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Topics for the CEPC Flavor White Paper

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2 Description of CEPC facility

The Circular Electron Positron Collider (CEPC) is a double-ring e^+e^- collider with a 100 km circumference and two interaction points (IP) designed to precisely measure the Higgs boson and related particles. The CEPC Conceptual Design Report [1] includes exquisite details of the CEPC detector system. It operates at $\sqrt{s} \sim 240$ - 250 GeV for Higgs Factory, Z-pole($\sqrt{s} \sim 91.2$ GeV) and the W^+W^- threshold($\sqrt{s} \sim 161$ GeV) for electroweak and flavour physics with nominal integrated luminosity of 2.8, 8 and 1.3 ab^{-1} per interaction point (IP), respectively. The baseline design [1] provides abundant particle production for flavor physics studies. About 3.5×10^{11} Z, 1×10^7 W^+W^- pairs, and 5×10^5 Higgs will be produced at each IP. Currently there are also plans to have a run with $\sqrt{s}$ around the $t\bar{t}$ threshold, producing $\mathcal{O}(10^6)$ top quark pairs.

2.1 Key Collider Features for Flavor Physics

As an e^+e^- collider operating around the EW scale, flavor physic studies at CEPC are affected by three major features. First of all, as $\sqrt{s} \gg m_{b,c,\tau}$, CEPC produces highly relativistic heavy flavor quarks or leptons. Their boosted decay products allow precise momentum and lifetime measurements. This contrasts the situations at low energy e^+e^- colliders such as Belle II [2], Barbar [3], BESIII [4] and other future proposals [5]. Secondly, as an e^+e^- collider, CEPC provides a clean environment for flavor physics studies: low QCD backgrounds, negligible pileups, and an almost fixed E_{cm}. Final states, including neural or invisible particles, can be identified and reconstructed better than at hadron collider experiments such as the LHCb [6]. The above arguments show the uniqueness of CEPC flavor physics studies. Finally, the large instant luminosity thanks to the advanced accelerator design grants $\mathcal{O}(10^5)$ times more statistics than LEP [7] at the Z pole. The search and analysis strategies may therefore differ significantly from relevant LEP studies. High signal statistics allow sharper cuts to reduce backgrounds. In the meantime, we need to carefully address other systematic uncertainty sources using the plethora of data. Hence, the large luminosity brings new challenges and invalidates several luminosity projections from LEP. Such challenges are especially severe for precision measurements or rare process searches.

2.2 Key Detector Features for Flavor Physics

Aside from collider features discussed above, flavor physics studies at CEPC benefit the avant-garde CEPC detector system under active developments. The major improvements contributing to flavor physics include: 1) High lifetime resolution from the tracking system. 2) Solid PID by combining various techniques. 3) Excellent neutral particle (photon and neutral hadrons) energy resolution. The lifetime resolution of $\mathcal{O}(10)$ fs is crucial for flavor physics studies. This is because such a precision matches many important timescales such as $B_s - \bar{B}_s$ mixing (~ 56 fs), D_s decay (~ 500 fs), and τ decay (~ 290 fs). The accurate lifetime measurement thus benefits flavor tagging, event reconstruction, and time-dependent CP violation measurements. The improvement of PID originates from different technologies like the dN/dx techniques [8], time of flight measurement [9, 10], Particle Flow Algorithm (PFA) in calorimetry [11], etc. The successful PID greatly suppresses the mis-ID background, which benefits all kinds of flavor physics studies in general. This is especially helpful when the mode has unique quantum charges, like the lepton or baryon number. The high angular and energy resolution of photons and neutral hadrons suppresses combinatoric backgrounds with extra neutral decay products. In the meantime, the high-quality neutral particle reconstruction enables searches using final states containing these particles. Last

Item	Benchmark	Ref.	Comments
Basic Performance			
Angular acceptance	$\|\cos\theta\| < 0.99$	[1]	
$\sigma(E_{\text{beam}})$	$\mathcal{O}(0.1\%)$	[1]	
$\sigma(\|\vec{p}_{\text{track}}\|)$	$\mathcal{O}(0.1\%)$	[1]	Threshold$\sim$100 MeV
$\sigma(E_\gamma)$	(3-15%)$\sqrt{E}$	[1]	Threshold$\sim$100 MeV
$\ell - \pi$ mis-ID	$< 1\%$	[15]	In jet, $\|\vec{p}\| > 2$ GeV, ECAL+$\frac{dE}{dx}$
$\pi - K$ separation	$> 3\sigma$	[1]	In jet, $\|\vec{p}\| > 1$ GeV, ECAL+$\frac{dE}{dx}$
Flavor Physics Benchmarks (Depending on the Above)			
b-jet efficiency$\times$purity	$\sim 70\%$	[1]	In Z hadronic decays
c-jet efficiency$\times$purity	$\sim 40\%$	[1]	In Z hadronic decays
$\sigma(m_{H,W,Z})$	3.7%	[1]	Hadronic decays
b flavor tagging $\epsilon_{\text{eff}} = \epsilon(1-2\omega)^2$	$15\% - 20\%$	[cite]	For B_s
π^0 efficiency$\times$purity	$\gtrsim 70\%$	[16]	In Z hadronic decays, $\|\vec{p}_{\pi^0}\| > 5$ GeV
K^0_S, Λ , D efficiency	60%-85%	[17]	In Z hadronic decays, all tracks
τ efficiency$\times$purity	70%	[18]	In $WW \to \tau\nu q\bar{q}'$, inclusive
τ mis-ID	$\mathcal{O}(1\%)$	[18]	In $WW \to \tau\nu q\bar{q}'$, inclusive

Table 1. Summary of detector performances and flavor physics benchmarks.

but not least, the missing energy is measured from the momentum conservation of the whole event, which is bottlenecked by the neutral particle resolution.

