What can a circular collider in the Z pole add to flavour factories?

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IP2I / Lyon University (FR)

International Workshop on the Circular Electron-Positron Collider
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Why Flavour?

Flavour Physics

Standard Model parameters:

3 gauge couplings

2 Higgs parameters

6 quark masses

3 quark mixing angles + 1 phase

3 (+3) lepton masses

(3 lepton mixing angles + 1 phase)

( ) = with neutrino masses

Flavour Parameters

Flavour is at the heart of the Standard Model!

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Flavour Parameters

Flavour is at the heart of the Standard Model!

Still, there is no explanation for the flavour structure of the Standard Model!

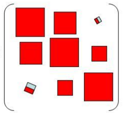
↦ The Standard Model flavour puzzle

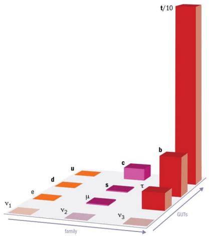
And several other fundamental questions remain unanswered:

↦ The New Physics flavour puzzle

↦ CP violation (new sources of CP violation are needed for baryogenesis)

CKM





Indirect search for NP

Flavour physics offers a range of observables sensitive to physics beyond the SM

- Flavour physics is sensitive to new physics at $\Lambda_{\rm NP} \gg E_{\rm experiments}$

  Flavour physics can discover new physics or probe it before it is directly observed in experiments

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Eratosthenes
discovered the roundness of Earth...

...about 2300 years before its direct observation!

Golden Channels

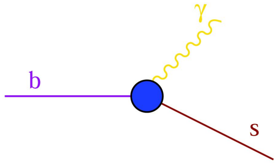
What Makes One?

- ➔ **Theoretical cleanliness:** e.g. ratios with reduced hadronic uncertainty
  $\rightarrow$ enhanced NP sensitivity
- ➔ **Experimentally visible** and reconstructible
- ➔ **Unique access** at CEPC: e.g., modes with neutrinos or photons
- ➔ **Discovery potential:** modes with low SM rates, high NP sensitivity

QCD at work

At the quark level, short-distance physics, described by electroweak part of Lagrangian

→ computed in perturbation theory



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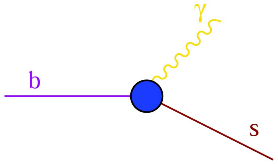
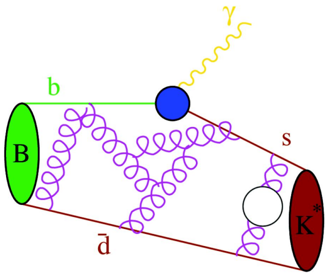


At the hadronic level, convoluted with long-distance physics, described by QCD

→ new hadronic quantities



Most studies rely on **QCD**, both **perturbatively** and **non-perturbatively**

Effective Theory

Basic idea: Fermi-like approach: separation between low and high energies

$$\mathcal{A}(A \to B) = \frac{G_F}{\sqrt{2}} \sum_i \lambda_i C_i \langle B|\mathcal{O}_i|A\rangle$$

Short distances: Wilson coefficients (perturbative)
Long distances: local operators (non-perturbative)

$$\mathcal{O}_7 \propto (\bar{s}\sigma^{\mu\nu} P_R) F^a_{\mu\nu}$$
$$\mathcal{O}_9 \propto (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell)$$
$$\mathcal{O}_{10} \propto (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \gamma_5 \ell)$$

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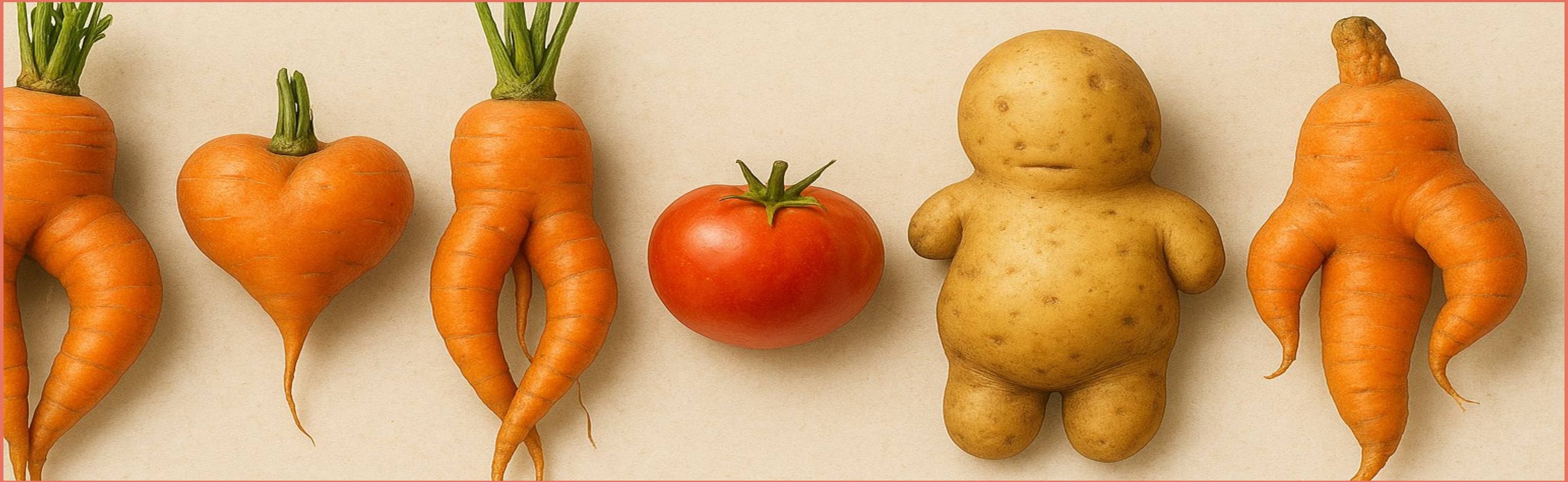
➔ Simplification of the problem, keeping only relevant degrees of freedom

