Snowmass2021 - Letter of Interest

Exploring new physics with $B_c \to \tau\nu_\tau$

Thematic Areas: (check all that apply □/■)

□ (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: We discuss the potential of studying the Standard Model and exploring new physics with the decay of $B_c \to \tau\nu_\tau$. Based on the collider specifications and the recent study done by the author and others, we believe an ee colliding Z factory could be a great enabler of this effort.

Weak decays of heavy mesons not only provide a unique platform to test the electroweak structures of the Standard Model (SM) but can also shed light on new physics (NP) beyond the SM. Among different species of heavy mesons, the B_c meson, discovered in 1998 by the CDF collaboration [1;2], is of particular interest in this regard. The B_c^+ meson has specific production and decay mechanisms, and accordingly the measurement of its mass, lifetime and decay branching ratios would help to probe the underlining quark dynamics and determine SM parameters.

Consisting of two heavy quarks of different types, the B_c^+ meson has three decay categories: 1) b-quark decay with spectator c-quark; 2) c-quark decay with spectator b-quark; 3) annihilation process (e.g. $B_c^+ \to \tau^+\nu_\tau, c\overline{s}$). The purely leptonic decay through the annihilation process is sensitive to the decay constant f_{B_c} and the CKM matrix element $|V_{cb}|$. Such a scheme has been used for the determination of $|V_{cd}|$ and $|V_{cs}|$ in $D^+/D_s^+ \to \tau^+\nu_\tau, \mu^+\nu_\mu$ [3]. For $|V_{cb}|$, since the $B_c^+ \to \tau^+\nu_\tau$ channel has not been discovered, it is measured using inclusive semileptonic $b \to c$ transitions and the exclusive channel of $\overline{B} \to D^* l\overline{\nu}_l$. However, even if $B_c^+ \to \tau^+\nu_\tau$ had been discovered, the decay $\overline{B} \to D^* l\overline{\nu}_l$ would still provide a more precise $|V_{cb}|$ measurement.

In recent years a few discrepancies have been found between the SM predictions and different experimental measurements in the bottom sector, especially in tauonic decay modes of B mesons [4–6]. In view of no clear signal in the direct searches of NP to date, the implications in low-energy processes are of great importance. The study of tauonic decay modes of B mesons, mostly $B \to D(^*)\tau\nu$ decays, have indicated some hints for lepton flavor universality violation. While these decay modes are very sensitive to vector/axial-vector type interactions, the (pseudo)scalar type interactions which can be induced in many popular NP models, e.g., the two-Higgs doublet and leptoquark models are less constrained by them. Due to the mass hierarchy $m_\tau \ll m_{B_c}$ that results in helicity suppression for $B_c^+ \to \tau^+\nu_\tau$ with $V-A$ interactions in the SM, $B_c \to \tau\nu$ has a better sensitivity to the (pseudo)scalar NP interactions [7;8]. Therefore, measurement of the branching ratio $\mathcal{B}(B_c^+ \to \tau^+\nu_\tau)$ can be a key in the search for NP. Based on the current knowledge, NP can affect $\mathcal{B}(B_c^+ \to \tau^+\nu_\tau)$ significantly [9], which highlights the study of this quantity in the future.

The recently proposed CEPC (Circular Electron Positron Collider) [10] provides an excellent opportunity to measure $\mathcal{B}(B_c^+ \to \tau^+\nu_\tau)$. It has a circumference of 100 km and two interaction points. Its primary objective is the precision Higgs study at a center-of-mass-energy ($\sqrt{s}$) of 240 GeV. Around 10^6 Higgs bosons will be produced during seven years of operation, improving most of the Higgs measurements by around 1 order of magnitude compared to the HL-LHC. In addition, a dedicated WW threshold scan ($\sqrt{s} = 158 - 172$ GeV) and the Z factory mode ($\sqrt{s} = 91.2$ GeV) will be operated for electroweak and flavor physics studies. The Z factory will produce up to one trillion Z bosons (Tera-Z) in two years, far exceeding LEP's production [11]. At this rate, the total B_c production is expected to reach to the order of 10^8. Various other b hadron productions will reach $10^{10\sim11}$. Such a huge data sample will enable high precision tests of the SM and allow to study many previously unobservable processes. Furthermore, the clean e^+e^- collision environment and the well-defined initial state compared to hadron colliders are advantages for this analysis at the CEPC. (Super) B factories operating at the Υ(4S) center-of-mass-energy are below the energy threshold for B_c^+ production. A detailed discussion on the various advantages and prospects on flavor studies at CEPC can be found in [10].

Recently the author and others did a study on the sensitivity of $B_c \to \tau\nu_\tau$ at CEPC [9]. And concluded that the signal strength can achieve relative accuracy of $\sim$1%. The main uncertainties arise from the theoretical predictions on the B_c production and decay, as well as limited simulated data constrained by the computing resources. Assuming the actual relative signal strength accuracy does not deviate too much from our prediction, we concluded that the channel could provide a significant constraint on the general effective Hamiltonian for the $b \to c\tau\nu$ transition. Regarding the $|V_{cb}|$ measurement, achieving the accuracy at least to the level of the uncertainty of B_c's total yield should be possible, and could reach 1% level as well if the latter can be determined to the similar level.

We believe an ee colliding Z factory such as CEPC, or the likes of which, holds a great potential on this nearly uncharted territory of B_c decay and would like to help make the case for its deserved attention.

References

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