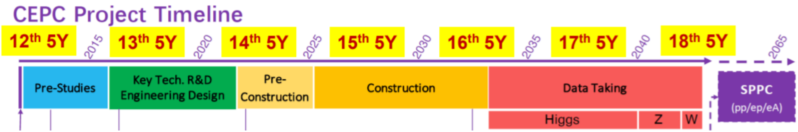
Flavor prospects at CEPC

Towards a Physics White Paper

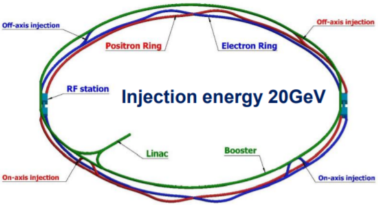
Lingfeng Li (Brown U.)

Nov. 29, CLHCP 2021

Intro: What's CEPC?



- 100 km collider and booster ring



	ttbar	Higgs	W	Z
Number of IPs		2		
Hour glass Factor	0.89	0.9	0.9	0.97
Luminosity per IP[1e34/cm^2/s]	0.5	5.0	16	115

	Operation mode	ZH	Z	W^+W^-	ttbar (new)
	$\sqrt{s}$ [GeV]	~ 240	~ 91.2	~ 160	~ 360
	Run time [years]	7	2	1	7.7
CDR	L / IP [$\times10^{34}$ cm^{-2}s^{-1}]	3	32	10	
	$\int L\,dt$ [ab^{-1}, 2 IPs]	5.6	16	2.6	
	Event yields [2 IPs]	1×10^6	7×10^{11}	2×10^7	
Latest	L / IP [$\times10^{34}$ cm^{-2}s^{-1}]	5.0	115	15.4	0.5
	$\int L\,dt$ [ab^{-1}, 2 IPs]	9.3	57.5	4.0	1.0
	Event yields [2 IPs]	**1.7×10^6**	**2.5×10^{12}**	**3×10^7**	**3×10^5**

Z-factory: $\sim 2.5\times$Tera-Z

W-factory: $\sim 3\times10^7\ W^+W^-$ pairs

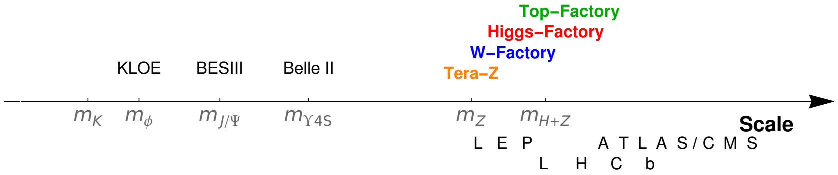
Higgs-factory: ~ 2 million Higgs

Flavor Physics at CEPC

Z Factory $\supseteq$ Flavor Factory

Particle-ID $\supseteq$ Flavor-ID!

Channel	Belle II	LHCb	Giga-Z	CEPC (Tera-Z)
B^0, B^0	5.3×10^{10}	$\sim 6 \times 10^{13}$	1.2×10^{8}	1.2×10^{11}
$B^{\pm}$	5.6×10^{10}	$\sim 6 \times 10^{13}$	1.2×10^{8}	1.2×10^{11}
B_s, $\bar{B}_s$	5.7×10^{8}	$\sim 2 \times 10^{13}$	3.2×10^{7}	3.2×10^{10}
$B_c^{\pm}$	-	$\sim 4 \times 10^{11}$	2.2×10^{5}	2.2×10^{8}
Λ_b, $\bar{\Lambda}_b$	-	$\sim 2 \times 10^{13}$	1.0×10^{7}	1.0×10^{10}
c, $\bar{c}$	2.6×10^{11}	$\gtrsim 10^{14}$	2.4×10^{8}	2.4×10^{11}
τ^+, τ^-	9×10^{10}	-	7.4×10^{7}	7.4×10^{10}



