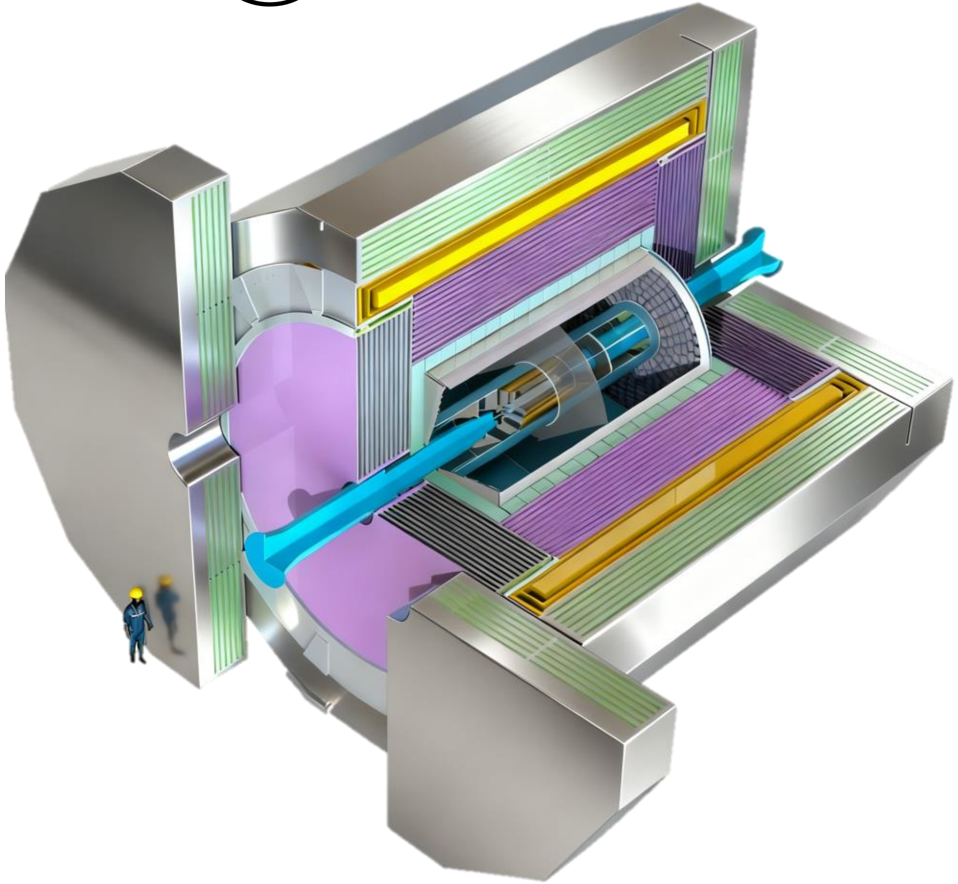
Flavour opportunities @ CEPC

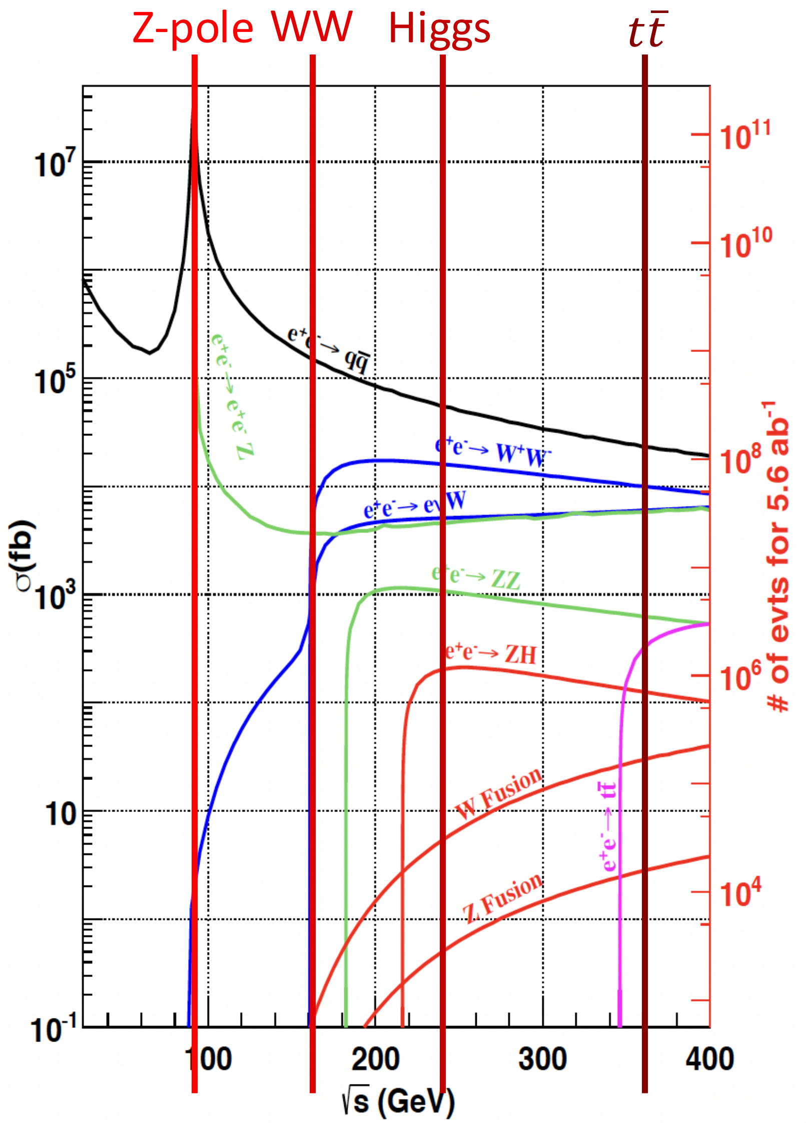


Shanzhen Chen

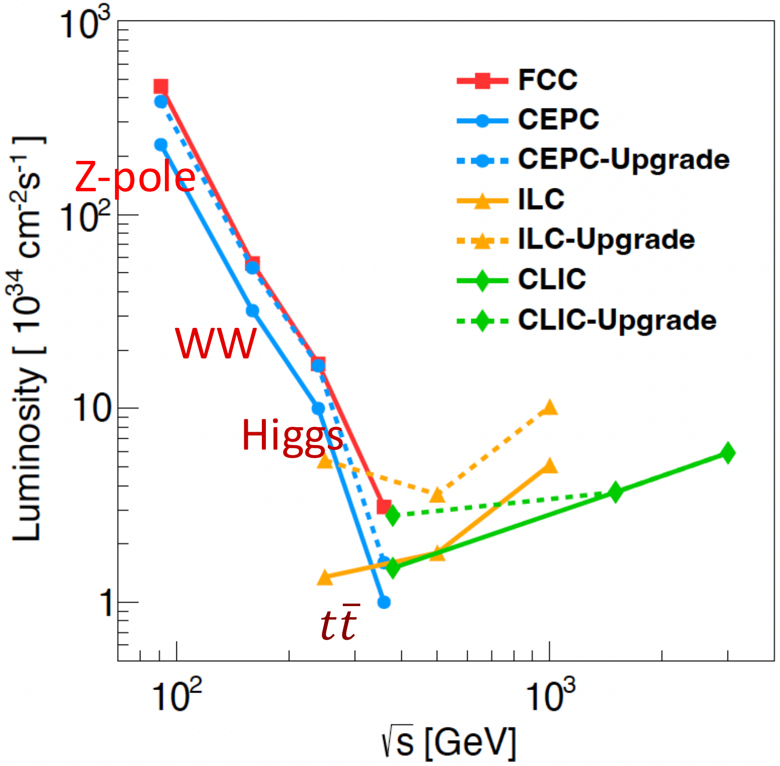
IHEP

27 October 2025

