Flavour opportunities of a Z factory in CEPC

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Flavour in the LHC era

- **Flavour observables** are sensitive probes to physics beyond the SM
  ➜ often probing energy scales $\Lambda \gg$ TeV
- Part of the **high-intensity** frontier of **indirect probes of NP**
  ➜ new particles need not be produced resonantly
- An active flavour program complements direct searches for NP
  ➜ if NP inaccessible at present/next-generation colliders, indirect probes of NP our best way to discover NP

Multiple ongoing/future experiments, here focus:

present **LHCb**

close future **Belle-2**

more distant future **a Z factory at the CECP**?

LHCb and Belle 2

LHCb

- pp collisions, hadronic environment
- forward detector, small acceptance
- at high-luminosity stage: $\mathcal{L} = 50\text{ab}^{-1}$.

Belle-2

- the B-factory legacy continues, first physics run in 2019
- threshold production of $b\bar{b}$ resonances from e^+e^-
- "cleaner environment", less hadronic activity
- phase-space limitations due to threshold production
- target goals $\mathcal{L} = 50\text{ab}^{-1}$ on $\Upsilon(4S)$ producing B^0's
  ($\mathcal{L} = 5\text{ab}^{-1}$ on $\Upsilon(4S)$ producing B_s's? Not clear at this stage.)

Qualitative differences to the Z factory at CEPC

Tera-Z at CEPC

- **production of 10^{12} Z's**
- ✓ no phase-space limitations like at Belle-2
- ✓ 4π coverage
- ✓ LEP environment, less hadronic activity than at LHCb
- ✘ larger $\sqrt{s}$ than at Belle-2, more hadronic activity
- ✓ decay products of Z **more boosted** than at Belle 2
  more separation in lab-frame, better experimental resolution?

It is **not clear (and process specific)** whether the combination of higher **hadronic activity** but larger **boost** is **beneficial** for CEPC. Input and dedicated studies needed.

Particle production

Particle	@ Tera-Z	@ Belle II		@ LHCb
***b* hadrons**				
B^+	6×10^{10}	3×10^{10}	$(50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S))$	3×10^{13}
B^0	6×10^{10}	3×10^{10}	$(50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S))$	3×10^{13}
B_s	2×10^{10}	3×10^{8}	$(5\,\mathrm{ab}^{-1}$ on $\Upsilon(5S))$	8×10^{12}
b baryons	1×10^{10}			1×10^{13}
Λ_b	1×10^{10}			1×10^{13}
***c* hadrons**				
D^0	2×10^{11}			
D^+	6×10^{10}			
D_s^+	3×10^{10}			
Λ_c^+	2×10^{10}			
τ^+	3×10^{10}	5×10^{10}	$(50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S))$	

From CEPC's CDR using fragmentation ratios from Amhis et al, 17

- Similar statistical sample of $B^{0,\pm}$, τ's at Belle 2 and CEPC
- Two order of magnitude more B_s at CEPC wrt to Belle 2
- b-baryon physics possible at the CEPC
- Limited possibilities for charm physics at Belle 2

Questions

First/rough estimation of CEPC's sensitivity to flavour observables

Aim:

- Focus on observables sensitive to NP (here mainly B/τ physics)
- Compare to LHCb's and Belle 2's sensitivity
- Identify channels for which CEPC outperforms LHCb and Belle 2

"Method":

- LEP similar environment to the tera-Z at CEPC
  ➜ Whenever possible rescale LEP bounds with statistics
- Otherwise naive rescaling of Belle 2 projections
  ✘ Caveat: Z and Υ-pole physics not identical

(very rough first estimates, should be followed by dedicated studies)

Outline

- Rare leptonic B decays, $B_{s,d} \to \ell\ell$
- Rare semileptonic B decays, $b \to s\ell\ell$
- Rare B decays with missing energy, $b \to s(d)\nu\nu$
- Lepton universality in $\tau \to \ell\nu\nu$
- Flavour violating Z decays

