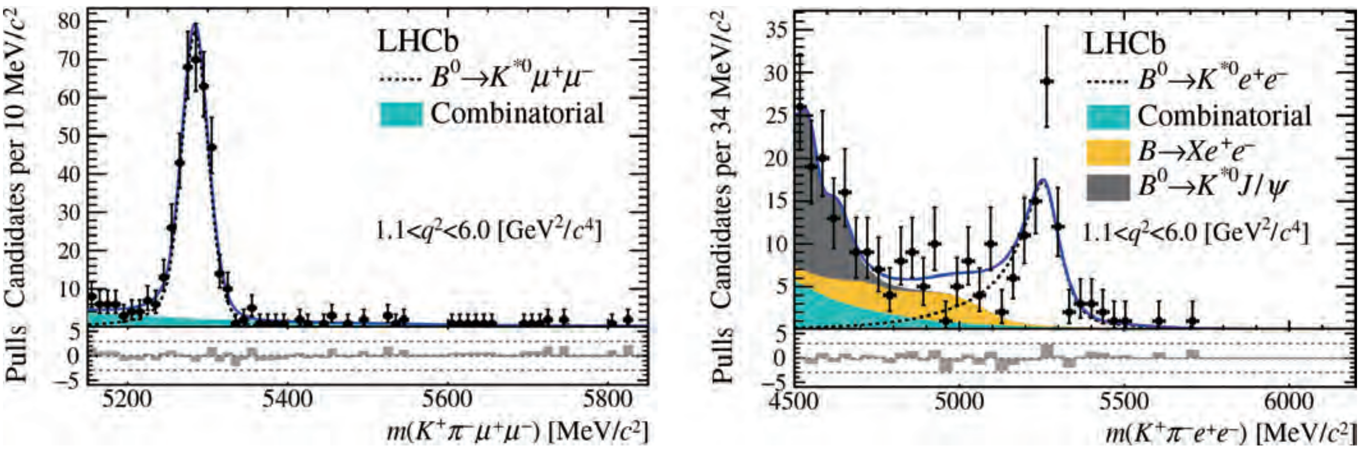

Fig. 2: Distributions of $m(K^-\pi^+\mu^+\mu^-)$ (left) and $m(K^-\pi^+e^+e^-)$ (right) for $1.1 < q^2 < 6.0$ GeV^2/c^4, measured by LHCb, taken from Ref. [5].

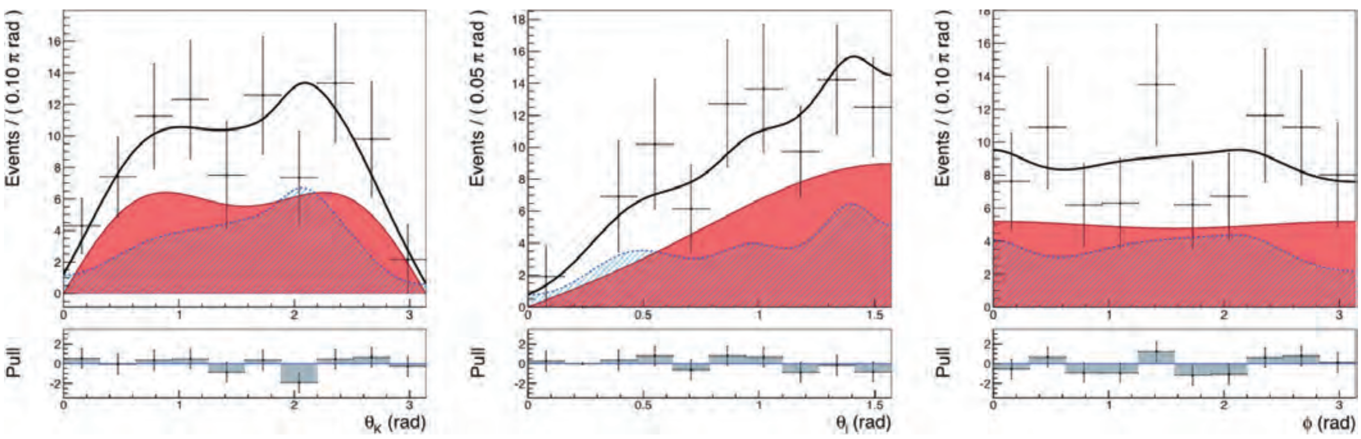

Fig. 3: Distributions of θ_K (left), θ_ℓ (middle), and ϕ (right) for $B \to K^*\ell^+\ell^-$, measured by Belle [8]. The red portion is for signal, and blue hatched for background.

the amplitudes can be measured and compared to the SM prediction.