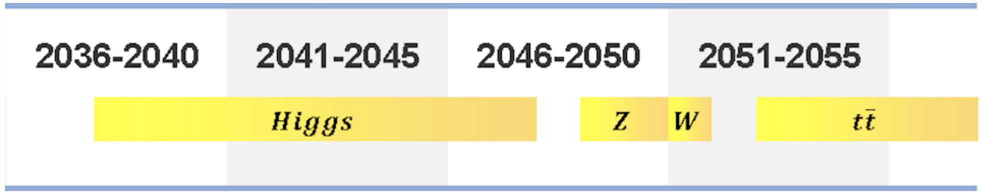
CEPC : a boson factory



- Yields ~ Xsec * Lumi * Time

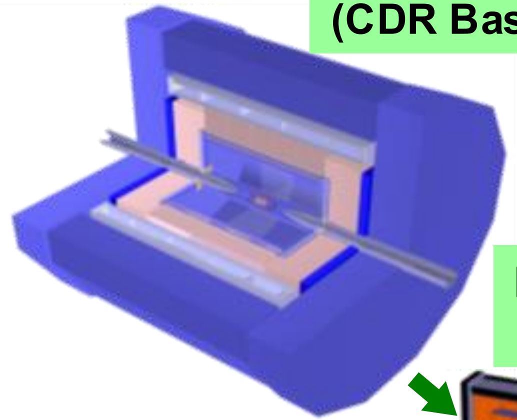


- Higgs: 10 years
  ~ 4 Million Higgs
- Z: 2 years
  ~ 4 Tera Z
- WW: 1 year
  ~ 0.2 Giga WW
- Upgradable:
  Top factory
  (~ 0.6 Million $t\bar{t}$)

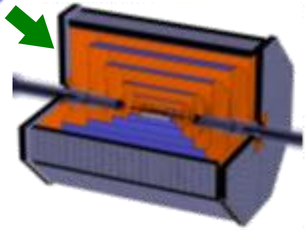


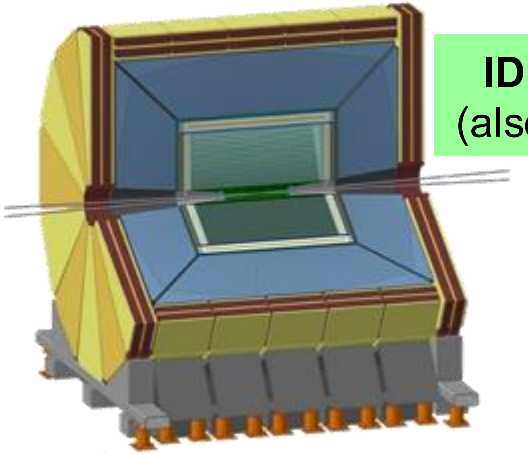
CEPC Conceptual Detector Designs

(CDR Baseline Design)