- Summary and outlook

$$\boldsymbol{B_{s,d} \to \ell^+\ell^-}$$

- highly suppressed in the SM (helicity/Cabibbo suppressed)
- accurate SM predictions $\simeq 10\%$ dominated by parametric uncertainties
  $\mathrm{BR_{SM}}(B_s \to ee) \sim 10^{-14}$, $\mathrm{BR_{SM}}(B_d \to ee) \sim 10^{-15}$,
  $\mathrm{BR_{SM}}(B_s \to \mu\mu) \sim 10^{-9}$, $\mathrm{BR_{SM}}(B_d \to \mu\mu) \sim 10^{-10}$,
  $\mathrm{BR_{SM}}(B_s \to \tau\tau) \sim 10^{-7}$, $\mathrm{BR_{SM}}(B_d \to \tau\tau) \sim 10^{-8}$

  [Bobeth et al, 14]
- sensitive probes of NP ($\tan\beta$ enhancement in SUSY/2HDM scenarios)
- muonic mode $\boldsymbol{B_s \to \mu^+\mu^-}$ first observed at LHCb

Muonic/Electronic modes

- LHCb expected sensitivity 10^{-10} (muonic) few$\times 10^{-10}$ (electronic)

  [Albrecht et al, 17]

- Linear rescaling of L3 collaboration bound from full LEP-I data sample (3×10^5 B_d and 9×10^4 B_s, mostly background-free measurement)

  [Acciarri et al, 97]

$$\mathrm{BR}(B_s \to e^+e^-)_{\text{tera-}Z} \sim 4 \times 10^{-10}$$
$$\mathrm{BR}(B_d \to e^+e^-)_{\text{tera-}Z} \sim 8 \times 10^{-11}$$
$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\text{tera-}Z} \sim 3 \times 10^{-10}$$
$$\mathrm{BR}(B_d \to \mu^+\mu^-)_{\text{tera-}Z} \sim 7 \times 10^{-11}$$

- **muonic mode:** LHCb will likely outperform CEPC by a factor of few
- **electronic mode:** CEPC's sensitivity competes with LHCb's

The rare decays $B_{s(d)} \to \ell^+\ell^-$ III

Tauonic mode

- uncharted territory
- existing bound from BaBar orders of magnitude away from SM
- very challenging at LHCb and no LEP result
- Belle 2 sensitivity to $B_d \to \tau\tau$ approximately 10^{-4} [Belle II Physics Book, 18]
- Similar sensitivity at CEPC **if boost does not help**
- Rescale LEP muonic bound assuming ratio as in Belle 2

$$\text{BR}(B_d \to \tau^+\tau^-)_{\text{tera-}Z} < 4 \times 10^{-6}$$
$$\text{BR}(B_s \to \tau^+\tau^-)_{\text{tera-}Z} < 2 \times 10^{-5}$$

- potentially more than an **order-of-magnitude improvement**

Exclusive decays: $B \to K^{(*)}\ell\ell$

Muonic/Electronic modes

- ✘ not as rare and clean
- ✓ 3-body decays, more observables (angular distributions, CP asymmetries, etc)
- 2-3σ tensions in current LHCb data (lepton-flavour universality violation, P_5')
- LHCb will outperform Belle 2 (CEPC's sensitivity similar to Belle 2)
- **if tensions persist**, CEPC's **independent data sample** will be **invaluable**
- ✓ **inclusive measurements** also possible at CEPC (as in Belle 2), $B \to X_s\mu\mu$ (inaccesible at LHCb)

Exclusive decays: $B \to K^{(*)}\tau\tau$

Tauonic modes

- uncharted territory (BaBar bound, 10^{-3}, orders of magnitude away from SM)
- expect improvements at Belle 2, BR$(B^+ \to K^+\tau\tau) < 2 \times 10^{-5}$ [Belle 2 Physics Book]
- FCC-ee study: 1000 reconstructed events from $B_d \to K^*\tau\tau$, **probe BR$\sim 10^{-8}$ at CEPC** [Kamenik et al, 17]
- See talk by Simon Wehle on Tuesday
- **additional channels** available at CEPC, e.g., $B_s \to \phi\tau\tau$, $\Lambda_b \to \Lambda\tau\tau$
- tera-Z at CEPC can provide the best (and only) measurements

Exclusive decays: $B \to K^{(*)}/\rho/\pi\nu\nu$

- rare ($BR_{SM} \sim 10^{-6}$) and theoretically "clean" decays

  ($\sim 10\%$ th. uncertainties, parametric and form factors)