Currently, the general CEPC detector performance studies based on fast simulation [12] are available. Similar studies based on the IDEA detector design for the FCC-*ee* [13] and the ILD detector design for the ILC (see [14]) are also available to the public. The benchmark performances of these baseline detector designs are in rough accordance with each other. Projections between these future lepton colliders and corresponding theoretical discussions are thus possible if the analyses are not extremely design-sensitive. In the context full simulation, serveral CEPC full simulation studies that are crucial for the flavor physics performance are released already, summarized in Table. 1.

3 Charged Current Semileptonic and Leptonic b Decays

Semileptonic and leptonic b decays induced by the charged current will remain crucial flavor topics in the CEPC era. Due to their significant decay rates, the potential statistics of (semi)leptonic b decays achieved at the CEPC can easily reach the $\mathcal{O}(10^9)$ level. These channels play central roles in SM parameter measurements such as the CKM matrix element V_{cb} and V_{ub}. Given the recent observation of charged current B anomalies [19, 20], these channels will also contribute to lepton flavor universality (LFU) tests. From the discussion in Section 2, the CEPC excels at measurements with τ final states since τ multi-body decays are difficult for B-factories. Meanwhile, the missing momentum from neutrinos is not accessible for hadron collider experiments. Additionally, the excellent B lifetime precision and the large sample size ($\gtrsim \mathcal{O}(10^7)$) for exclusive $b \to c\ell\nu$ decays allows time-dependent CPV measurements in semileptonic decays. One of the recent highlights is the CPV in B^0 and B_s mixings, denoted by $\mathcal{A}^d_{\text{SL}}$ and $\mathcal{A}^s_{\text{SL}}$ [21, 22].

Fortunately, there are already a few published works addressing the topic. For $B_c \to \tau\nu$ decays where the current experimental bounds are weak (BR$\lesssim 30\%$), the search at the Z-

factory mode can measure the BR with a $\mathcal{O}(10^{-4})$ precision. The CEPC study [23] uses full simulation and $\tau^\pm \to \ell^\pm \nu\bar{\nu}$ decay, while the FCC-ee based study [24] but uses fast simulation and $\tau^\pm \to \pi^\pm\pi^\pm\pi^\mp\nu$ decays. A work in preparation [cite] studies R_{D_s}, $R_{D_s^*}$, $R_{J/\psi}$, and R_{Λ_c} in the general Tera-Z context and the fast simulation template of the CEPC. The results from these studies are promising. The relative uncertainty (stat. only) of $R_{J/\psi}$ may reach $\lesssim 3\%$ with 10^{12} Z produced. The numbers are $\sim 0.5\%$ for $R_{D_s^{(*)}}$, and $\sim 0.2\%$ R_{Λ_c} [cite]. Their S/B are of $\gtrsim 1$, ensuring robustness against background uncertainties. Although complete projections of these semileptonic observables are yet available for Belle II and LHCb, we can still compare them with the projected $\sigma(R_{D^{(*)}}) \sim 2(1)\%$ (stat.) at Belle II [2], $\sigma(R_{J/\psi}) \gtrsim 3\%$ (stat.+syst), and $\sigma(R_{\Lambda_c}) \sim 2.5\%$ (stat.+syst) after LHCb upgrade II [25]. It is clear that the potential of semileptonic measurements at CEPC is stronger than other experiments.

However, there are still many open topics in this field to be explored. For example, R_D and R_{D^*} and relevant differential measurements seems necessary. It may need specific work using full simulation, as data from other experiments keeps accumulating at Belle II [26] and LHCb [27]. The competition will be inevitable. The measurement of higher D-meson resonances like $B \to D^{**}\ell(\tau)\nu$ decays [28], providing further new observables sensitive to new physics, complementary to the ones mentioned above. The multi-body decays of $D^{**} = D_0^*(2300), D_1(2420), D_1(2430)^0, D_2^*(2460)$ may limit the relevant sensitivities at Belle II. Additionally, the searches for remaining baryonic decays such as R_{Ξ_c} from Ξ_b decay are viable. R One may further extend the trend to search for the inclusive $b \to X_c\ell(\tau)\nu$ decay rates at CEPC, but it could be challenging. Moreover, the searches of exclusive $b \to u\ell\nu$ decays are viable at CEPC, as long as the hadronic u final state like $\pi^\pm$ and ρ^0 can be well reconstructed. Finally, if the systematic uncertainty from lepton mis-ID is under control, the LFU tests between the first two generations, *e.g.*, $\frac{\mathrm{BR}(b\to c+\mu\nu)}{\mathrm{BR}(b\to c+e\nu)}$ become relevant. We may soon deliver the estimated limit once the performance study is done. Finally, from the time-dependent asymmetry of semileptonic $B_{d,s}$ decays we can extract the valuable CPV from $B_{d,s} - \bar{B}_{d,s}$ mixing, namely $\mathcal{A}_{\mathrm{SL}}^{\lceil}$ and $\mathcal{A}_{\mathrm{SL}}^{\int}$, contributing to the global picture of the phase β and β_s [29]. The current experimental uncertainty $\sim \mathcal{O}(10^{-3})$ [30] is still far from the SM prediction ($\mathcal{O}(10^{-4})$ for $\mathcal{A}_{\mathrm{SL}}^d$ and $\mathcal{O}(10^{-5})$ for $\mathcal{A}_{\mathrm{SL}}^s$) [31]. It will be interesting to validate the suggested precision of $\mathcal{O}(10^{-5})$ at the FCC-ee [21] and $\mathcal{O}(10^{-4})$ at the future LHCb [25].