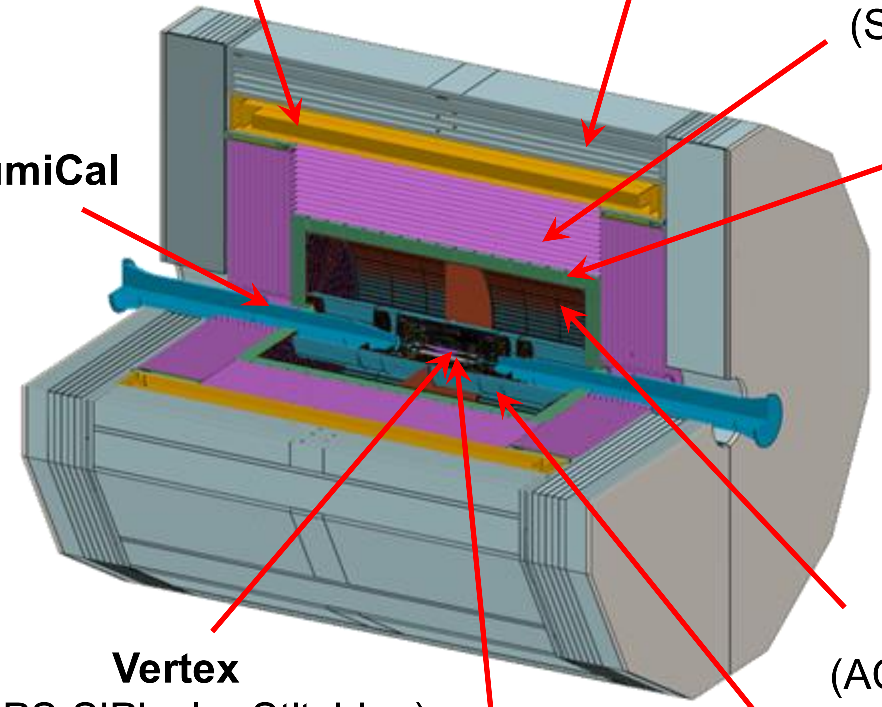
Full Silicon Tracker

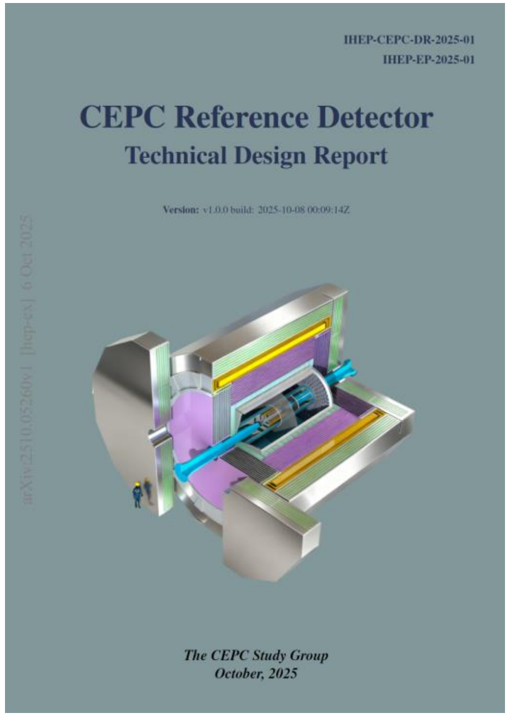




IDEA concept
(also for FCC-ee)