- interplay with $K \to \pi\nu\nu$ decays searched for at NA62 and KOTO

- neutrinos not tagged

  ➜ bounds on decays to light "invisible" NP particles, e.g., axiflavon

  [Calibbi et al, 17]

- not yet observed, target measurements at Belle 2, goal BR $\sim 10^{-6}$

- expect similar sensitivity of CEPC to $B \to K^{(*)}\nu\nu$, $B \to \pi\nu\nu$, $B \to \rho\nu\nu$

  (same results from rescaling LEP bounds)

  Caveat: as long as calorimetric isolation not an issue

Decays with missing energy $b \to s(d)\nu\nu$ II

- with respect to Belle 2, factor 100 more B_s produced plus 10^{10} b-baryons
- **new channels become available** at CEPC:

$$B_s \to \phi\nu\nu \quad \Lambda_b \to \Lambda\nu\nu$$

- CECP's sensitivity similar to $B \to K\nu\nu$: **BR** $\boldsymbol{\sim 10^{-6}}$
- multiple probes of members of the same family of decays:
  pseudoscalar–pseudoscalar
  pseudoscalar–vector
  fermion–fermion transitions
- probe multiple dimesions-six operators, disentangle NP contributions from **right-handed currents**
- **a unique opportunity for the CEPC**

τ decays: lepton universality I

- current best measurements of $\tau \to \ell\nu\nu$ from LEP

$$\text{BR}(\tau \to e\nu_\tau\bar{\nu}_e) = (17.319 \pm 0.070 \pm 0.032)\%$$
$$\text{BR}(\tau \to \mu\nu_\tau\bar{\nu}_\mu) = (17.837 \pm 0.072 \pm 0.036)\%$$

[ALEPH, Schael et al, 05]

- LEP measurement are statistics limited
- number of $\tau\tau$ pairs at CEPC and Belle 2: $\approx 10^{10}$
- assuming systematic uncertainties reduced by factor of 10
  ➜ **CEPC/Belle2 measurement with relative a 0.01% uncertainty!**
- Similarly, expect order of magnitude improvement in measurement of **τ lifetime** (current uncertainty from Belle 0.2%)

τ decays: lepton universality II

$$\boldsymbol{R_\tau = \frac{\mathrm{BR}(\tau \to \mu\bar{\nu}_\mu\nu_\tau)}{\mathrm{BR}(\tau \to e\bar{\nu}_e\nu_\tau)}}$$

- highly accurate SM prediction $R_\tau^{\mathrm{SM}} = 0.972559 \pm 0.000005$ [Pich, 14]
- independent of τ lifetime
- current measurement $R_\tau^{\mathrm{BaBar}} = 0.9796 \pm 0.0016 \pm 0.0036$ [Aubert et al, 10]
- based on statistics and reduced systematics
  ➜ 0.1% precision feasible at the CEPC
- important if current tensions $R_{K^{(*)}}$, $R_{D^{(*)}}$ persist
  ➜ typical NP effects in R_τ at the few permille level

Flavour violating Z decays

Quark sector: $Z \to qq'$

- suppressed in SM: $\text{BR}(Z \to bs) \sim \left|\frac{g^2}{16\pi^2} V_{tb} V_{ts}^*\right|^2 \times \text{BR}(Z \to bb) \sim 10^{-9}$
- NP enhancement possible but constrained by rare decays / mixing
- too challenging measurement due to large dijet background

Lepton sector: $Z \to \ell\ell'$

- tiny in SM BR $10^{-50} - 10^{-60}$
- tightest current bounds from LEP (mostly background free)
- rescaling with statistics

$$\text{BR}(Z \to \mu e)_{\text{CEPC}} \lesssim 3 \times 10^{-9} \;\; [1/\sqrt{N} \text{ scaling}]\,, \;\; 7 \times 10^{-12} \;\; [1/N \text{ scaling}]$$
$$\text{BR}(Z \to \tau e)_{\text{CEPC}} \lesssim 2 \times 10^{-8} \;\; [1/\sqrt{N} \text{ scaling}]\,, \;\; 4 \times 10^{-11} \;\; [1/N \text{ scaling}]$$
$$\text{BR}(Z \to \tau \mu)_{\text{CEPC}} \lesssim 2 \times 10^{-8} \;\; [1/\sqrt{N} \text{ scaling}]\,, \;\; 5 \times 10^{-11} \;\; [1/N \text{ scaling}]$$