One of the dynamical observables that LHCb used to test the SM was P'_5, which is defined as

$$P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}},$$

where S_5 is the amplitude for the term $\sin 2\theta_K \sin\theta\ell \cos\phi$ and F_L is the fraction of longitudinal polarization. This definition aims to reduce form-factor dependence [6]. LHCb measured P'_5 and found the measured values larger than SM predictions by 2.8σ and 3.0σ, for $4.0 < q^2 < 6.0$ GeV$^2/c^4$ and $6.0 < q^2 < 8.0$ GeV$^2/c^4$, respectively [7].

The Belle collaboration has also joined the efforts of testing the SM in the angular analyses of $B \to K^*\ell^+\ell^-$. Figure 3 shows the projection of the $B \to K^*\ell^+\ell^-$ decay distribution to each angle, θ_K, θ_ℓ and ϕ measured by Belle [8]. Belle measured P'_5 and found in the region $4.0 < q^2 < 8.0$ GeV$^2/c^4$, where LHCb found significant deviation from the SM, as the measured value was 2.5σ larger than SM. The directions of deviation are the same between Belle and LHCb. Belle also measured $Q_5 \equiv P'^{\mu}_5 - P'^{e}_5$, thus testing the LFU violation in this observable, and saw no deviation from SM in any q^2 range.

ANOMALY IN $\bar{B} \to D^{(*)}\tau^-\bar{\nu}$

The quark-level semileptonic decay $b \to c\ell^-\bar{\nu}$ occurs with a tree-level diagram and is very well understood in the SM. Moreover, measured branching fractions of $B \to Xe^-\bar{\nu}$ and $B \to X\mu^-\bar{\nu}$ confirms the LFU in this process. If, however, there exists a charged Higgs ($H^\pm$) from NP, it may affect the rates of $B \to X\ell^-\bar{\nu}$. Since τ is much heavier than the other charged leptons, it is much more sensitive to $H^\pm$. Therefore, LFU-violating effects may appear in the semitauonic decay $b \to c\tau^-\bar{\nu}$. Unlike $\bar{B} \to D^{(*)}e^-\bar{\nu}$ and $D^{(*)}\mu^-\bar{\nu}$, where the only invisible particle in the final state is the neutrino, the $\bar{B} \to D^*\tau^-\bar{\nu}$ decays contain at least two neutrinos in the final state and its experimental observation has occurred much later than $D^{(*)}e^-\bar{\nu}$ and $D^{(*)}\mu^-\bar{\nu}$.

Exclusive $\bar{B} \to D^*\tau^-\bar{\nu}$ decay was first observed in 2007 by Belle in the mode $\bar{B}^0 \to D^*\tau^-\bar{\nu}$ [9]. Later in 2012, the BaBar collaboration measured $\bar{B} \to D^*\tau^-\bar{\nu}$ and $B \to D\tau^-\bar{\nu}$. Exploiting the feature of $e^+e^- \to \Upsilon(4S) \to B\bar{B}$, they tagged the accompanying B by fully reconstructing its hadronic final state and identified the remaining particles as the signal B meson. BaBar uses the leptonic τ decays, $\tau^- \to \ell^-\nu_\ell \bar{n} u_\tau$ and the observables $m^2_{\rm miss}$ and $|p^*_\ell|$ to measure the yields of $B \to D^{(*)}\tau^-\bar{\nu}$ events. Figure 4 shows the $m^2_{\rm miss}$ (left) and $|p^*_\ell|$ (right) distributions for $\bar{B} \to D^0\ell^-X$ (top) and $\bar{B} \to D^*\ell^-X$ (bottom), where X consists of the invisible neutrino(s) in the final state. In the figure, the green part corresponds to $D^*\tau^-\bar{\nu}$ and red to $D\tau^-\bar{\nu}$ signals. It is noted that the $B \to D\tau^-\bar{\nu}$ candidates contain large feed-down events from $D^*\tau^-\bar{\nu}$ with $D^* \to D\pi$. To reduce the systematic uncertainties, hence making the test of SM more sensitive, BaBar has defined the ratios:

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

They found $R_D = 0.440 \pm 0.058 \pm 0.042$ and $R_{D^*} = 0.332 \pm 0.024 \pm 0.018$ [10], each of which is larger than

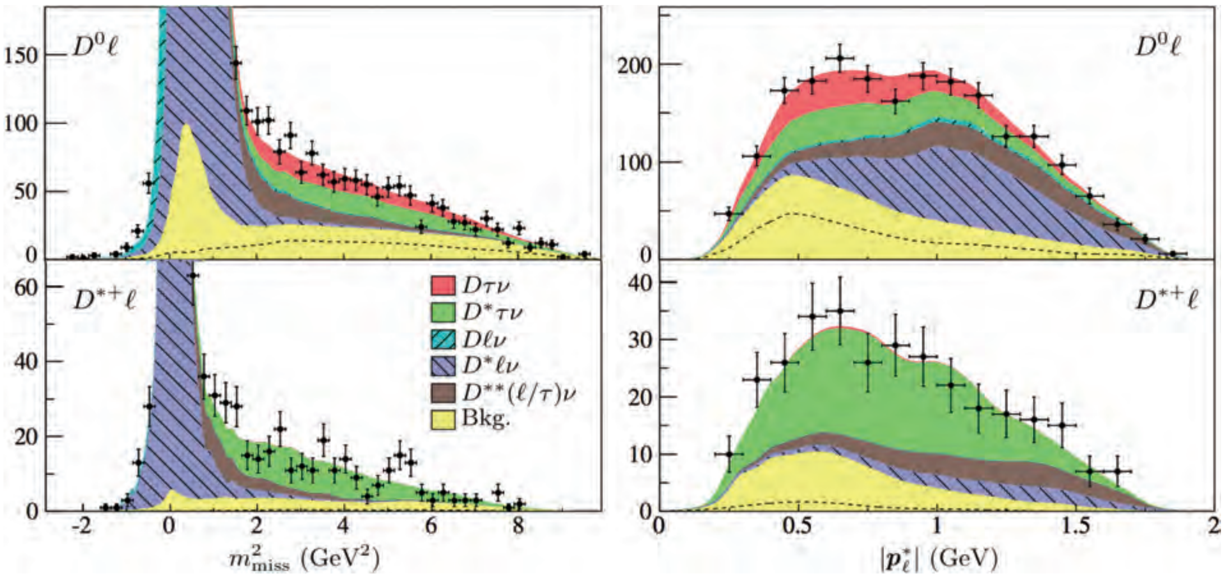

Fig. 4: Distributions of the observables, $m^2_{\rm miss}$ (left) and P^*_μ (right) for $B \to D^{(*)}\tau^-\overline{\nu}$, measured by BaBar, taken from Ref. [10]. Figures in the top row are for $D^0\ell^-$ final states, mainly measuring $B \to D\tau^-\overline{\nu}$, and those in the bottom row are for $D^{*+}\ell^-$ measuring $\overline{B} \to D^*\tau^-\overline{\nu}$.

the corresponding SM prediction. Combining R_D and R_{D^*}, the deviation is 3.4σ. Moreover, BaBar has studied the effect of the type-II two-Higgs doublet model (2HDM) for this deviation and discovered that their result is not consistent with this particular model of NP.

Later measurements of R_{D^*} and R_D by Belle and LHCb have found results similar to BaBar's. Figure 5 shows the observables $m^2_{\rm miss}$ and E^*_μ in the analysis of $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}$ by LHCb [11], in a particular region, $9.35 < q^2 < 12.60$ GeV$^2/c^4$, where E^*_μ is the energy of the muon in the B meson rest frame. To calculate observables in the B rest frame, the information on the momentum vector of the B meson is needed. The magnitude is estimated by the momentum vectors of the visible final-state particles. The direction is obtained by the unit vector to the B decay vertex from the primary vertex of the event. Using a multivariate analysis to separate signal candidates from background, they measured $R_{D^*} = 0.336 \pm 0.027 \pm 0.030$. It is the first such measurement from hadron collisions and is 2.1σ larger than what was expected (0.252 ± 0.003 [12]) by LFU in the SM.