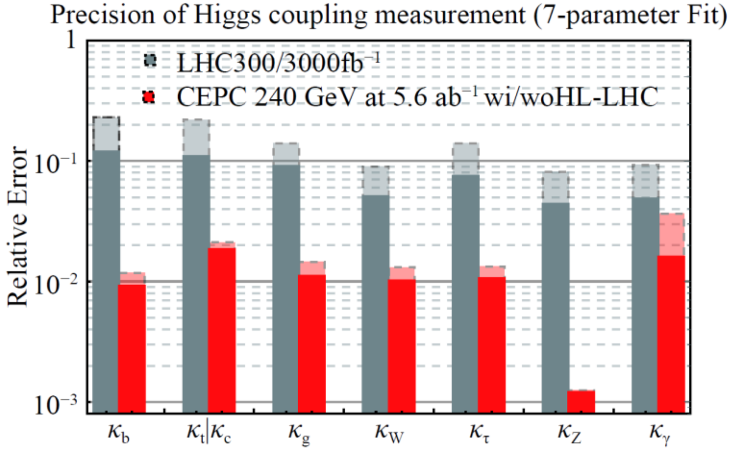
Reference TDR Concept



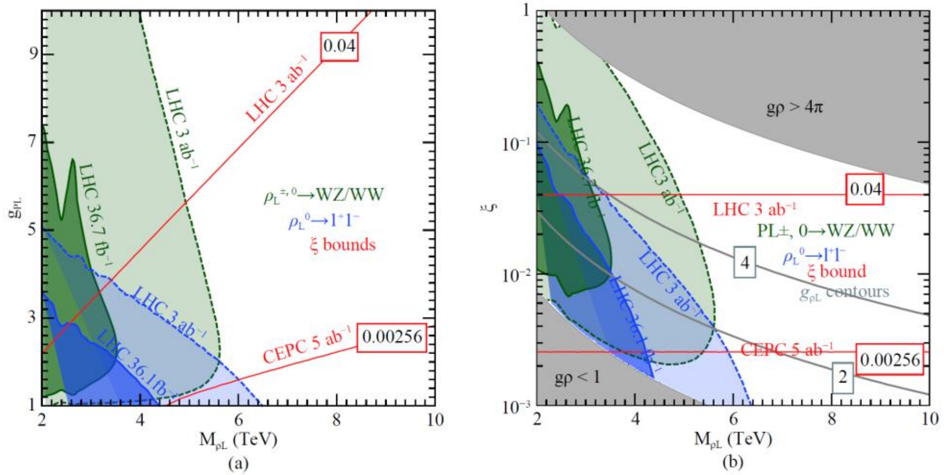


CEPC physics opportunity

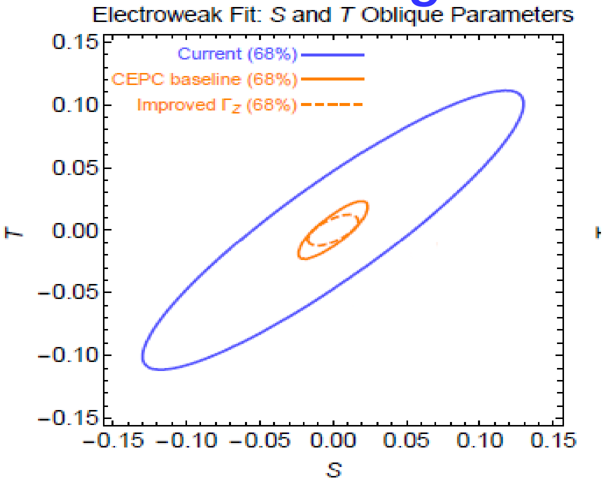
Precision of Higgs coupling measurement higher than HL-LHC by 1 order of magnitude

