Snowmass2021 - Letter of Interest

Testing Lepton Flavor Universality at Z pole

Thematic Areas:

☐ (EF01) EW Physics: Higgs Boson properties and couplings
☐ (EF02) EW Physics: Higgs Boson as a portal to new physics
■ (EF03) EW Physics: Heavy flavor and top quark physics
☐ (EF04) EW Precision Physics and constraining new physics
☐ (EF05) QCD and strong interactions: Precision QCD
☐ (EF06) QCD and strong interactions: Hadronic structure and forward QCD
☐ (EF07) QCD and strong interactions: Heavy Ions
☐ (EF08) BSM: Model specific explorations
☐ (EF09) BSM: More general explorations
☐ (EF10) BSM: Dark Matter at colliders
■ (RF1) Weak decays of b and c quarks

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Abstract: $b \to s\tau\tau$ and $b \to c\tau\nu$ measurements are highly motivated for addressing lepton-flavor-universality-violating (LFUV) puzzles, such as $R_{D^{(*)}}$, $R_{J/\psi}$ and $R_{K^{(*)}}$ anomalies, raised by the data of LHCb, BELLE and BarBar. The planned operation of future e^-e^+ colliders as a Z factory provides a great opportunity to conduct such measurements, because of its relatively high production rates and reconstruction efficiency for B mesons at Z pole. In this project we will pursue a systematic sensitivity study on these measurements at future Z factories. The implications of the outcomes for LFUV new physics will be also explored.

It has been known for a while that multiple anomalies exist in the measurements of B-meson physics. Deviations from the SM prediction appear in flavor-changing-charged-current (FCCC) processes which involve the transitions of $b \to c\ell(\tau)\nu$. One prominent example of this type is $R_{D^{(*)}}$, defined as:

$$R_{D^{(*)}} \equiv \frac{\mathrm{Br}(B \to D^{(*)}\tau\nu)}{\mathrm{Br}(B \to D^{(*)}\ell\nu)} \, . \tag{1}$$

The anomalies of $\sim 1.3\sigma$ and $\sim 2.7\sigma$ have been observed in measuring R_D and R_{D^*}, respectively [1]. Another example is

$$R_{J/\psi} \equiv \frac{\mathrm{Br}(B_c \to J/\psi\tau\nu)}{BR(B_c \to J/\psi\ell\nu)} \, . \tag{2}$$

As the analogue of $R_{D^{(*)}}$ in B_c-meson decays, $R_{J/\psi}$ is measured to be $\sim 2\sigma$ away from its SM prediciton [2]. Anomalies also present in flavor-changing-neutral-current (FCNC) $b \to s\ell\ell$ processes, often termed as $R_{K^{(*)}}$ anomaly, with $R_{K^{(*)}}$ being given by

$$R_{K^{(*)}} \equiv \frac{\mathrm{Br}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{Br}(B \to K^{(*)}e^+e^-)} \, . \tag{3}$$

Since these values are ratios between lepton-flavored quantities, systematic errors are expected to be largely cancelled in measuring these observables. The presence of the said anomalies may indicate the existence of new physics violating lepton flavor universality (LFU), although more data need to be accumulated before any conclusive statement can be made.

Addressing these anomalies naturally requests precise measurements of $b \to c\tau\nu$ and extending the FCNC measurements from $b \to s\ell\ell$ to $b \to s\tau\tau$. So far, the full run of Belle II and upgrades of LHCb in the future are expected to provide relative precisions of percent level on $R_{D^{(*)}}$ measurements [3;4]. Meanwhile, the sensitivities on $b \to s\tau\tau$ decay rates can also reach $\mathcal{O}(10^{-4})$ [3;4]. With large statistics, systematic errors may play important roles in these measurements and start to dominate at Belle II [3]. Therefore, independent results from other experiments provide valuable cross-checking of their results. It is also well known that at B factories like Belle II, the number of heavy b-hadrons such as B_s produced are limited. For even heavier b-hadrons, e.g. B_c or Λ_b, they cannot be produced at Belle II. Consequently, for LFU tests of these heavy b-hadrons, we have to rely on LHCb solely in the future without other new experiments.