4 Rare/Penguin and Forbidden b Decays

FCNC $b \to s$ and $b \to d$ decays are forbidden at the tree-level in the SM. These decays are induced by EW penguin or box diagrams in the SM at the one-loop level, making them rare processes in general. Rich phenomena thus emerge as physics at the EW scale meets QCD, ideal for testing SM at high precision. Moreover, as the SM rates are suppressed by the off-diagonal CKM matrix elements and the loop factor, these FCNC modes are also sensitive to small new physics contributions. At the CEPC's Z-pole run, the high luminosity ensures large signal statistics even if the target mode has a typically small BR $\lesssim 10^{-5}$.

4.1 Dileptonic Modes

The CEPC full potential for dileptonic decays of b is still under evaluation. For light leptons, the event reconstruction is relatively straightforward, limited by statistics, lepton identification systematics, and the reconstruction of the hadronic decay products. In contrast, for di-τ modes, the missing momentum from neutrino makes the event reconstruction challenging. The background level also increases due to the large number of D mesons produced by Z and inclusive b-hadron decays. Fortunately, the advanced detector system and the clean environment make the di-τ mode one of the most valuable targets at the CEPC. The sensitivity and discovery potential will be orders of magnitude higher than those at other flavor physics experiments.

The sensitivity of several exclusive $b \to s\tau^+\tau^-$ decays are evaluated using $\tau^\pm \to \pi^\pm\pi^\pm\pi^\mp\nu$ decays [32, 33]. The sensitivity are estimated together with the typical background level, reaching $\mathcal{O}(10^{-5})$ for the two-body $B_s \to \tau^+\tau^-$ mode and $\mathcal{O}(10^{-7})$ for other three-body modes. For the baseline CEPC luminosity, such sensitivities can $O(1)$ deviations from the SM. The SM rates of $b \to s\tau^+\tau^-$ will be directly measured if the luminosity is comparable to that of FCC-ee. It is noteworthy that these CEPC upper limits are 1-2 orders of magnitude smaller than the Belle II and LHCb upgrade two ones [2, 25], making them one of the flagships of CEPC flavor physics. A further study using full simulation might be available in the future (see also [34]). For light dilepton decays, a fast simulation study on $B^0 \to \mu^+\mu^-$ and $B_s \to \mu^+\mu^-$ measurements (see [34] for more details). The preliminary result indicates the measurement of $\mathrm{BR}(B_s \to \mu^+\mu^-)$ is statistic limited, reaching $\mathcal{O}(10^{-10})$. On the other hand, $\mathrm{BR}B^0 \to \mu^+\mu^-$ measurement is strongly affected by the $B^0 \to \pi^+\pi^-$ background with $\pi - \mu$ mis-ID.

Other than above studies that are published or in preparation, several valuable analyses to be done. The evaluation of $R_{K^{(*)}}$ potential at the CEPC is yet done. There will be multiple final states like K^+ or $K^*(892)^0 \to K^\pm\pi^\mp$ available at the CEPC. The lepton-ID induced systematics will be the bottleneck of the projection. However, the excellent electron-ID from the future detector will provide some advantage against the LHCb. Other similar topics include R_{pK} [35], R_ϕ [36], $R_{f_2'}$ [36] (potentially large deviations from the SM!), and R_Λ coming from heavier b-hadron decays. The latter may require a new analysis framework as the Λ lifetime is large. In addition, $b \to u\ell^+\ell^-$ searches may share similar systematic uncertainty sources with $b \to s\ell^+\ell^-$ decays, complimentary to LHCb measurements[1]. For di-τ modes, it is worth probing the possibility of differential measurements like the forward-backward asymmetry and the τ polarimetry, which further improves the constraint on new physics [32]. Other channels such as $\Lambda_b \to \Lambda\tau^+\tau^-$ are also noteworthy.

4.2 Neutrino Modes

FCNC $b \to s/d\nu\bar{\nu}$ decays are similar to dileptonic modes. They are thus important for testing the SM. Also, they can provide the possibility of extracting the elements of the CKM matrix and search for the origin of the CP violations. Because they are not affected by the non-factorizable corrections and no photonic penguin contributions, there will be

[1] There are ~ 900 LHCb events yields for $B^+ \to \pi^+e^+e^-$ at by the end of HL-LHC era [25]

theoretically cleaner predictions than $b \to s/d\ell^+\ell^-$ transitions. In this case, the SM $b \to s/d\nu\bar{\nu}$ decay rates becomes smooth functions of $q^2 \equiv m_{\nu\bar{\nu}}^2$ without large QCD loop and hadronic resonance corrections, while only the low-q^2 regions of $b \to s/d\ell^+\ell^-$ decays are sensitive to new physics. Any large deviation at a particular narrow q^2 bin may indicate new invisible particles produced. Therefore the search is also useful for BSM physics with light feebly interacting particles [37, 38]. At CEPC's Z pole run, these searches will heavily depending on the neutral energy resolution and the second vertex identification.