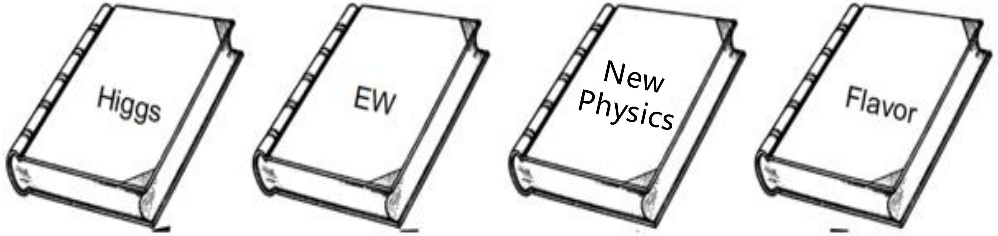


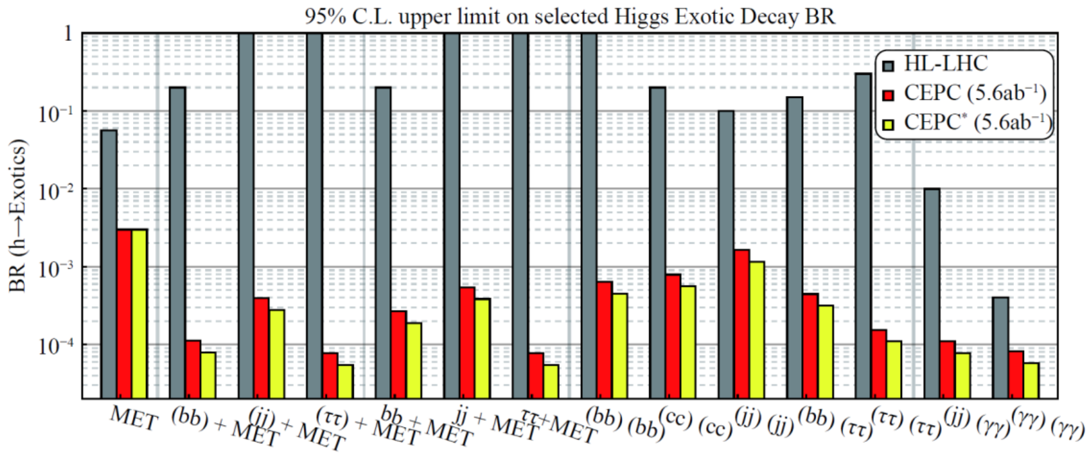
Sensitive to NP up to 10 TeV



Improve precision of EW measurement by 1 order of magnitude







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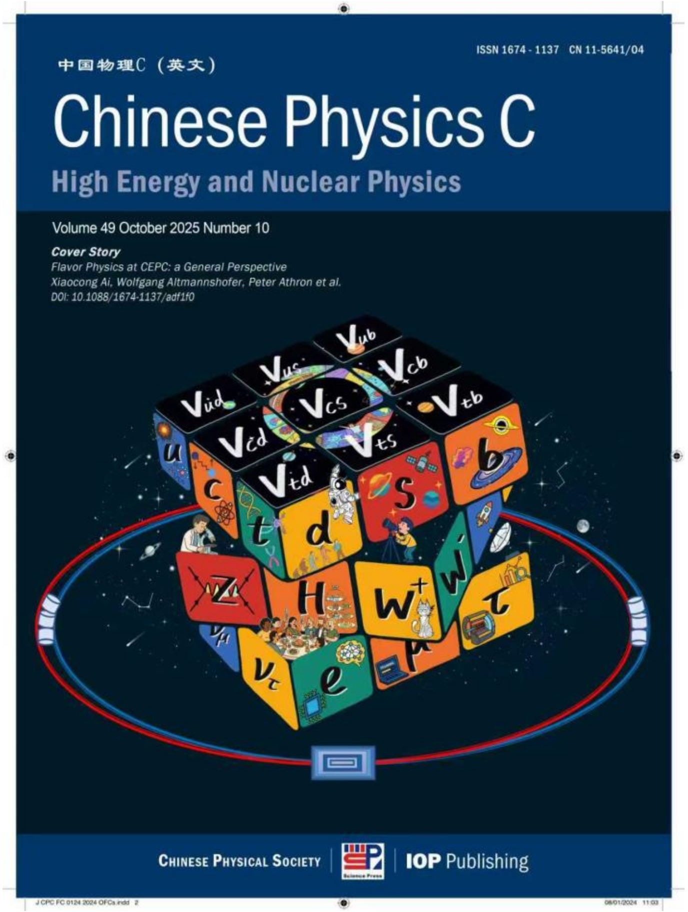
White paper for Higgs, Flavour, New Physics completed,
White paper for EW in progress, +~300 Journal/AxXiv citables

CEPC Flavour physics white paper

- CEPC detectors not specifically designed for flavour physics, but we have demonstrated that it can do many flavour physics programs

- Phase II of CEPC flavour physics feasibility studies will focus on:
  - CKM elements
  - Weak phases
  - CP-violations
  - …



Contents

CPC 49 103003

CEPC Tera-Z mode

- CEPC 50 MW scenario: 4 Tera Z. Z decay modes: $c\bar{c}$ (12.03 ±0.21) % $b\bar{b}$ (15.12 ±0.05) %
- Heavy flavour particle yields
  - One of the largest heavy flavour samples from e^+e^- collider

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}

Tera Z collider as a flavour factory

- Luminosity
  - L=100/ab, O(10^{12}) Z decays ⇒ O(10^{11}) *bb*, *cc*, and $\tau\tau$ pairs

- Energy
  - besides producing states inaccessible at Belle II
    $M_Z \gg 2m_b, 2m_\tau, 2m_c$ ⇒ surplus energy, boosted decay products
    (better tracking and tagging, lower vertex uncertainty etc.)