Belle has updated their study of $B \to D^{(*)}\tau^-\overline{\nu}$ using two different methods of tagging the accompanying B meson ($B_{\rm tag}$), (i) by hadronic $B_{\rm tag}$ decays, and (ii) by semi-leptonic $B_{\rm tag}$ decays. Using the hadronic tagging, Belle has obtained $R_D = 0.375 \pm 0.064 \pm 0.026$ and $R_{D^*} = 0.293 \pm 0.038 \pm 0.015$ [13]. This result deviates in the same direction as that of BaBar's but with less significance (~2.0σ).

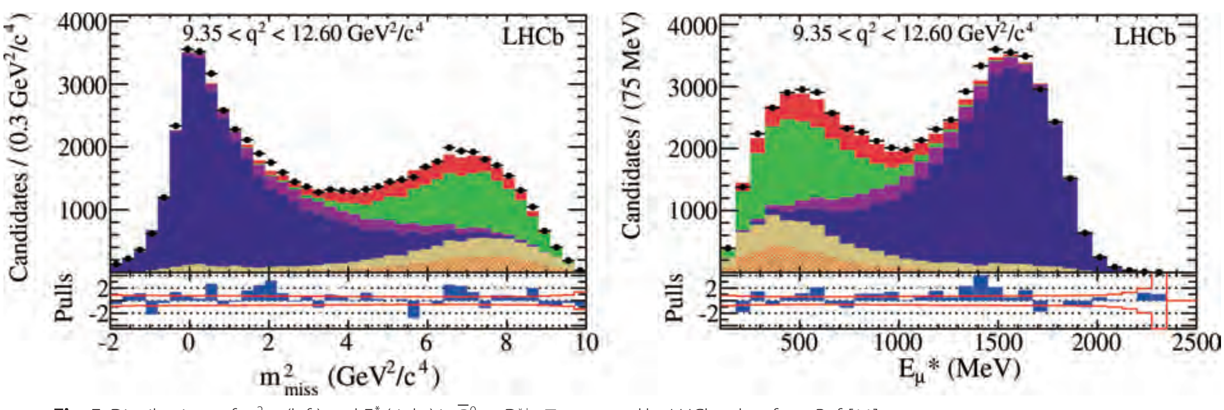

Fig. 5: Distributions of $m^2_{\rm miss}$ (left) and E^*_μ (right) in $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}$ measured by LHCb, taken from Ref. [11]

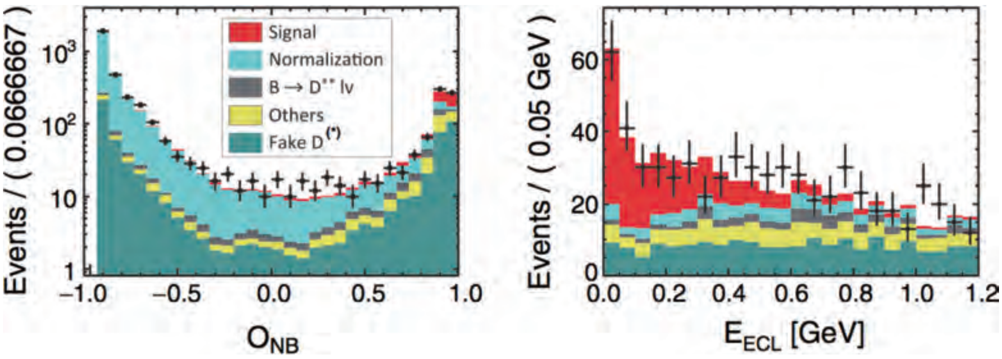

Fig. 6: Distributions of the observables, $\mathcal{O}_{NB}$ (left) and E_{ECL} (right) for $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}$, measured by Belle, taken from Ref. [14].