An on going project [cite] studies the differential measurement of $B_s \to \phi\nu\bar{\nu}$ using full simulation of the CEPC. The estimate absolute sensitivity reaches $\mathcal{O}(10^{-7})$ level and the relative uncertainty is about 1%.

Potential topics include $B^0 \to K^{0*}\nu\bar{\nu}$ decays, while the search for $K^{\pm(*)}$, K^0, or $K^\pm + \nu\bar{\nu}$ modes are more challenging. This is because we cannot locate the secondary vertex well with these final states. The expected relative uncertainty of modes above are about 10% at Belle II [2]. Beyond these $B_{u,d}$ decays, $\Xi_b \to \Xi_c\nu\bar{\nu}$, $\Lambda_b \to \Lambda\nu\bar{\nu}$, and $\Lambda_b \to p^-K^+\nu\bar{\nu}$ maybe more interesting since they are out of the reach of most B-factories. The secondary vertex of Λ_b decay is available in the later case, allowing differential measurements.

4.3 Radiative Modes

The measurement of b-hadron radiative decays ($b \to s\gamma$) serve as an efficient way to probe the tree-level suppressed FCNC amplitudes. The time-dependent CP violation in radiative decays also provides valuable input in the global fit of the CKM matrix.

So far, there is no dedicated study for radiative modes at Z factories, possibly due to the unknown photon identification performance inside a b-jet. There could be several of them in preparation [39]. One benchmark for b radiative decays at the CEPC will be $B_s \to \phi(\to K^+K^-)\gamma$, where the current LHCb measurements is limited by the QCD background [40]. The invariant mass and B_s lifetime resolutions of this channel require excellent photon angular and momentum resolution. At LHCb upgrade II, the statistical uncertaintly of $BR(B_s \to \phi\gamma) \sim 0.1\%$ and the CP asymmetry parameter (typical time scale $\Delta\Gamma_{B_s} \sim 0.1$ ps) $\mathcal{A}^\Delta \sim 2\%$ [25]. The measurement of $\mathcal{S}_{CP}$ and $\mathcal{C}_{CP}$ of $B_s \to \phi\gamma$ (time scale from $B_s - \bar{B}_s$ mixing, ~ 50 fs) might be possible and needs to be evaluated. Similarly, the CEPC sensitivity on $\Lambda_b \to \Lambda\gamma$ channel could be higher than that of LHCb [41], so as $\Xi_b \to \Xi\gamma$. If the ECAL performance at a particular detector allows effective π^0 or $\eta \to \gamma\gamma$ reconstruction, the potential will also exist for double-radiative decays $B_{s,d} \to \gamma\gamma$. The different dependences on four-quark operators between single-and double-radiative modes complement each other [42]. For BR($B_s \to \gamma\gamma$), the estimated Belle II relative sensitivity is $\sim 23\%$ [2], leaving some room for the CEPC improvement.

4.4 Lepton Flavor Violating (LFV), Lepton Number Violating(LNV) and Baryon Number Violating (BNV) Decays

LFV, LNV, and BNV modes are sensitive to new physics. For example, the LFV effect in the SM only presents neutrino flavor oscillation, which is suppressed by the very light neutrino masses. Meanwhile, LNV and BNV processes can only come from BSM physics, with strong experimental bounds.

There are a few b forbidden decays to be studied at the CEPC. For two body LFV decays, there are $B \to \mu^\pm e^\mp$ (with a projected limit of $\mathcal{O}(10^{-11})$ at LHCb upgrade II) decays and $B \to \tau^\pm \mu^\mp$ decays (projected limit $\mathcal{O}(10^{-6})$ at LHCb upgrade II) [25]. Their constraints from the CEPC could be comparable to the LHCb ones, and the relative improvement will be more significant for $B \to \tau^\pm e^\mp$ decays since CEPC will have excellent electron identification. The sensitivity on $B \to K^{(*)}\tau^\pm\mu^\mp$ and $B \to K^{(*)}\mu^\pm e^\mp$ decays may be inferred from the analysis of R_K and R_{K^*}. The analysis for LNV modes such as $B^+ \to \pi^-\ell^+\ell^+$ shall be straightforward, only limited by statistics and lepton (charge) identification. Compared to relevant LHCb studies focusing on same sign di-muon modes [43, 44], CEPC may contribute more for same sign di-electron cases since low mis-ID for electron is achievable. For BNV searches, the possibility signals at the CEPC include the forbidden baryon-antibaryon oscillations (see [45]) and explicit BNV decays. A practical example is $\Xi_b^- \to \ell^-\ell^+\ell^-$ decays, which can be generated from dimension-5 $qq'q''\ell$ opeartors.

5 Hadronic b Decays and CP Violation Measurements

Measuring b hadronic decays and their corresponding CPV properties is one of the most important tasks of b physics. At CEPC, the precision of such measurements relies on sample statistics, low background level, successful hadron PID, and the extreme displacement (or equivalently decay time) resolution. Many rare hadronic decay modes measure at CEPC, especially those of heavy b-hadrons, and have neutral outgoing particles. Eventually, they lead to a better understanding and precision of the CKM matrix and the CP violating phases. At FCC-ee, the projected uncertainty of CKM angle γ reaches 4×10^{-3}, for β and ϕ_s they are 5×10^{-3} and 2×10^{-3}, respectively [46]. However, the validity of this projection needs to be carefully examined for CEPC.