- **more than an order of magnitude improvement** feasible at the CEPC
  (unique sensitivity to NP models with lepton-flavour violation in Z decays, heavy sterile ν's)

Highlights

[From CEPC's CDR]

Observable	Current sensitivity	Future sensitivity	Tera-Z sensitivity
$\mathrm{BR}(B_s \to ee)$	2.8×10^{-7} (CDF) [10]	$\sim 7 \times 10^{-10}$ (LHCb) [18]	$\sim$ few $\times 10^{-10}$
$\mathrm{BR}(B_s \to \mu\mu)$	0.7×10^{-9} (LHCb) [8]	$\sim 1.6 \times 10^{-10}$ (LHCb) [18]	$\sim$ few $\times 10^{-10}$
$\mathrm{BR}(B_s \to \tau\tau)$	5.2×10^{-3} (LHCb) [9]	$\sim 5 \times 10^{-4}$ (LHCb) [18]	$\sim 10^{-5}$
R_K, R_{K^*}	$\sim 10\%$ (LHCb) [5, 4]	$\sim$few% (LHCb/Belle II) [18, 40]	$\sim$few %
$\mathrm{BR}(B \to K^* \tau\tau)$	–	$\sim 10^{-5}$ (Belle II) [40]	$\sim 10^{-8}$
$\mathrm{BR}(B \to K^* \nu\nu)$	4.0×10^{-5} (Belle) [44]	$\sim 10^{-6}$ (Belle II) [40]	$\sim 10^{-6}$
$\mathrm{BR}(B_s \to \phi\nu\bar{\nu})$	1.0×10^{-3} (LEP) [15]	–	$\sim 10^{-6}$
$\mathrm{BR}(\Lambda_b \to \Lambda\nu\bar{\nu})$	–	–	$\sim 10^{-6}$
$\mathrm{BR}(\tau \to \mu\gamma)$	4.4×10^{-8} (BaBar) [24]	$\sim 10^{-9}$ (Belle II) [40]	$\sim 10^{-9}$
$\mathrm{BR}(\tau \to 3\mu)$	2.1×10^{-8} (Belle) [37]	$\sim$ few $\times 10^{-10}$ (Belle II) [40]	$\sim$ few $\times 10^{-10}$
$\frac{\mathrm{BR}(\tau \to \mu\nu\bar{\nu})}{\mathrm{BR}(\tau \to e\nu\bar{\nu})}$	3.9×10^{-3} (BaBar) [23]	$\sim 10^{-3}$ (Belle II) [40]	$\sim 10^{-4}$
$\mathrm{BR}(Z \to \mu e)$	7.5×10^{-7} (ATLAS) [3]	$\sim 10^{-8}$ (ATLAS/CMS)	$\sim 10^{-9} - 10^{-11}$
$\mathrm{BR}(Z \to \tau e)$	9.8×10^{-6} (LEP) [17]	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8} - 10^{-11}$
$\mathrm{BR}(Z \to \tau\mu)$	1.2×10^{-5} (LEP) [13]	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8} - 10^{-10}$

Conclusions and Outlook

- 10^{12} Z bosons at the CEPC produce many b/c hadrons and τ's

  (BR($Z \to b\bar{b}$) $\sim 15\%$ BR($Z \to c\bar{c}$) $\sim 12\%$ BR($Z \to \tau\bar{\tau}$) $\sim 3\%$)

- It will be possible to build a **competitive** and, in specific channels, **leading** flavour program at the CEPC

- Demostrated that **key measurements involve** B_s, b-baryons, and τ's

- **Dedicated studies** are absolutely **necessary** for more realistic assessment of CEPC's sensistivity

  ➜hadronic activity and boost important to compare with Belle 2

- Flavour program much richer: B_c decays, charm-physics program, …

- Results from LHCb and Belle 2 may guide and elevate CEPC's flavour efforts