Snowmass2021 - Letter of Interest

Searching for $B_s \to \phi\nu\nu$ and other $b \to s\nu\nu$ processes at CEPC

☐ (EF01) EW Physics: Higgs Boson properties and couplings
☐ (EF02) EW Physics: Higgs Boson as a portal to new physics
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Abstract: The rare $b \to s\nu\nu$ decays are sensitive to new physics contributions and help resolve the puzzle of several B flavor anomalies. In this letter we propose to study this channel at a future lepton collider working at the Z pole. In particular, we will use the full simulation of the CEPC detector to study its sensitivities of $b \to s\nu\nu$ transitions, especially the $B_s \to \phi\nu\nu$ decay. Preliminary analysis suggests a substantial improvement over the current best limit. The result of our search will be an important input to flavor physics and constraining beyond standard model effects. The study will also further motive detector R&D for the CEPC and other proposed experiments.

1 Introduction

The rare flavor-changing-neutral-current (FCNC) decays $b \to s\nu\nu$ are widely recognized as important flavor probes. Being suppressed by the loop factor and heavy weak boson masses, the decay rates of these modes ranges from 10^{-5} to 10^{-6}. Even small contributions from new physics to $b \to s\nu\nu$ decays may significantly change the observed rates substantially. They are also not affected by non-factorizable corrections and no photonic penguin contributions, thus theoretically cleaner compared to $b \to s\ell\ell$ transitions. The measurement of the inclusive decay rate probably can not be achieved due to the missing neutrinos. however, the exclusive channels like $B_s \to \phi\nu\nu$ are more promising as far as the branching ratios with related observables and main background are concerned. Since the small perturbative α_s and the non-perturbative corrections, these decays do not suffer from the form factor uncertainties and are very sensitive to the search for new physics beyond the SM. Experimental constraints and corresponding theoretical predictions are summarized in Table 1.

	Experimental	SM Prediction
BR$(B^0 \to K^0\nu\bar{\nu})$	$< 2.6 \times 10^{-5}$[1]	$(2.17 \pm 0.30) \times 10^{-6}$[2]
BR$(B^0 \to K^{*0}\nu\bar{\nu})$	$< 1.8 \times 10^{-5}$[1]	$(9.48 \pm 1.10) \times 10^{-6}$[2]
BR$(B^\pm \to K^\pm\nu\bar{\nu})$	$< 1.6 \times 10^{-5}$[1]	$(4.68 \pm 0.64) \times 10^{-6}$[2]
BR$(B^\pm \to K^{*\pm}\nu\bar{\nu})$	$< 4.0 \times 10^{-5}$[1]	$(10.22 \pm 1.19) \times 10^{-6}$[2]
BR$(B_s \to \phi\nu\bar{\nu})$	$< 5.4 \times 10^{-3}$[1]	-

Table 1: Constraints and predictions for various $b \to s\nu\bar{\nu}$ decays.

It is also well known that multiple anomalies exist in the measurements of B-meson physics, e.g., $R_{K^{(*)}}$ anomalies in FCNC $b \to s\ell\ell$ transitions. Anomalies also dwell in in flavor-changing-charged-current (FCCC) $b \to c\tau(\ell)\nu$ decays, such as $R_{D^{(*)}}$ or $R_{J/\psi}$. Recent data shows that these values are $2 - 3\sigma$ deviate from their SM predictions[3;4]. To address these anomalies in terms of new physics, it is natural to consider the relations between $b \to c\tau(\ell)\nu$ and $b \to s\ell\ell$ transitions via gauge invariance. Indeed, $b \to s\nu\nu$ transitions play important roles when constraining new physics, as all of $b \to s\nu\nu$, $b \to c\tau(\ell)\nu$ and $b \to s\ell\ell$ are generated by the same set of gauge invariant effective operators if new physics respects SM $SU(2)_L$ gauge invariance[5–7]. Measuring $b \to s\nu\nu$ transitions in multiple decay channels is thus crucial for constraining possible new physics and the understanding of its gauge structure.

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 2: 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[8]. 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[9]. As for $B_c^\pm$, we use its production rate at Z pole in[10] 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[11;12], 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 2. 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[13] and upgraded Tera-Z (namely, $10\times$Tera-Z)[14] respectively.

A Z factory also enjoys negligible pile up, good detector geometric coverage and a fixed center of mass energy, allowing a good precision on missing momentum. The advanced calorimetry[15–17] and the state-of-the-art track system[18;19] proposed for future detector further improves the sensitivity. Since in $b \to s\nu\nu$ decays the outgoing neutrinos only manifest themselves as missing momenta, this advantage for $b \to s\nu\nu$ measurements at Z pole is indisputable. The situation is drastically different at the hadron collider detector such as LHCb, where the missing momentum of a certain event hence cannot be directly determined. In addition, when compared to B factories like Belle II, the higher b hadron boost achieved at Z pole makes tracking more accurate. 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 tracker, and hence allows them to be measured with a higher precision in both energy/momentum[20] and direction/displacement[11;12]. This feature will in turn lead to better separation between signal and other heavy flavor decays as SM backgrounds.

2 Proposal

In this LOI we propose to study various measurement $b \to s\nu\nu$ transitions and focus on the decay processes $B_s \to \phi\nu\nu$ at Z pole. In particular, a full simulation of the CEPC detector response[11] will be applied to signal/background simulations. Our preliminary result based on simulated $Z \to b\bar{b}$ shows a $\mathcal{O}(10^{-6})$ sensitivity on BR($B_s \to \phi\nu\nu$), which is improved by a factor of $\gtrsim 10^3$ on top of the current limit given by the LEP measurement[21].

This study is also a great opportunity to test and evaluate the CEPC baseline design in multiple aspects. As discussed in the introduction, the successful $b \to s\nu\nu$ signal reconstruction is based on excellent detector resolutions on tracks and neutral particles. In particular, we wish to figure out the impact on $b \to s\nu\nu$ measurements if the following properties vary:

- Momentum resolution of charged particles.
- Impact parameter resolution of charged particles.
- Particle identification (e.g. between $\mu^{\pm}$, $\pi^{\pm}$ and $K^{\pm}$) performance.
- Energy resolution of the calorimeter system
- Time of arrival resolution of the calorimeter system.
- Dependence on the missing energy/momentum reconstruction.
- Particle flow algorithm.

Such result will serve as a useful input to the detector R&D community. The methodology and conclusions of this study can also be applied to other Z-factories such as FCC-ee and benefit the overall picture of flavor physics.

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