➔ Can be applied to any process

➔ Easy implementation of New Physics (change C, new O)



Anomalies

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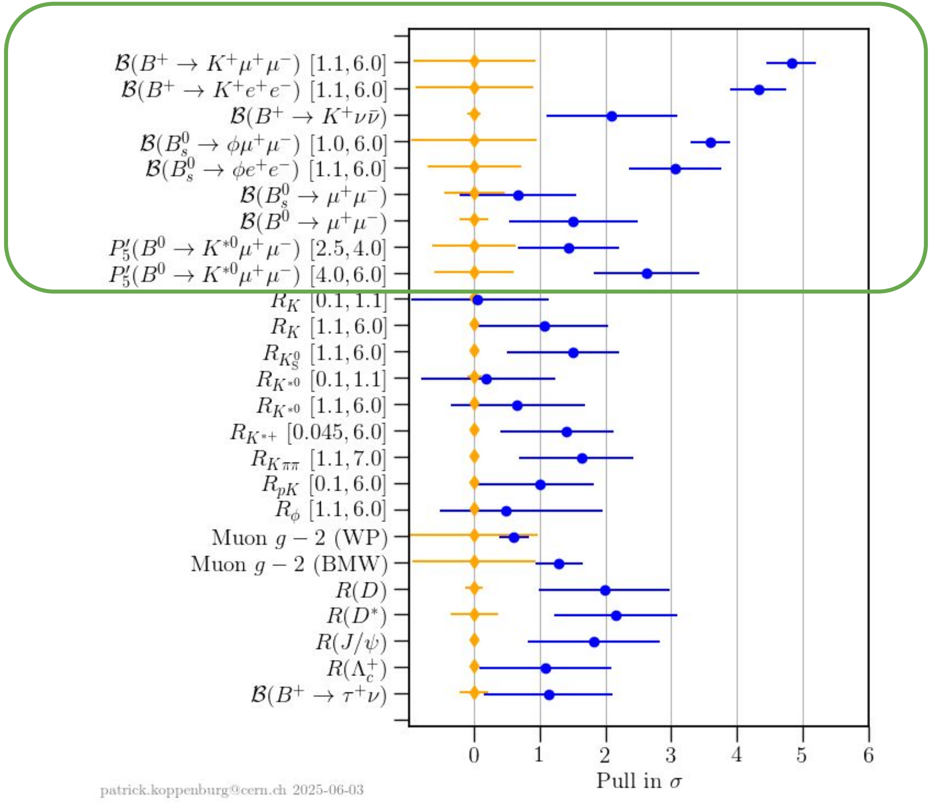
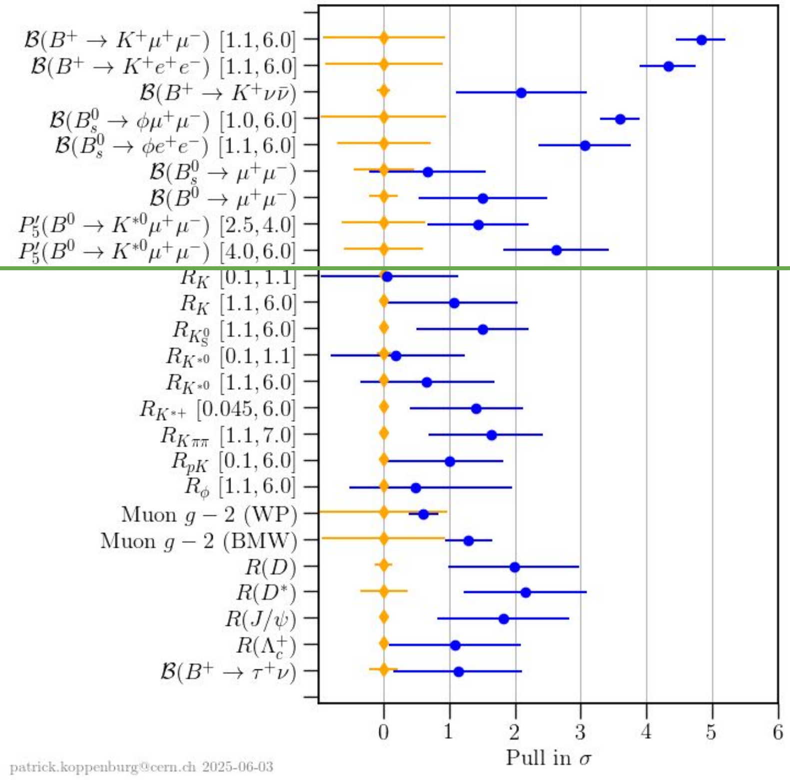


Significant tensions in the semileptonic decays

Anomalies



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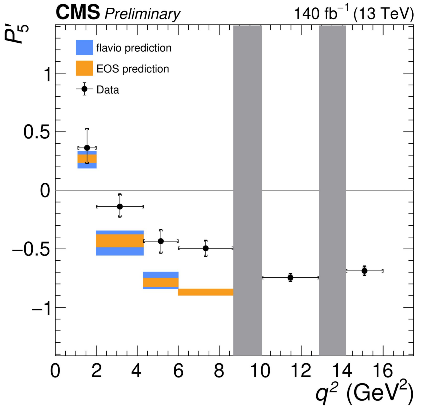
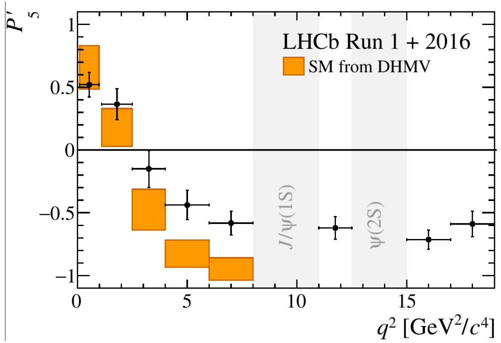