Some FCC-ee or CEPC based studies on hadronic b decays are in preparation. For the fully charged decay case, the $B_s \to J/\psi\phi \to \mu^+\mu^-K^+K^-$ channel is one of the important benchmarks as it is the major contributor of ϕ_s measurement. According to the CEPC full simulation study in preparation [cite], the uncertainty of ϕ_s will be reduced to $\sim 3\times10^{-3}$, slightly better than the LHCb upgrade II result [25]. The improvement mainly comes from the larger b flavor tagging power ($\epsilon^{\text{eff}} \sim 20\%$) and a higher b acceptance. Another study targets probing $B_{d,s} \to \pi^0\pi^0 \to 4\gamma$ modes, using fast simulation of CEPC [cite]. The large photon combinatorics makes the background rejection very challenging. The detector calorimetry thus greatly impacts the result. If the ECAL energy resolution is reduced to $\sim 3\%\sqrt{E}\bigoplus 1\%$, the expected $\sigma(\text{BR}(B_s \to \pi^0\pi^0)) \sim 6\%$ and $\sigma(\text{BR}(B_d \to \pi^0\pi^0)) \sim 0.5\%$. The ongoing study for FCC-ee [47]focuses on the $B_s \to D_sK$ decay with $D_s^\pm \to \phi\pi^\pm$ and $D_s^\pm \to \phi\rho^\pm$ final states. The estimate shows that this channel alone provides a $\sim 7\times10^{-3}$ sensitivity on phase γ at FCC-ee.

The richness of b hadronic modes makes an exhaustive enumeration of CEPC opportunities impractical. Here we will mention several conventional measurements and a few less discussed ones. It will be interesting if one or multiple neutral particles are in the final state, such as $\pi^0 \to \gamma\gamma$. The same may happen for modes with η in the final state as

$\eta \to \gamma\gamma$ or $\pi^+\pi^-\pi^0$ can be constructed with higher efficiency/purity than $\pi^0 \to \gamma\gamma$. For α measurement that requires $b \to u\bar{u}d$ transitions [29], the decay rates are small in general. Channels such as $B_{d,s} \to \pi^+\pi^-$ are certainly viable at CEPC. For example, [34] suggested to use $B_{d,s} \to \pi^0\pi^0(\to e^+e^-\gamma)$ final state to extract the time-dependent CPV parameters. There are also channels like $\Lambda_b^0 \to p\rho^-(\to \pi^0\pi^-)$ [48]. For β and β_s measurement, we need $b \to c\bar{c}s$ or $b \to c\bar{u}d$ transitions. Examples for β measurement include $B^0 \to J/\psi K^{(*)0}$ and $B^0 \to \bar{D}^0 h^0$. For measuring β_s we also have $B_s \to \psi(2S)\eta$ [49] and $B_{(s)} \to J/\psi\eta^{(\prime)}$ [50]. Decays via $b \to c\bar{u}s$ and $b \to u\bar{c}s$ is necessary when it comes to the determination of γ. Typically they are $B \to DK$ type of decays. Potential targets could be $B_s \to \bar{D}^{(*)0}\phi$ and $B_0 \to \bar{D}^0 K^{*0}$. Aside from the channels discussed above, CEPC can also measure other rare hadronic decay modes of interest, such as, $B_s \to D^{(*)0}\bar{D}^{(*)0}$, $B_s \to \pi^0\eta'(\to \pi^+\pi^-\eta)$ [51], and $B_c^+ \to \pi^+\omega(\to \pi^+\pi^-\pi^0)$ [52], etc.

6 Spectroscopy and Exotics

Exotic heavy-flavored states beyond the traditional meson-baryon interpretation of hadrons open a new direction in hadron physics [53]. Since the first discovery of the state $X(3872)$ at Belle [54], dozens of such exotic states have been found. Their masses are usually near the $D\bar{D}$ or $B\bar{B}$ threshold. Our knowledge of such exotic states is still lacking, and the theoretical development is in great need of experimental data. CEPC will generate known exotic states from either b-hadron decays or direct production from $Z \to b\bar{b}, c\bar{c}$ processes. The discovery potential for new exotic states is also strong because of the high luminosity and $\sqrt{s}$ at the Z pole. Nevertheless, the search and investigation of "conventional" heavy-flavored mesons and baryons are also important tasks at CEPC, including excited states hadrons and doubly/triply heavy baryons such as Ξ_{bb} [55].

The recent studies focusing on this field are focusing on the theory prediction rather than phenomenological prospects. The inclusive decay rate rate $\mathrm{BR}(Z \to X + T^{\{cc\}}_{[\bar{q}\bar{q}']}) \sim \mathcal{O}(10^{-6})$, $\mathrm{BR}(Z \to X + \Xi_{cc}) \sim 1 \times 10^{-5}$, and $\mathrm{BR}(Z \to X + \Omega_{cc}) \sim 5 \times 10^{-5}$ at the Z pole are deduced from simplified assumptions and parton-level simulation [56]. The authors of [57] also calculates $\mathrm{BR}(Z \to X + T^{\{bb\}}_{[\bar{q}\bar{q}']}) \sim \mathcal{O}(10^{-6})$. However, a phenomenological overview of exotic states at CEPC has yet formed, and the hadronization simulation codes need to be modified.