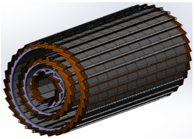
VS. B Factories

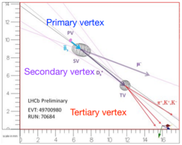
- Much higher b quark boost
- Abundant heavy b hadron

VS. Hadron Colliders

- Clean environment
- Direct missing momenta measurement

Key Detector Features for Flavor Physics



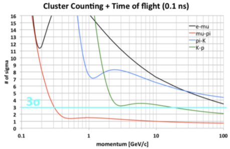


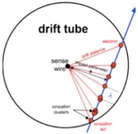
Tracking sys, grants $\mathcal{O}(10)$ fs sensitivity.

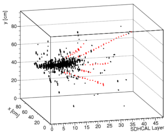
- High time precision for CPV measurements.
- Authentic c/τ reconstruction inside a jet.
- Greater acceptance for displaced signals.

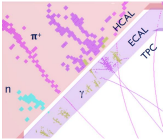
Advanced PID coming from the combination of different methods.

- Flavor tagging for everything.
- Suppressing backgrounds in general.
- Clean leptonic/baryonic modes.









Calorimetry gives neutral energy and angular resolution.

- Better $\not{p}$ measurement for neutrinos.
- Excited states such as D_s^* and radiative decays.
- Distinguishing π^0/η..., allowing h^0X modes.

CEPC Workshop 2021 (Flavor Part)

10:30 **$b \to s\tau\tau$ at a Tera-Z** *30'*
Speaker: Lingfeng Li (Brown University)
Material: **Slides**

11:00 **Flavor/CPV prospects and opportunities at a Tera-Z** *30'*
Speaker: Zoltan Ligeti (UC Berkeley)
Material: **Slides**

11:30 **Lepton identification and backgrounds for flavor studies at the CEPC** *30'*
Speaker: Dan YU (IHEP)
Material: **Slides**

12:00 **Tests of lepton flavor universality at high-energy e+e- colliders** *30'*
Speaker: Andreas Crivellin (PSI)

14:00 **Strange jet tagging** *30'*
Speaker: Yuichiro Nakai (Shanghai Jiao Tong University)
Material: **Slides**

14:30 **LFV Z decays at a Tera-Z factory** *30'*
Speaker: Xabier Marcano (Madrid U)
Material: **Slides**

15:00 **Prospects for $B_c \to \tau\nu$** *30'*
Speaker: Yasmine Amhis (IJCLab Orsay)
Material: **Slides**

10:30 **Physics analyses and detector requirement study from Benchmark study of B0/Bs->2 pi0** *24'*
Speaker: Yuexin Wang
Material: **Slides**

10:54 **Jet Charge Reconstruction based on leading jet charged particle** *24'*
Speaker: CUI Hanhua
Material: **Slides**

11:18 **Physics analyses and detector optimization study based on Benchmark study of H->bb, cc, gg** *24'*
Speaker: 朱永峰
Material: **Slides**

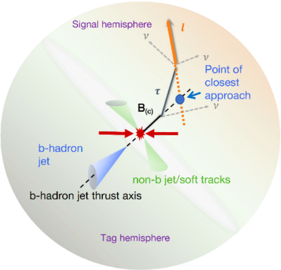
Flavor Physics White Paper

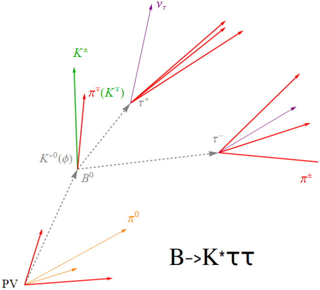
- To quantify CEPC flavor physics potential with benchmark analyses, and global interpretation.
- To guide the design/optimization of the facility & maximize the physics output.