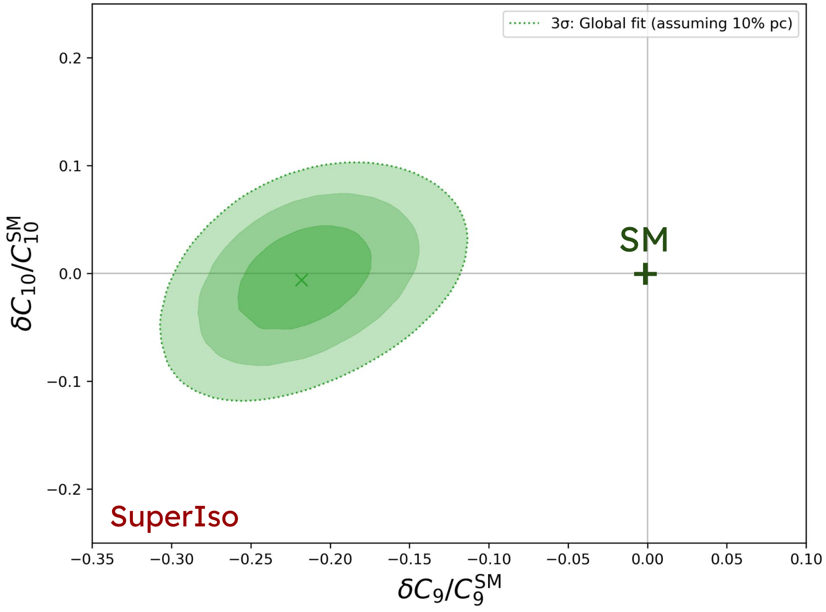
Phys.Lett.B 864 (2025) 139406



Phys. Rev. Lett. 125, 011802 (2020)

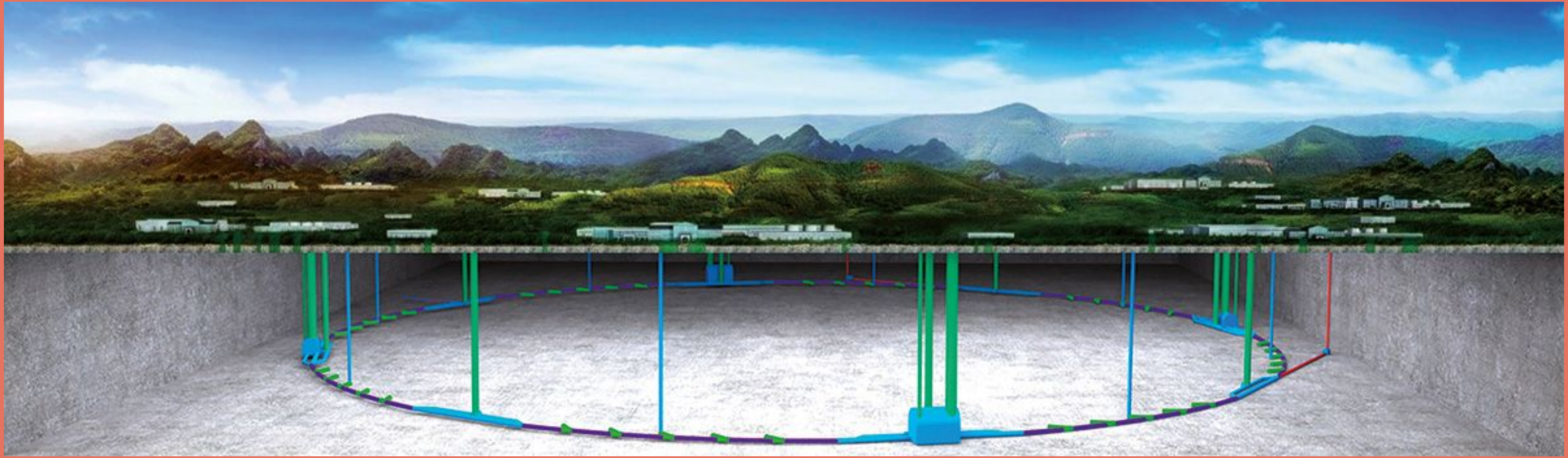
NP implication

Global fit to all available
$bs\ell\ell$ data



T. Hurth, FM, Y. Monceaux, S. Neshatpour, 2025

<u>Caveat</u>: given certain
assumptions for
hadronic uncertainties



Flavour at CEPC

CEPC and Flavour Physics

Key advantages:

- **High integrated luminosity** available at the CEPC Z pole
- **Clean experimental environment** from e^+e^- collisions
- **Advanced detector technology** and cutting-edge analysis techniques

The CEPC produces highly boosted heavy-flavour quarks and leptons
→ Their relativistic decay products enable precise momentum and lifetime measurements

Compared to hadron colliders, the CEPC offers better capabilities for identifying and reconstructing final states involving neutral or invisible particles

Uniqueness of CEPC flavour physics studies!

CEPC as a Z factory

- 4×10^{12} Z bosons in 2 years of running

- Clean e^+e^- collisions
  $\longrightarrow$ excellent signal reconstruction

The abundant production of bottom and charm quarks, as well as tau leptons from Z decays, create opportunities for a wide range of key flavour physics measurements

CEPC's Z pole statistics allow precision and rare probes that go beyond what current flavour factories provide!