There are many relevant phenomenology studies to be done in this field. For $c\bar{c}$ exotic states such as $X(3872)$ and $P_c(4450)$, the major production mechanism at CEPC will be $b \to c\bar{c}s$ transitions in B meson decays. The final state will be boosted with high statistics. Many of their absolute BRs will be measured for the first time, and even more new decay modes will be confirmed. For doubly heavy baryons (bbq, bcq and ccq) and heavy exotic states (*e.g.*, tetraquark $bb\bar{u}\bar{d}$ [58] and pentaquark $b\bar{b}uud$ [59]), their high mass threshold making Z inclusive decays their major production mechanism. As their production requires a pair of heavy quarks with similar momentum, the unique pattern imprinted in the hadron shower will help recognize them. Such unique signatures in event shapes will be even stronger if there is any double heavy flavor process. Last but not least, several excited states such as $B_c(1^3S_1)$ that only decays to $B_c\gamma$ will also be nice targets since they are hard to access in other experiments.

7 Charm Physics

The high BR$(Z \to c\bar{c}) \simeq 12\%$ comparable to BR$(Z \to b\bar{b}) \sim 15\%$ makes CEPC also an c-factory. The charm physics studies enjoy the high luminosity, low background level, and good detector system at the CEPC. Unfortunately, few solid statements about charm physics are available at the current stage. On the other hand, the recent observation of CPV in charm decays [60–62] raises the necessity of charm physics studies and constrain new physics.

Here we also arrange possible valuable topics in the similar manner of Section 3, 4, and 5. For example, the semileptonic c-hadron decays and corresponding tests. Some theoretical discussions are done for rare $c \to u\nu\bar{\nu}$ decays [63], while the phenomenology at the Z pole is yet understood. Hadronic c decay modes will play important roles not only in charm physics but also in b physics, as $b \to c + X$ EW decay is the major b decay mode. Aside from decays to tracks only, other decay including neutral particles will further increase the c-hadron tagging efficiency. Examples include $D^0 \to K^-\pi^+\pi^0$, with its BR= 14.2% and the decay vertex reconstructable. Similar modes include $D^0 \to K^0_S\pi^+\pi^-\pi^0$ (BR=5.1%) or $D^0 \to K^-2\pi^+\pi^-\pi^0$ (BR=4.2%). For D_s, we may consider the reconstruction of $D_s^+ \to K^+K^-\pi^+\pi^0$ (BR=6.3%), $D_s^+ \to \eta\rho^+$ (BR=8.9%), or $\eta'\rho^+$ (BR=5.8%). In the mean time, c-hadron to CP eigen states (e.g. $D^0 \to K^0_S\pi^0, K^0_S\omega, K^0_S\phi$) is useful to extract CPV parameters from $B \to DK$ type decays and hence useful for determining the CKM γ angle [30], as discussed in Section 5. In terms of direct CPV in charm decays, the key is to precisely measure the parameter $\Delta\mathcal{A}_{\rm CP} \equiv \mathcal{A}_{\rm CP}(K^+K^-) - \mathcal{A}_{\rm CP}(\pi^+\pi^-)$ and compare it with the LHCb upgrade II prospect $\sim 3 \times 10^{-4}$ [25]. Other useful decays to probe CPV include, *e.g.*, $D^+ \to \pi^+\pi^0$, $D^0 \to K^0_S\bar{K}^0_S$, and $D^+_{(s)} \to K^+K^0_S\pi^+\pi^-$, etc.

8 τ Physics

At the Z pole, CEPC produces as many $\tau^+\tau^-$ pairs as $\sim 3\%$ of Z produced ($N_{\tau^+}3 \times 10^{10}$ according to [1]) and potentially upgradeable. The τ production at the Z pole comes without other particles and large boosts ($\gamma_\tau \sim 26$). Therefore, the number of τ at CEPC will be comparable with that generated at Belle II ($N_{\tau^+} \sim 5 \times 10^{10}$) with an expected tagging efficiency 2-3 times higher. Similarly, the number and tagging efficiency at CEPC will also exceed those at the future STCF project [5]. All of these advantages make CEPC an ideal place to study τ physics.

The reference [64] summarized many recent τ physics projections and discussions at the Z pole. Most studies reviewed were based on fast simulation within the FCC-*ee* context but still provides us valuable benchmarks. The study focuses on several aspects: the precision decay time and mass measurement; the LFU test in leptonic τ decays; LFV τ decays. In Table 2, we list the FCC-*ee* projections in [64] and the comparison with current limits. In [18], the tagging efficiency of inclusive τ hadronic modes using CEPC full simulation was studied. The inclusive hadronic τ efficiency times purity is $\sim 70\%$, evaluated in W^+W^- events. Another ongoing study focus on the exclusive tagging of major τ decay modes with the dual-readout calorimeter at the Z pole [65]. The preliminary result shows that the averaged τ-tagging accuracy of seven common decay modes is $\sim 90\%$.