Figure 6 shows the two observables, $\mathcal{O}_{NB}$ and E_{ECL}, that were used in the semi-leptonic-tagging analysis of $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}$ by Belle [14]. $\mathcal{O}_{NB}$ is the neural-network output for separation of the $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}$ signal from the more abundant $D^{*+}\ell^-\overline{\nu}$ background, and E_{ECL} is the extra energy in the electromagnetic calorimeter. By fitting the 2D ($\mathcal{O}_{NB}$, E_{ECL}) distributions, they obtained $R_{D^*} = 0.302 \pm 0.030 \pm 0.011$. By using the observables p_{D^*} and p_ℓ measured in the $\Upsilon(4S)$ rest frame, they checked the signal distributions against the SM and other new physics models. The distribution is consistent with the SM and also with type-II 2HDM, but appears inconsistent with a leptoquark model of R_2 -type [15].

Another observable to test the SM and search for NP in $B \to D^{(*)}\tau^-\overline{\nu}$ is P_τ, the polarization of τ. In the SM, $W^\pm$ mediates the decay, but in an NP model where $H^\pm$ exists, the decay can also occur with $H^\pm$ as the intermediate particle. Since $H^\pm$ and $W^\pm$ have different spin, the resulting $B \to D^{(*)}\tau^-\overline{\nu}$ decays are expected to show different P_τ values. In the SM, the predicted values are $P_\tau(D) = 0.325 \pm 0.009$ and $P_\tau(D^*) = -0.497 \pm 0.014$ [16]. Belle measures P_τ in $\overline{B} \to D^*\tau^-\overline{\nu}$ by using τ^- decays to $\pi^-\nu$ and $\rho^-\nu$, and hadronic tagging of B_{tag}. Figure 7 shows the observables E_{ECL} and $\cos\theta_{hel}$, where θ_{hel} is the helicity angle of $\tau^- \to \pi^-\nu$ or $\rho^-\nu$. E_{ECL} measures the $D^*\tau^-\overline{\nu}$ signal yield and $\cos\theta_{hel}$ distribution determines $P_\tau(D^*)$. Belle obtained $R_{D^*} = 0.270 \pm 0.035\,^{+0.028}_{-0.025}$ and $P_\tau(D^*) = -0.38 \pm 0.51\,^{+0.21}_{-0.16}$ [17, 18]. It is the first experimental measurement of τ polarization in $\overline{B} \to D^*\tau^-\overline{\nu}$ and the result is consistent with SM.

Combining all the R_{D^*} and R_D measurements available so far, the world average value is approximately 4σ away from the SM prediction [19].

Perhaps, the ultimate test of LFU can be done by comparing $B^- \to \tau^-\overline{\nu}$ to $B^- \to \ell^-\overline{\nu}$ or (ℓ = e or μ). In the SM, the ratio is free from any uncertainties, e.g. due to V_{ub} or f_B, etc., but it depends only on the masses of the charged leptons. $B^- \to \tau^-\overline{\nu}$ has been measured by Belle and BaBar, and the average value of the branching fraction is $\mathcal{B}(B^- \to \tau^-\overline{\nu}) = (1.09 \pm 0.24) \times 10^{-4}$ [20]. But there has not yet been any experimental evidence for $B^- \to \mu^-\overline{\nu}$ or $e^-\overline{\nu}$. Recently, Belle has searched for $B^- \to \mu^-\overline{\nu}$ using the 3-momentum magnitude P^*_μ of the final-state μ^- in