Tera-Z in Numbers

Particle	BESIII	Belle II (50 ab^{-1} on $\Upsilon(4S)$)	LHCb (300 fb^{-1})	CEPC (4×Tera-Z)
B^0, $\bar{B}^0$	-	5.4×10^{10}	3×10^{13}	4.8×10^{11}
$B^\pm$	-	5.7×10^{10}	3×10^{13}	4.8×10^{11}
B_s^0, $\bar{B}_s^0$	-	6.0×10^8 (5 ab^{-1} on $\Upsilon(5S)$)	1×10^{13}	1.2×10^{11}
$B_c^\pm$	-	-	1×10^{11}	7.2×10^8
Λ_b^0, $\bar{\Lambda}_b^0$	-	-	2×10^{13}	1×10^{11}
D^0, $\bar{D}^0$	1.2×10^8	4.8×10^{10}	1.4×10^{15}	8.3×10^{11}
$D^\pm$	1.2×10^8	4.8×10^{10}	6×10^{14}	4.9×10^{11}
$D_s^\pm$	1×10^7	1.6×10^{10}	2×10^{14}	1.8×10^{11}
$\Lambda_c^\pm$	0.3×10^7	1.6×10^{10}	2×10^{14}	6.2×10^{10}
$\tau^+\tau^-$	3.6×10^8	4.5×10^{10}		1.2×10^{11}

CEPC White paper, 2412.19743

- Orders of magnitude more charm, bottom, and tau hadrons than Belle II
- Statistically competitive with LHCb, but with much cleaner environment

Both FCC-ee and ILC feature a Z factory phase

FCC-ee Z-pole run proposes an integrated luminosity (~180 ab^{-1}) comparable to that of CEPC

→ Some FCC-ee studies are therefore also relevant for CEPC

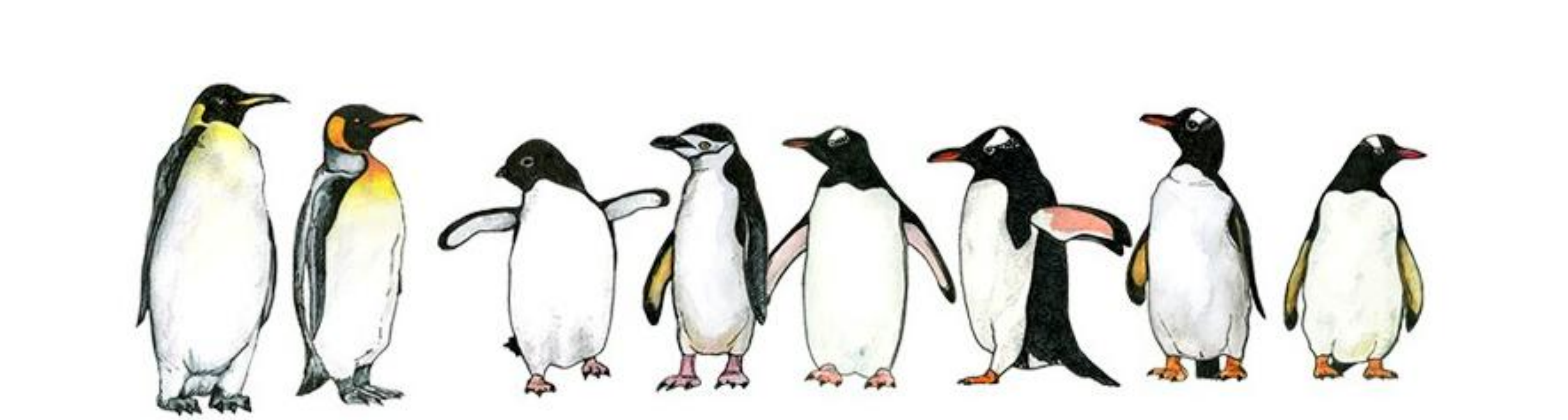
CEPC Challenges

- Improve background understanding and control systematic effects to avoid systematic uncertainties becoming dominant

- Multitude of viable channels to be studied
  $\rightarrow$ identifying the "**golden channels**"

- Control of theoretical uncertainties, in particular
  - Non-perturbative hadronic quantities
  - Perturbative QCD and electroweak corrections to Wilson coefficients
  - Lattice QCD calculations of heavy-flavour form factors

To rigorously test the SM and search for NP, the theoretical precision must match the accuracy of experimental measurements!



Observables

FCNC Decays

Flavour changing neutral currents are forbidden in the SM at tree level

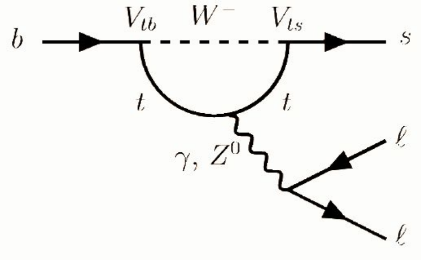
- SM: loop-suppressed
- suppressed by off-diagonal CKM matrix elements

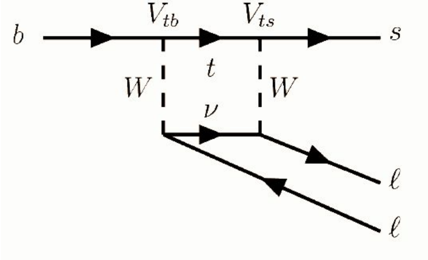
→ **excellent NP probes!**

- Operators: vector, axial, dipole, scalar

CEPC provides precise rates and angular observables with reduced backgrounds

$b \to s\ell^+\ell^-$





- A plethora of observables!
  - Branching ratios
  - Angular observables (e.g., P_5')
  - LFU ratios
- Can test flavour anomalies and fit new Wilson coefficients
- CEPC cleanly reconstructs full event
- Access to electron and muon modes equally

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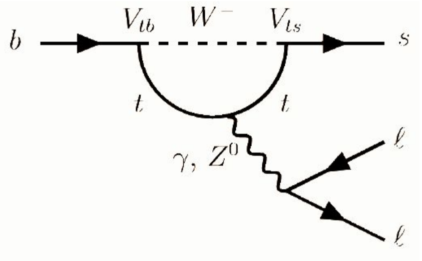

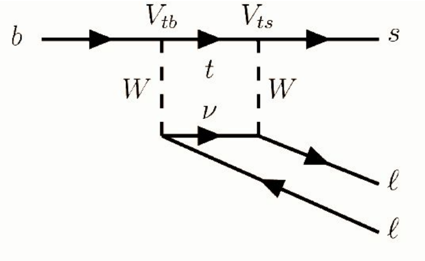

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- The **τ modes** can be accessible at the CEPC!