Measurement	Current [66]	FCC Projection	Comments
Lifetime [sec]	$\pm 5 \times 10^{-16}$	$\pm 1 \times 10^{-18}$	3-prong decays, stat. limited
$\mathrm{BR}(\tau \to \ell\nu\bar{\nu})$	$\pm 4 \times 10^{-4}$	$\pm 10^{-6} \pm 3 \times 10^{-5}$	Assumed $0.1\times$ syst.(ALEPH)
$\mathrm{m}(\tau)$ [MeV]	± 0.12	$\pm 0.004 \pm 0.1$	$\sigma(\vec{p}_{\mathrm{track}})$ limited
$\mathrm{BR}(\tau \to 3\mu)$	$< 2.1 \times 10^{-8}$	$\mathcal{O}(10^{-10})$	bkg free
$\mathrm{BR}(\tau \to 3e)$	$< 2.7 \times 10^{-8}$	$\mathcal{O}(10^{-10})$	bkg free
$\mathrm{BR}(\tau^\pm \to e\mu\mu)$	$< 2.7 \times 10^{-8}$	$\mathcal{O}(10^{-10})$	bkg free
$\mathrm{BR}(\tau^\pm \to \mu ee)$	$< 1.8 \times 10^{-8}$	$\mathcal{O}(10^{-10})$	bkg free
$\mathrm{BR}(\tau \to \mu\gamma)$	$< 4.4 \times 10^{-8}$	$\sim 2 \times 10^{-9}$	$Z \to \tau\tau\gamma$ bkg , $\sigma(p_\gamma)$ limited
$\mathrm{BR}(\tau \to e\gamma)$	$< 3.3 \times 10^{-8}$	$\sim 2 \times 10^{-9}$	$Z \to \tau\tau\gamma$ bkg, $\sigma(p_\gamma)$ limited

Table 2. The summarized projections of τ physics for FCC-*ee* [64]. We use absolute precisions and upper limits instead of relative ones. For $\tau \to 3e$, $\tau \to \mu ee$, and $\tau \to e\mu\mu$ limits, we assume the same efficiency and background situation as those of $\tau \to 3\mu$.

Many interesting τ physics questions remain unknown for the CEPC. The complete evaluation of τ LFV decay upper limits at CEPC is yet available. Around 50 different τ LFV decay modes are discussed [2], based on the luminosity projections of previous Belle limits. The theoretical importance of various τ LFV decay modes discriminating different models is well established [67, 68]. Since there is no neutrino in most LFV modes above, the τ mass resolution plays an essential role in background suppression. For fully charged modes such as $\tau^\pm \to \ell^\pm K^+K^-$, the limit depends on systematic uncertainties such as the $\mu - K$ mis-ID and will be sensitive to a BR$\sim \mathcal{O}(10^{-10})$. CEPC will also be the leading experiment in τ inclusive decay measurements. So far, the LEP measurement of α_s is still the most precise result, which comes from the inclusive $\tau \to \nu +$ hadrons. The decays with high hadron invariant mass $s_{\mathrm{had}} \equiv m^2_{\mathrm{hadron}}$ usually have high hadron multiplicity, leaving relatively soft and adjacent outgoing particles. These systematics thus limit previous LEP measurements [69, 70]. Also, in the large-s region where $(p_\tau - m_\nu)^2 \sim m_\tau^2$, the current best results from LEP suffer from inadequate statistics and complex final states simultaneously. We expect that CEPC will provide much better τ inclusive decay measurements, especially for the aforementioned high hadron multiplicity and large-s regime. Another interesting measurement that can be done in terms of hadronic τ decays is the precise measurement V_{us} from inclusive $\tau \to K + X$ decay modes [2]. Further theoretical details can be found in [71].

9 Flavor Physics at Higher Energies

In the sections above, we have discussed the prospects of flavor physics studies for the CEPC, mainly in the context b, c, and τ decays. The results are thus not very sensitive to the production details of heavy-flavored particles. However, operating at a $\sqrt{s} \gg m_{b,c,\tau}$, CEPC can directly produce EW gauge bosons, Higgs, and top quarks, enabling us to scrutinize flavor physics at the energy much higher than heavy-flavored particle masses.

9.1 Flavor Physics from Z Decays

Most available Z decay flavor physics results present in terms of LFV Z decays. In [64], results at FCC-ee are estimated. For the $Z \to \mu e$ decay rates, the key is the lepton-ID between μ and e. Assuming a mis-ID rate $\sim 3 \times 10^{-7}$ from the dE/dx alone, the FCC-ee reach for $Z \to \mu e$ will be of $\mathcal{O}(10^{-8})$ and goes to the statistical limit of $\mathcal{O}(10^{-10})$ if another independent method is available. For $Z \to \mu\tau$ and $Z \to e\tau$ modes, we can use the $\tau^\pm \to \rho^\pm\nu$ or $3\pi\nu$ hadronic modes with a mono-energetic lepton. The backgrounds then becomes the $Z \to \tau\tau$ decay with one $\tau \to \ell\nu\nu$ decay having $\vec{p}_\ell \approx \vec{p}_\tau$. The background level then depends on the beam energy spread and track energy resolution (both of $\mathcal{O}(10^{-3})$). The final bounds for these two channels at the FCC-ee are then of $\mathcal{O}(10^{-9})$.