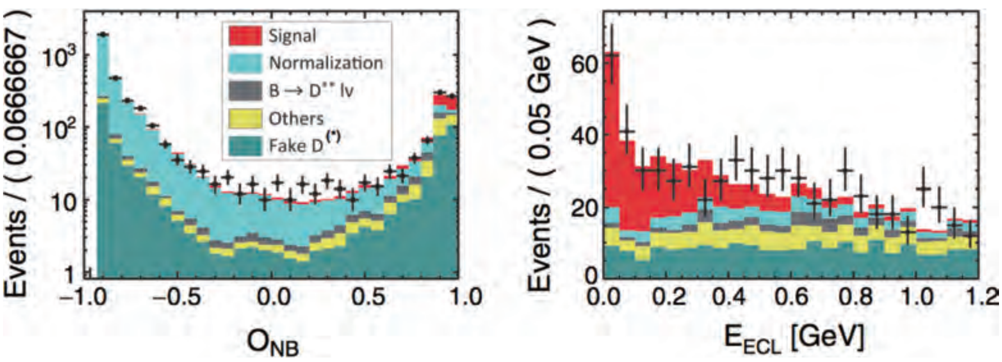

Fig. 7: Distributions of E_{ECL} for $\overline{B}^0 \to D^*\tau^-\overline{\nu}$ in the region $\cos\theta_{hel} < 0$ (left) and $\cos\theta_{hel} > 0$ (right), measured by Belle, taken from Ref. [18].

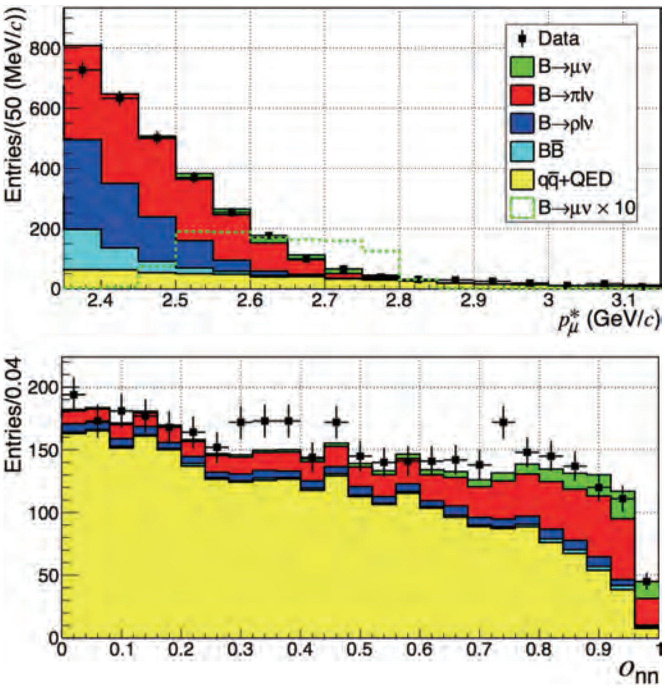

Fig. 8: Distributions of P_μ^* (top) and $\mathcal{O}_{NN}$ (bottom) for $B^- \to \mu^- \bar{\nu}$, measured by Belle, taken from Ref. [21].

the B^- rest frame as the key observable. For separation of signal events from background, a neural network was utilized. They measured the signal yield by 2D-fitting to P_μ^* and $\mathcal{O}_{NN}$, which is the neural network output. Figure 8 shows the P_μ^* and $\mathcal{O}_{NN}$, projections of the 2D fit result. The measured branching fraction was $\mathcal{B}(B^- \to \mu^- \bar{\nu}) = (6.46 \pm 2.22 \pm 1.60) \times 10^{-7}$ and it is away from zero by 2.4σ. At this moment, the significance is not enough to characterize as evidence, but it will be interesting to check this result with higher-statistics events in the future.

SUMMARY AND OUTLOOK

In this write-up, we have gone through the existing measurements of the so-called $R_{K^{(*)}}$ and $R_{D^{(*)}}$ anomalies. If either or both of these anomalies are confirmed with larger datasets and improved measurements, these anomalies might then yield clues regarding possible areas for NP. Upgrading the KEKB e^+e^- collider to the even more powerful SuperKEKB, the Belle II experiment will start taking data and produce physics results in this year. Moreover, LHCb is also planning a detector upgrade. It will remain a very interesting and important subject to search for new physics beyond the SM, hence improving our understanding of the Universe and potentially expanding our horizons to unexplored physics territories.

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References

[1] To be precise, a B meson consists of a $\bar{b}$ quark, the anti-particle of b, and a lighter quark such as u, d, s or c, while a $\bar{B}$ meson consists of a b quark and a lighter anti-quark.
[2] Since W boson is much heavier than b, this process cannot occur with W on its mass-shell. However, with an off-shell state W^*, it is allowed. The charge-conjugate state is also implied thorughout this write-up, unless explicitly stated otherwise.
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