  Since τ decays produce neutrinos, $b \to s\tau\tau$ events are not fully visible

  $\to$ The reconstruction of $b \to s\tau\tau$ is more involved compared to $b \to see$, $s\mu\mu$

$b \to s\tau^+\tau^-$

Channel	Belle II [10]	LHCb [9]	Giga-Z	Tera-Z	10×Tera-Z
$B^0 \to K^{*0}\tau^+\tau^-$	-	-	$5.0^{+2.1}_{-1.5}(22, 27) \times 10^{-6}$	$1.6^{+0.7}_{-0.5}(6.8, 8.5) \times 10^{-7}$	$5.0^{+2.1}_{-1.5}(22, 27) \times 10^{-8}$
$B_s \to \phi\tau^+\tau^-$	-	-	$1.5^{+0.6}_{-0.4}(4.9, 5.9) \times 10^{-5}$	$4.8^{+1.9}_{-1.4}(15, 19) \times 10^{-7}$	$1.5^{+0.6}_{-0.4}(4.9, 5.9) \times 10^{-7}$
$B^+ \to K^+\tau^+\tau^-$	$< 2.0 \times 10^{-5}$	-	$4.4^{+1.6}_{-1.1}(19, 25) \times 10^{-6}$	$1.4^{+0.6}_{-0.3}(6.0, 8.0) \times 10^{-7}$	$4.4^{+1.6}_{-1.1}(19, 25) \times 10^{-8}$
$B_s \to \tau^+\tau^-$	$< 8.1 \times 10^{-4}$	5×10^{-4}	$4.9^{+0.9}_{-0.7}(5.6, 6.3) \times 10^{-4}$	$1.5^{+0.3}_{-0.2}(1.8, 2.0) \times 10^{-5}$	$4.9^{+0.9}_{-0.7}(5.6, 6.3) \times 10^{-6}$

Li, Liu, JHEP 06 (2021) 064

Because of their boost, signal b-hadrons travel farther before decaying, compared to, e.g., Belle II

A tracker-based reconstruction strategy for $b \to s\tau\tau$ has been developed

$b \to s\tau^+\tau^-$

Channel	Belle II [10]	L		10× Tera-Z
$B^0 \to K^{*0}\tau^+\tau^-$	-		0^{-7}	$5.0^{+2.1}_{-1.5}(22, 27) \times 10^{-8}$
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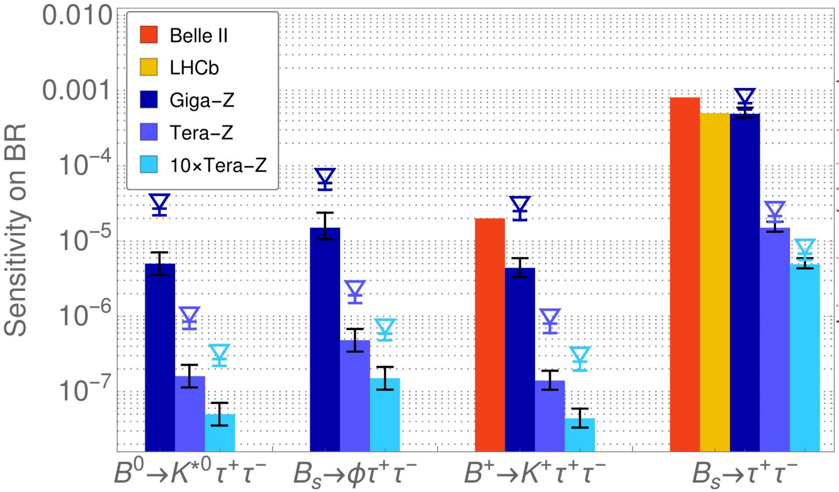

Li, Liu, JHEP 06 (2021) 064

Tera-Z can measure $B^0 \to K^{*0}\tau\tau$, $B_s^0 \to \phi\tau\tau$, $B^+ \to K^+\tau\tau$ with absolute precision of $O(10^{-7} - 10^{-6})$

can reach $O(10^{-6} - 10^{-5})$ precision for $B_s^0 \to \tau\tau$

Belle II and LHCb are either insensitive to these modes or limited to sensitivities **1-2 orders of magnitude weaker**

And more…

To cover different possible new physics directions:

- Use of differential observables such as **forward-backward asymmetry** and **τ polarimetry**

Kamenik et al., Eur. Phys. J. C 77 (2017) 701

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- LFU tests: Measurements of ratios like $R_K^{(*)}$, R_{pK} , R_ϕ , $R_{f_2'}(1525)$, and R_Λ offer additional insight to lepton flavour universality violation

  -> For some of these, **PID-related systematics** may dominate; but future detectors' **superior e/μ ID** capabilities can offer a significant advantage over LHCb

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- Exploration of $b \to d\ell^+\ell^-$ transitions remains an important complementary direction

  These are extremely hard to access at hadron colliders due to low rates and high backgrounds

CEPC White paper, 2412.19743

Neutrino modes: $b \to s\nu\bar{\nu}$

- SM: very clean theoretically, rare ($\sim 10^{-5}$)
- First evidence for $B^+ \to K^+\nu\bar{\nu}$ by Belle II is 2.7σ above the SM prediction
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- Invisible final states easy at CEPC, hard at LHCb
- CEPC can measure B^0 and baryon decays, which are not accessible at Belle II:

  $B^0 \to K^*\nu\bar{\nu}$ $B^0_s \to \varphi\nu\bar{\nu}$ $B^0 \to K^0_S\nu\bar{\nu}$ $\Lambda^0_b \to \Lambda^0\nu\bar{\nu}$ $\Xi^\pm_b \to \Xi^\pm\nu\bar{\nu}$

  CEPC can reach few-% precision!