Many interesting topics about flavor physics in Z decays remain unexplored. The b-hadron productions at the Z pole from LEP are summarized by [30]. Although for $B_{u,d,s}$, the corresponding production fraction $f_{u,d,s}$ are measured with reasonable precision, the exclusive baryonic ($\Lambda_b, \Sigma_b, \Xi_b$, etc.) and B_c production factions remains unknown. These measurements will benefit most b physics studies at the Z pole. With good c-jet tagging, similar measurements for c-hadrons are also possible. CEPC is also suitable for polarimetry measurements in Z decays, including leptonic (τ) modes and hadronic modes (b and c). Measuring the polarization of τ produced in Z decays provides a way to study the LFU and input to the EWPT global fit [72]. A published study at ILC ($\sqrt{s} = 500$ GeV, $L = 4\text{ab}^{-1}$) evaluates the potential of τ polarimetry using full simulation [73]. The result shows that the precision of τ polarization is $0.5 - 2\%$, depending on beam polarization setups. I is worth noticing that $\tau^\pm \to \rho^\pm\nu$ mode leads to a slightly better precision compared to $\tau^\pm \to \pi^\pm\nu$l. One of the most promising ways to measure heavy quark polarization directly is to measure the polarization of their baryons for hadrons. According to HQET, b- and c-hadronization to baryons can partially keep the initial quark polarization [74, 75]. The most recent measurements of Λ_b polarization comes from LEP ($\langle P_L^{\Lambda b}\rangle \in [-0.87, -0.13]$) [76, 77], using its semileptonic decay. At the CEPC, we expect an improvement of $\gtrsim \mathcal{O}(10^2)$ based on the luminosity and detector efficiencies. Flavor physics from Z decays may also overlap with QCD studies. For example, by studying the exclusive $Z \to$hadron decay modes like $J/\psi\gamma$ with a suppressed BR$\sim 10^{-7}$ [78] (current limit: $< 1.4 \times 10^{-6}$ [79]). The precise measurement then provides a clean way to extract or test QCD factorization parameters at higher energy. Another example is the study of $Z \to Q\bar{Q}Q'\bar{Q}'$ double heavy flavor decays. It is closely related to the B_c physics studies since B_c comes from $Z \to b\bar{b}c\bar{c}$ decays. The double heavy flavor Z decays are also helpful in many exotic state studies mentioned in Section 6.

9.2 Flavor Physics from W Decays

At CEPC W-factory mode, abundant samples of W pairs allows precise measurements of CKM matrix elements such as $|V_{cb}|$ and $|V_{cs}|$. By now there are only statistical based projections at the FCC-ee. For $|V_{cb}|$, based on the typical b- and c-jet tagging performances, the stastical uncertainty is $\mathcal{O}(10^{-4})$. For $|V_{cs}|$, a similar statistical uncertainty $\sim 3\times 10^{-4}$ is achieved based on a larger sample size but lower tagging power. It is noteworthy that $|V_{cb}|$ will be the bottleneck for BSM searches in B meson mixings [21]. The flavor physics studies from W decays also share many similarities with ones from Z decays. Therefore, following the discussions above, we can also try to form topics such as W exclusive hadronic decays [78].

9.3 Flavor Physics from Higgs and Top

Most collider studies fit in this part will have serious overlap with and thus covered by Higgs and top physics. Some flavor-specific examples include the Higgs exclusive hadronic decays [80] or the FCNC decay of top quarks [81].

10 Two Photon and ISR Physics with Heavy Flavors

The energetic and high luminosity CEPC beams make ISR photon collisions relevant to flavor physics. The process occurs as $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-X$, with the typical scale $m_X^2 = Q^2 \equiv (q_1+q_2)^2$ and $q_{1,2}$ the momenta of virtual photons. The formal expression of the photon collision cross section depends on the outgoing lepton momenta and thus the virtuality q^2 of each photon [82]. Since the major contribution to flavor physics comes from the low-q^2 region, the full $\gamma\gamma$ collision rate is simplified by the Equivalent Photon Approximation. In the interested regime where $Q^2 \lesssim 4m_b^2 \ll 4E_{\rm beam}^2$, the effective luminosity of $\gamma\gamma$ collision is enhanced by the large $\log^2(E_{\rm beam}/m_e)\log(2E_{\rm beam}/Q)$ [83]. The large luminosity at low Q^2 leads to large statistics of $X = c\bar{c}$, $b\bar{b}$, $\tau^+\tau^-$ and unique observables. However, flavored X from $\gamma\gamma$ collision decays to soft particles, boosted in the beam direction. A reliable event reconstruction may require tagging the recoiling beam leptons in the forward region, especially for the low photon virtuality case. The fact motivates the detector design and simulation in the high-$|\eta|$ region.

The current study [cite] demonstrates the potential of $\gamma\gamma$ collisions at the Higgs factory mode ($\sqrt{s}$ = 240 GeV, $L \sim 5$ ab^{-1}). The authors focus on the quarkonium spectroscopy and $\tau^+\tau^-$ production. Since the radiative diphoton decay widths of C-even quarkonium are well studied, one can derive their production from $\gamma\gamma$ collision accordingly. The simulation shows that the raw CEPC $\gamma\gamma$ collision yields for various $c\bar{c}$ states are of $\mathcal{O}(10^7 - 10^9)$. The number reduces to $\mathcal{O}(10^4 - 10^5)$ when we require a single tagged recoiling electron. For the double tagged electron case, the expected yield further drops to $\mathcal{O}(10^2 - 10^4)$. It is noteworthy that single and double tagged event statistics strongly depend on the forward electron reconstruction. For example, the size of double tagged event increases by $\sim 10^2$ times when the minimal angle of detection reduces from 6 to 1.9 degrees. Several bottomonium rates are also simulated, which are factors of $\mathcal{O}(10^{-3})$ smaller than those of charmonium. Since the larger q^2 on average leads to larger electron recoil, the efficiencies of double tagged events are higher. The detailed event reconstruction with two recoiling electrons can also help measure the radiative decay widths of exotic states to $\gamma\gamma$. The large $\sigma(\gamma\gamma \to \tau^+\tau^-) \sim 570$ pb at $\sqrt{s}$=240 GeV produces $\sim 3\times 10^9$ τ pairs throughout the 5 ab^{-1} run. The process' absolute cross section allows us to measure the anomalous magnetic moment of τ (a^τ) [84] and significant improvements are expected. Nevertheless, fast or full detector are still necessary for all the above studies.

11 Summary

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