Channel	Belle II	LHCb	Giga-Z	Tera-Z	10×Tera-Z
B^0, $\bar{B}^0$	5.3×10^{10}	$\sim 6 \times 10^{13}$	1.2×10^{8}	1.2×10^{11}	1.2×10^{12}
$B^\pm$	5.6×10^{10}	$\sim 6 \times 10^{13}$	1.2×10^{8}	1.2×10^{11}	1.2×10^{12}
B_s, $\bar{B}_s$	5.7×10^{8}	$\sim 2 \times 10^{13}$	3.2×10^{7}	3.2×10^{10}	3.2×10^{11}
$B_c^\pm$	-	$\sim 2 \times 10^{11}$	2.2×10^{5}	2.2×10^{8}	2.2×10^{9}
Λ_b, $\bar{\Lambda}_b$	-	$\sim 2 \times 10^{13}$	1.0×10^{7}	1.0×10^{10}	1.0×10^{11}

Table 1: Number of b-hadrons expected to be produced in Belle II, LHCb and future Z factories. We assume that Belle II will run at $\Upsilon(4S)$ mode with an integrated luminosity of 50 ab^{-1} and at $\Upsilon(5S)$ with 5 ab^{-1}, and estimate the LHCb productions following the $b\bar{b}$ acceptance in [5]. The production fractions for $B^0/\bar{B}^0$, $B^\pm$, $B_s/\bar{B}_s$ and $\Lambda_b/\bar{\Lambda}_b$ are taken as the average proposed in [6]. As for $B_c^\pm$, we use its production rate at Z pole in [7] for calculation, with B_c^* decays being included, and then project this number to LHCb by increasing its value by three orders as a rough estimation. Note, Belle II will have no statistics on the $B_c^\pm$ and $\Lambda_b/\bar{\Lambda}_b$ productions due to the limitation of energy threshold.

It turns out that Z factories are great new options for studying the flavor physics, because of their relatively high production rates and reconstruction efficiency of heavy flavored hadrons. The flavor physics potential of Z factories is pointed out in[8;9], but far from complete. We first notice the large number of b-hadrons produced at Z factories. The number of b-hadrons expected to be produced in Belle II, LHCb and future Z factories is summarized in Table 1. At Tera-Z as planned for CEPC, the productions of $B^0/\bar{B}^0$ and $B^{\pm}$ are comparable to those at Belle II, while $B_s/\bar{B}_s$ is nearly two orders more. ILC and FCC-ee are expected to run at Z pole also, with a plan of Giga-Z[10] and upgraded Tera-Z (namely, $10\times$Tera-Z)[11] respectively.

Furthermore, the high center of mass energy achieved at Z pole makes LFU tests more advantageous there. In fact, the relevant $b \to c\tau\nu$ and $b \to s\tau\tau$ measurements heavily rely on the reconstruction of the displaced decaying τ lepton or c-hadron. The said Z factories produce b-hadrons more boosted, compared to Belle II. This feature results in a weaker effect of multiple scattering for particles such as the charged decay products of the τ lepton and c-hadron in the tracker, and hence allows them to be measured with a higher precision in both energy/momentum[12] and direction[8;9]. Moreover, boosted particles tend to decay with a larger displacement, which will further reduce the uncertainty of reconstructing their decay vertexes.

Another reason why Z factories are the ideal facilities for LFU tests is their nature of lepton collider. In particular, Z factories enjoy negligible pile up, good detector geometric coverage and a fixed center of mass energy, allowing a good precision on missing momentum. The situation is drastically different at the hadron collider detector such as LHCb, which has a limited geometric coverage, large combinatorial backgrounds and uncertainties coming from proton PDF. The missing momentum of a certain event hence cannot be directly determined at LHCb by momentum conservation. Since extra neutrinos will be produced in $b \to c\tau\nu$ or $b \to s\tau\tau$ decays, the precise missing momentum reconstruction will be beneficial for testing LFU.

Based on the discussions above, Z factories may serve as the leading experiments for many flavor physics searches. We propose to evaluate the full potential of multiple $b \to c\tau\nu$ and $b \to s\tau\tau$ measurements at future Z factories systematically. The constraints on LFUV new physics will be also be studied based on projected sensitivities.

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