Y. Amhis et al., JHEP01, 144 (2024)

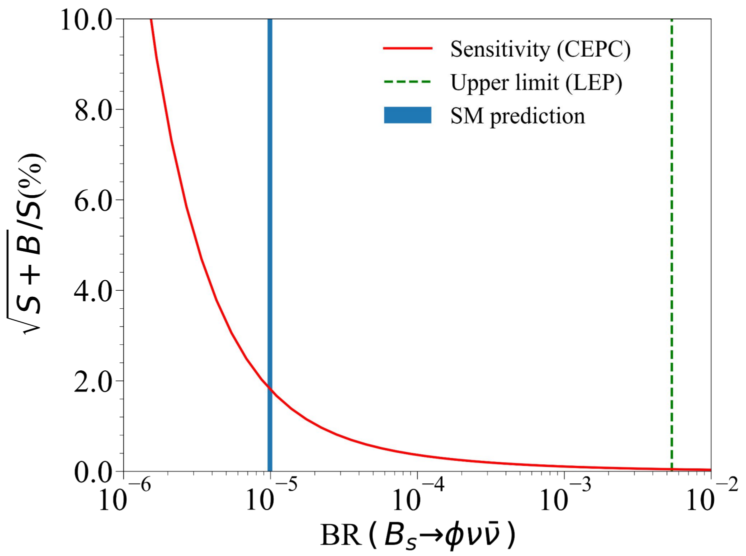
L. Li et al., Phys.Rev.D 105 (2022) 11, 114036

Unique opportunities at CEPC!

Neutrino Channels: $b \to s\nu\bar{\nu}$

$B^0_s \to \varphi\nu\bar{\nu}$

- Large B_s statistics at CEPC
- High signal-to-background ratio (≃77%)



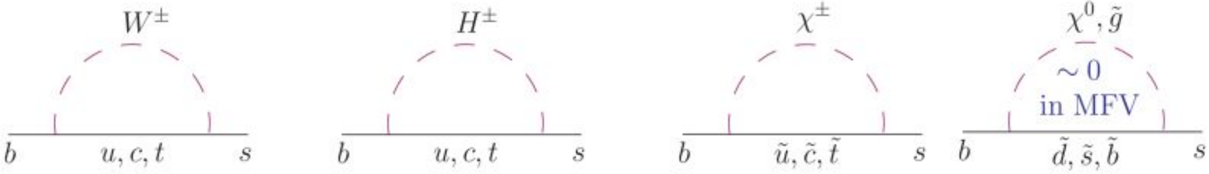
L. Li et al., Phys.Rev.D 105 (2022) 11, 114036

A relative precision ≲2% can be achieved for measuring the SM $B^0_s \to \varphi\nu\bar{\nu}$ signal

Radiative Decays: b → sγ

The first penguin ever observed!
(In 1994 by CLEO experiment)

Contributing loops:



SM | 2HDM | Supersymmetry

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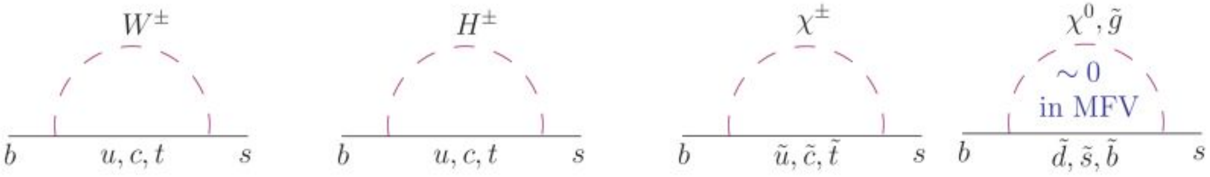

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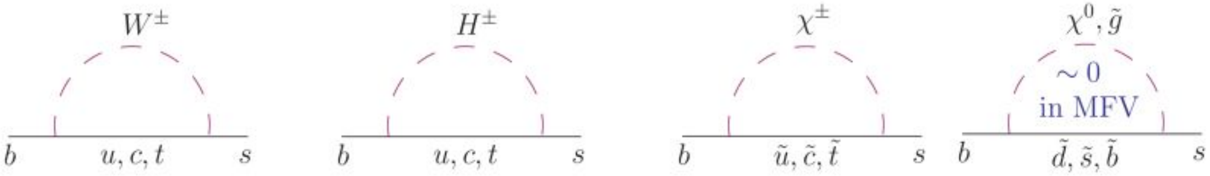

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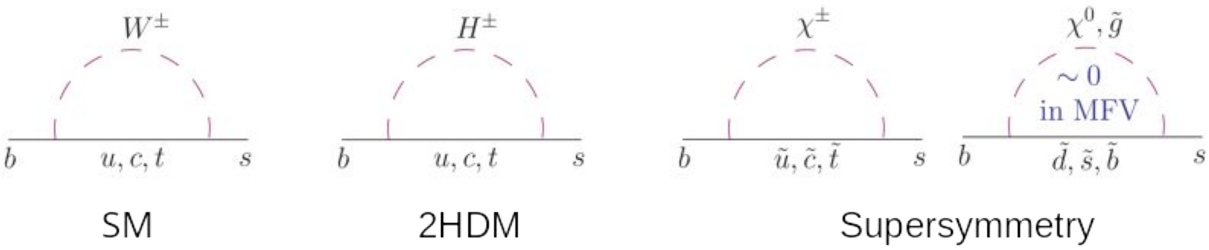