- Cleanliness
  - as for any leptonic machine, full knowledge of the initial state
    (e.g. Z mass constraint on invariant masses more powerful)
    ⇒ it enables searches involving neutral/invisible particles

CEPC detector as a flavour experiment

- Large acceptance
  - solid angle coverage of at least $|\cos\theta| < 0.99$.
  - low energy and momentum thresholds at the 100 MeV level to record and recognize low energy objects
- Able to identify the relevant physics objects – including neutrals
  - and to precisely reconstruct their properties — especially their energies and momenta
- High efficiency/purity PID
  - not only suppresses the combinatorial background, but also separates decays with similar topologies in the final states
- High-precision and low-material vertex system
  - critical for determining the decay time or lifetime

Performance of CEPC detectors & some suggested objectives

Item	CDR [2]	4^{th} concept [42]	Comments
	Basic Performance		
Acceptance	$\lvert\cos\theta\rvert < 0.99$ [2]		
Threshold	200 MeV [43, 44]	100 MeV	For tracks & photons
Beam energy spread	$\mathcal{O}(0.1\%)$ [2]		
Tracker momentum resolution	$\mathcal{O}(0.1\%)$ [2]		
ECAL energy resolution	$17\%/\sqrt{E(\text{GeV})} \oplus 1\%$ [2]	$3\%/\sqrt{E(\text{GeV})}$ [32]	
HCAL energy resolution	$60\%/\sqrt{E(\text{GeV})} \oplus 1\%$ [2]	$30\%/\sqrt{E(\text{GeV})}$ [45]	
Vertex resolution	10–200 μm [2]	5–100 μm	
Jet energy resolution	3–5% [2, 46]		For 20–100 GeV
$\ell - \pi$ mis-ID	$< 1\%$ [47]		In jet, $\lvert\vec{p}\rvert > 2$ GeV
$\pi - K$ separation	$> 2\sigma$ [2]	$> 3\sigma$ [36]	In jet, $\lvert\vec{p}\rvert > 1$ GeV, TOF+dE/dx
	Flavor Physics Benchmarks (Depending on the Above)		
$\sigma(m_{H,W,Z})$	3.7% [2]		Hadronic decays
b-jet efficiency×purity	$\sim 86\%$ [33]		In Z hadronic decays
c-jet efficiency×purity	$\sim 64\%$ [33]		In Z hadronic decays
b-jet charge tagging $\epsilon_{\text{eff}} = \epsilon(1-2\omega)^2$	$\sim 37\%$ [33]		
c-jet charge tagging $\epsilon_{\text{eff}} = \epsilon(1-2\omega)^2$	$\sim 58\%$ [33]		
π^0 efficiency×purity	$\gtrsim 70\%$ [44]	$\gtrsim 80\%$ [32]	In Z hadronic decays, $\lvert\vec{p}_{\pi^0}\rvert > 5$ GeV
K_S^0, Λ efficiency	60%-85% [48]		In Z hadronic decays, all tracks
τ efficiency×purity	70% [49]		In $WW \to \tau\nu q\bar{q}'$, inclusive
τ mis-ID	$\mathcal{O}(1\%)$ [49]		In $WW \to \tau\nu q\bar{q}'$, inclusive

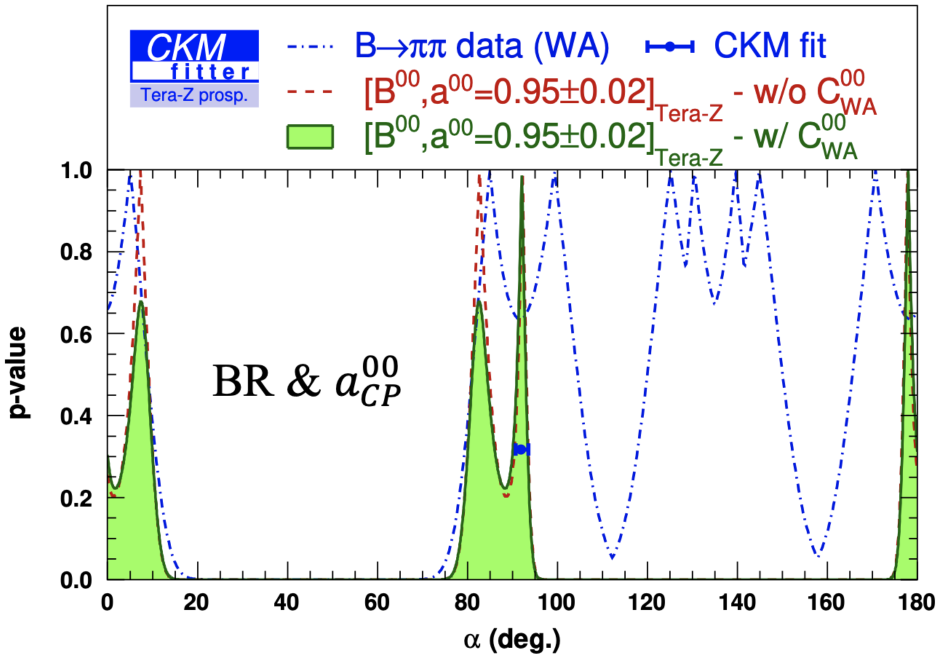
Physics Goal 1: Ultra-Precise Standard Model Tests