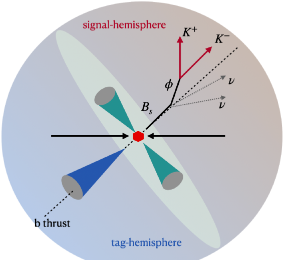
Contents

- (Semi)leptonic b decays.
- EW penguin b rare decays.
- Hadronic decays with neutrals.
- CKM matrix measurements.
- Lepton Flavor Violation in τ and Z decays.
- Exclusive Z hadronic decays.
- Detector benchmark studies.
- Hadronic spectroscopy and exotic states.
- Flavorful $\gamma\gamma$ fusion.

Pinning Down B Anomalies and LFUV







Charged current $b \to c\tau\nu$ decays [Zheng et al., 2020, Amhis et al., 2021]. Absolute precision $\sim 10^{-4}$.

Neutral current $b \to s\tau\tau$ decays [Li and Liu, 2020].

Absolute precision $\lesssim 10^{-6}$: $\sim 10^3 - 10^4$ improvement from current limits.

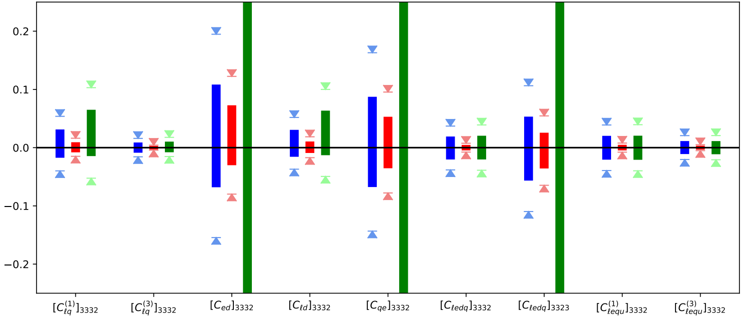
Neutral current $B_s \to \phi\nu\bar{\nu}$ decay [In preparation]

Not an anomaly yet but closely related

Absolute precision $\sim 10^{-7}$.

Unique opportunities at the Z-pole

Constraint on LFUV Operators (Prelim.)



$\Uparrow$ Tera-Z, $10\times$Tera-Z, Tera-Z but forgot $b \to s\tau\tau$

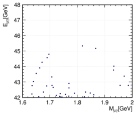
(The worst three $\sim \mathcal{O}(0.5)$.)

Probing ~ 10 TeV scale for $\mathcal{O}(1)$ couplings.

Lepton Flavor Violation Materials from Dan Yu's talk

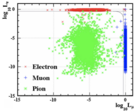
LFV — $\tau \to \mu(e)\gamma$

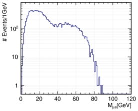
- Physics background: $Z \to \tau\tau\gamma$, $\tau \to \mu\nu\nu$
- Current bound: 2.7×10^{-8} (Babar) FCC-ee estimation: 2×10^{-9}
- Key distribution: $M(\mu\gamma)$, $E(\mu\gamma)$
  - Signal resolution: $\sigma(m)$ = 26 MeV, $\sigma(E)$=850MeV (Ecal energy resolution ⊕ Track momentum resolution ⊕ Position resolution, from Mogens' paper)
  - Background surviving: 1*SF ~ 25k
- Sensitivity: 10^{-10}



LFV — $Z \to \mu e$

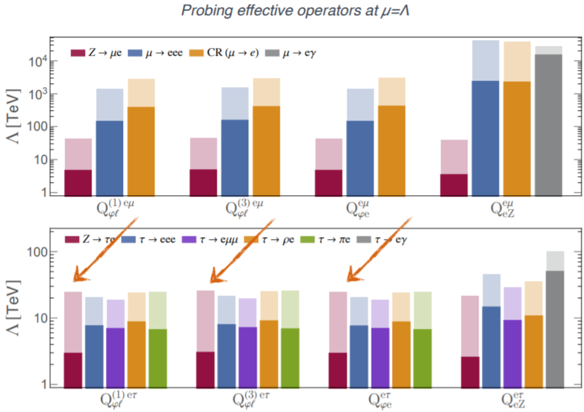
- Physics background: $Z \to$ bhabha/$\mu\mu$/$\tau\tau$
- Current bound: 7.5×10^{-7} (ATLAS)
  - FCC-ee estimation: 10^{-9}
- Key distribution:
  - μ/e mis-id rate: by sacrificing the id efficiency, barely bhabha/$\mu\mu$ surviving (except for muon decay: 10^{-7})
  - Invariant mass: no $\tau\tau$ surviving
- Sensitivity ~ 10^{-10}