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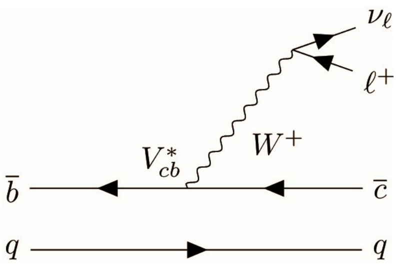
- Better sensitivities also for baryonic radiative decays: $\Lambda_b \to \Lambda\gamma$ and $\Xi_b \to \Xi\gamma$
- Double-radiative decays of $B_{s,d} \to \gamma\gamma$ could also be measured

FCCC Decays

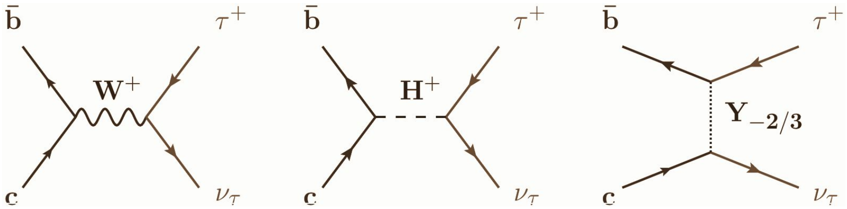


Main interests:

- Determining the values of the CKM matrix elements
  $b \to c\ell\nu$ and $b \to u\ell\nu$ can be used to extract $|V_{cb}|$ and $|V_{ub}|$
- Testing lepton flavour universality
  Particularly interesting: measurements involving τ decays
- Scalar/pseudoscalar operators probed via τ final states
- CEPC access to B_c, Λ_b
  new observables not accessible or planned to produce at B-factories
- Strong sensitivity in EFT framework

$B_c \to \tau\nu$: A Clean Window

$$\Gamma_{\rm SM}(B_c^+ \to l^+\nu_l) = \frac{G_F^2}{8\pi}|V_{cb}|^2 f_{B_c}^2 m_{B_c} m_l^2 \left(1 - \frac{m_l^2}{m_{B_c}^2}\right)^2$$



- Pure leptonic decay: theory clean

- Sensitive to scalar NP (2HDM, leptoquarks)

- Large SM branching ratio of $B_c \to \tau\nu$ ~ 2.3 × 10−2

- Current constraint relatively weak: BR($B_c \to \tau\nu$) ≲ 30%

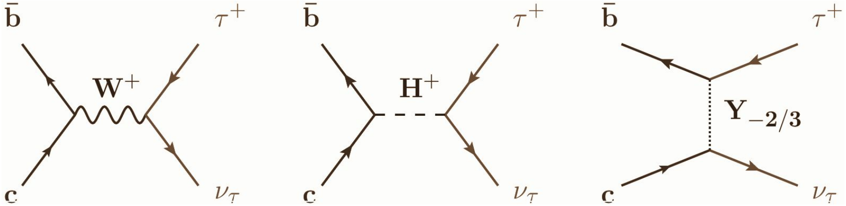
CEPC can measure this BR with a precision of O(10^{-4})

Zuo et al., Eur. Phys. J. C 84 (2024)

Zheng et al., Chin.Phys.C 45 (2021) 2, 023001

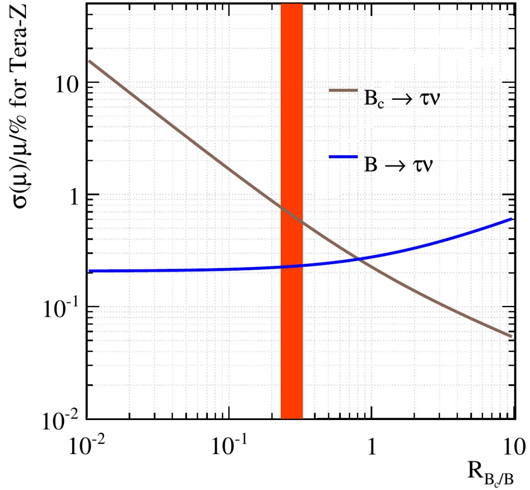
$B_c \to \tau\nu$: A Clean Window

$$\Gamma_{\rm SM}(B_c^+ \to l^+\nu_l) = \frac{G_F^2}{8\pi}|V_{cb}|^2 f_{B_c}^2 m_{B_c} m_l^2 \left(1 - \frac{m_l^2}{m_{B_c}^2}\right)^2$$



- CEPC expected precision:

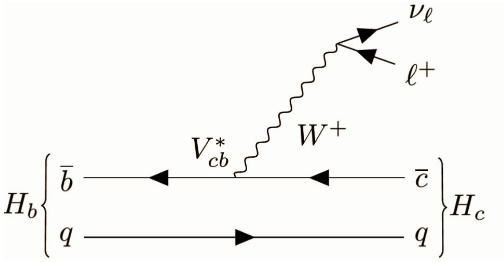
~1% on BR with 4×Tera-Z



Zheng et al., Chin.Phys.C 45 (2021) 2, 023001

Semileptonic LFU: Ratios

- Recent anomalies in R_K/R_D prompted focus on LFU
- CEPC adds new channels like $R_{J/\psi}$, $R_{\Lambda c}$, R_{Ds} with great precision
- SM predictions known, hadronic uncertainties cancel in ratios