CEPCWS2021 22

Channel	$Z\to\tau\mu$	$Z\to\mu e$	$\tau\to\mu\gamma$	$\tau\to 3\mu$	$Z\to\pi\pi$	$Z\to\pi^+\pi^-\pi^0$	$Z\to J/\psi\ \gamma$	$Z\to\rho\gamma$	$Z\to\pi^{+/-} W^{-/+}$
Current Bounds/ BR prediction	1.2×10^{-5}	7.5×10^{-7}	4.4×10^{-8}	2.1×10^{-8}	10^{-12}	10^{-8} ~10^{-5}	2.6×10^{-6}	10^{-9}	7.5×10^{-5}
Earlier Estimation	10^{-9}	10^{-9}	10^{-9}	10^{-10}	-	-	10^{-8}	10^{-9}	10^{-10}
FullSim Estimation	10^{-9}	10^{-9}	10^{-10}	10^{-10}	10^{-10}	10^{-9}	10^{-9} ~10^{-10}	10^{-9}	10^{-10}

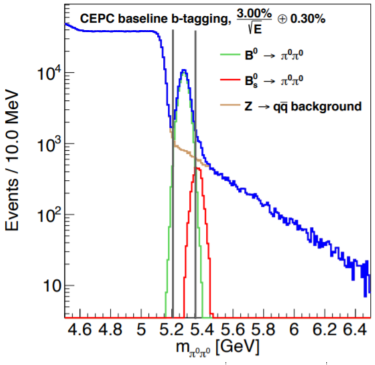


Powerful limits when combining Z and τ LFV decay channels!

Hadronic and Inclusive B Decays

Materials from Hanhua Cui's and Yuexin Wang's talk.

Fully neutral $B_{(s)} \to 2\pi^0$ channel:



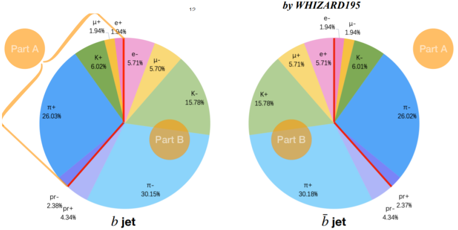
Accuracy	$B^0 \to \pi^0\pi^0$	$B^0_s \to \pi^0\pi^0$
$17\%/\sqrt{E} \oplus 1\%$ (CEPC baseline)	~1.32%	~23.1%
$3\%/\sqrt{E} \oplus 0.3\%$ (σ_{mB} ~30 MeV)	~0.44%	~4.4%

~36 times better than the current world average precision
~5 times better than the anticipated accuracy at the Belle II

$Z \to b\bar{b}$ **Percent of B hadrons of b jet and $\bar{b}$ jet**

percent (bbar jet →, b jet ↓)	B^0	B^+	B_s^0	B_c^+	$\Lambda_b$bar	others	all
B^0bar	17.360%	17.350%	3.369%	0.022%	2.759%	0.688%	41.548%
B^-	17.350%	17.359%	3.364%	0.022%	2.765%	0.689%	41.550%
B_s^0bar	3.355%	3.362%	0.652%	0.004%	0.545%	0.144%	8.062%
B_c^-	0.022%	0.022%	0.004%	0.00003%	0.004%	0.001%	0.052%
Λ_b	2.762%	2.762%	0.543%	0.004%	0.451%	0.121%	6.644%
others	0.653%	0.655%	0.136%	0.001%	0.119%	0.579%	2.144%
all	41.503%	41.511%	8.068%	0.053%	6.641%	2.225%	100%

by WHIZARD195



Inclusive flavor charge tagging

CKM Measurements

FCC-ee proposed target [Abada et al., 2019]:

Observable / Experiments	Current W/A	Belle II (50 /ab)	LHCb-U1 (23/fb)	FCC-ee
CKM inputs				
γ (uncert., rad)	$1.296^{+0.087}_{-0.101}$	1.136 ± 0.026	1.136 ± 0.025	1.136 ± 0.004
$\|V_{ub}\|$ (precision)	5.9%	2.5%	6%	1%
Mixing-related inputs				
$\sin(2\beta)$	0.691 ± 0.017	0.691 ± 0.008	0.691 ± 0.009	0.691 ± 0.005
ϕ_s (uncert. rad 10^{-2})	-1.5 ± 3.5	n/a	-3.65 ± 0.05	-3.65 ± 0.01
Δm_d (ps^{-1})	0.5065 ± 0.0020	same	same	same
Δm_s (ps^{-1})	17.757 ± 0.021	same	same	same
$a^d_{\rm fs}$ (10^{-4}, precision)	23 ± 26	-7 ± 15	-7 ± 15	-7 ± 2
$a^s_{\rm fs}$ (10^{-4}, precision)	-48 ± 48	n/a	0.3 ± 15	0.3 ± 2

The goal at CEPC shall be similar, but validation is necessary.

CPV in mixing, BSM may not contain an m_c^2/m_b^2 suppressions specific to the SM

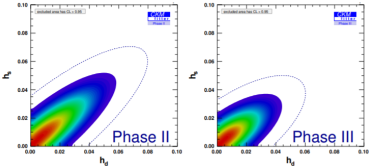
[hep-ph/0202010]

$$A_{\rm SL} = \frac{\Gamma[\overline{B}^0(t) \to \ell^+ X] - \Gamma[B^0(t) \to \ell^- X]}{\Gamma[\overline{B}^0(t) \to \ell^+ X] + \Gamma[B^0(t) \to \ell^- X]}$$

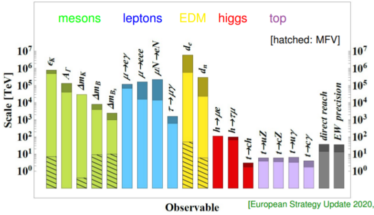
In large classes of BSM models, the dominant deviations from the SM may be in neutral meson mixing amplitudes, with smaller impacts on decay rates

Tera-Z expectation: exp uncertainty $\sim 2.5 \times 10^{-5}$ for both

Removing the bottle neck from $|V_{cb}|$ measurements:



Contribution from the WW mode



[European Strategy Update 2020, arXiv:1910.11775]

Opportunities to observe CP violating scales $\gg$ TeV!

Summary

- CEPC is a powerful machine to study flavor physics.
- Flavor studies at CEPC benefit from:
  1. Large luminosity (from accelerator physics)
  2. Clean environment and moderate energy (from m_Z)
  3. Good or even revolutionary detectors (from detector R&D)
- We need a white paper to form the consensus about what should be done, what chould be done, and what we have done.

- Abada, A. et al. (2019).
  FCC Physics Opportunities.
  Eur. Phys. J., C79(6):474.

- Amhis, Y., Hartmann, M., Helsens, C., Hill, D., and Sumensari, O. (2021).
  Prospects for $B_c^+ \to \tau^+ \nu_\tau$ at FCC-ee.

- Li, L. and Liu, T. (2020).
  $b \to s\tau^+\tau^-$ Physics at Future Z Factories.

- Zheng, T., Xu, J., Cao, L., Yu, D., Wang, W., Prell, S., Cheung, Y.-K. E., and Ruan, M. (2020).
  Analysis of $B_c \to \tau\nu_\tau$ at CEPC.