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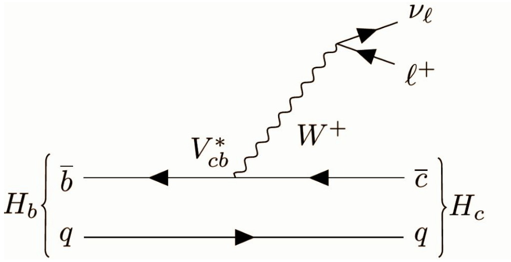
- SM predictions known, hadronic uncertainties cancel in ratios
- CEPC achieves sub-% statistical precision



Physical Quantity	SM Value	Tera-Z	10×Tera-Z	Belle II	LHCb
$R_{J/\psi}$	0.289	4.25×10^{-2}	1.35×10^{-2}	-	-
R_{D_s}	0.393	4.09×10^{-3}	1.30×10^{-3}	-	-
$R_{D_s^*}$	0.303	3.26×10^{-3}	1.03×10^{-3}	-	-
R_{Λ_c}	0.334	9.77×10^{-4}	3.09×10^{-4}	-	-

Ho et al., PRD 109 (2024) 093004

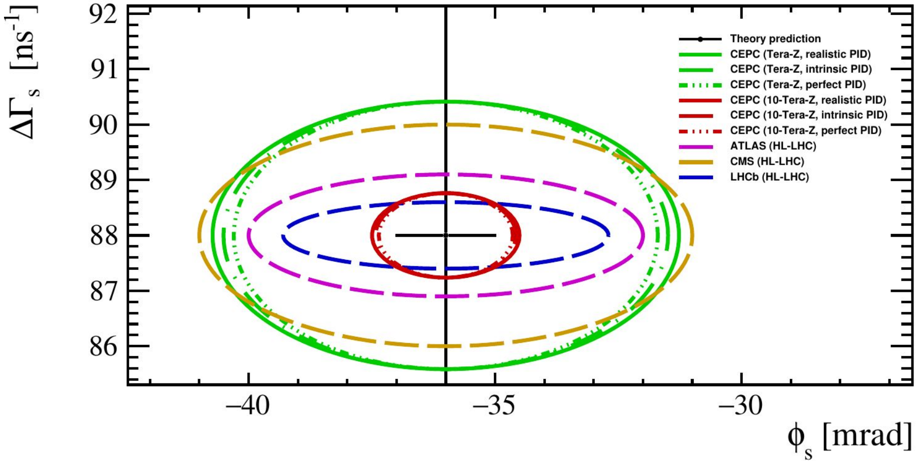
CP Violation: Targets

Important to address the puzzle of BAU

Example: Time-dependent CPV in $B_s \to J/\psi\phi$

CEPC advantages:

- high statistics
- low backgrounds
- efficient hadron ID
- excellent displacement resolution



X. Li, M. Ruan, M. Zhao, Eur. Phys. J. C 84 (2024) 859

R. Aleksan, L. Oliver, E. Perez, Phys. Rev. D105(2022) 053008

Charm Physics

In the SM: $BR(Z \to c\bar{c}) \simeq 12\%$ $\Rrightarrow$ CEPC can also serve as a charm factory!

- Semileptonic c-hadron decays
  - -> stronger GIM suppression than rare B decays
  - -> High sensitivity to NP
- LFU tests in $c \to u\ell^+\ell^-$ decays
- Search for LFV decays: $D \to \pi e\mu$, $D_s \to K e\mu$
- Angular distributions in $c \to u\ell^+\ell^-$
- Neutrino modes, eg $D \to \pi\nu\bar{\nu}$ and $D_s \to K\nu\bar{\nu}$
- Hadronic c-hadron decays, eg $D^0 \to K^0_S\, \pi^0$, $K^0_S\omega$, $K^0_S\varphi$
- …

More dedicated studies for CEPC are needed!

Strange Physics

The CEPC offers **promising reconstruction capabilities** for K_S^0 and Λ decays into a pair of charged tracks

with an efficiency $\gtrsim$80% and a purity ~95%

Zheng et al., Eur. Phys. J. Plus 135 (2020) 274

With over 10^{12} K_S^0 produced in hadronic Z decays, the CEPC will have **sensitivity to rare decays** like $K_S^0 \to \mu^+\mu^-$ and probing new physics

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Zheng et al., Eur. Phys. J. Plus 135 (2020) 274

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The CEPC sensitivity could also extend to rare decays involving additional neutral particles, e.g., $K_S^0 \to \mu^+\mu^-\gamma$ or $K_S^0 \to \mu^+\mu^-\pi^0$

-> Given their low rates, need for careful evaluation of systematic uncertainties

Other probes

τ Physics

- LFV: $\tau \to \mu\gamma$, 3μ
- LFU: $\tau \to e\nu\nu$ / $\mu\nu\nu$
- Hadronic τ = probe of QCD and structure
- CEPC: high stats and clean tau reconstruction!

Spectroscopy & Exotics

- Exotic hadrons (tetraquarks, glueballs)
- Displaced decays, ALPs, dark photons
- CEPC = ideal for long-lived searches

Summary

- CEPC Z pole run offers unprecedented flavour physics reach

- Unique opportunities in golden modes

- Complementary to Belle II, LHCb

Attribute	$\Upsilon(4S)$	pp	Z
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
High geometrical acceptance	✓		✓
Low backgrounds	✓		✓
Flavour-tagging power	✓		✓
Initial-energy constraint	✓		(✓)

J. F. Kamenik et al., Contribution to EPSSU 2025

More work needed for:

- Full study (Simulation) of relevant decays
- Identify golden modes at the CEPC that may have been overlooked as they are not suited for the existing experiments
- Theory needs to match precision

CEPC = a discovery machine for flavour

Thank You!