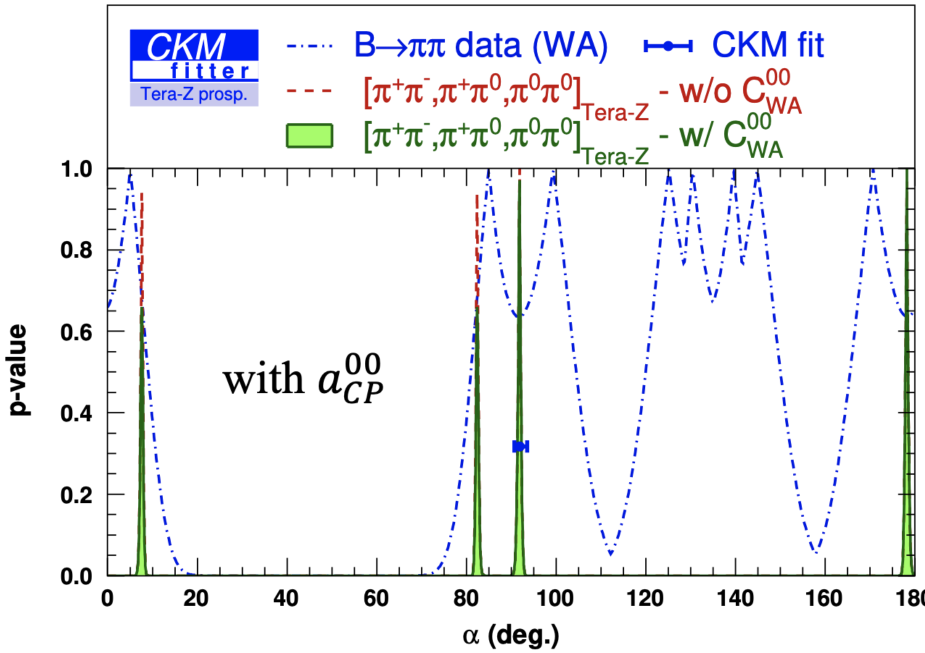
- CKM matrix elements measurements:
  - CKM matrix universality test by combining the measurements of CP violating phases.
- CP violation searches:
  - Direct / indirect CP violation searches with large statistics.
- Lepton universality:
  - Measure R($D^{(*)}$), R(J/ψ) ratios in B decays and $Z \to \ell\ell$ branching fractions to 10^{-4} precision, probing anomalies hinting at new physics.

α measurements with $B \to \pi\pi$

- Studied with $B \to \pi^0\pi^0$, $B_s \to \pi^0\pi^0$, $B \to \eta\eta$, $B_s \to \eta\eta$ samples
  - Only $B \to \pi^0\pi^0$ used in the estimation of CKM phase α
- Scenario 1, only use $B \to \pi^0\pi^0$

Scenario 2, projected to three $B \to \pi\,\pi$ modes





- precision of α: 2~3°

precision of α: 0.4°

Theoretical systematic uncertainties ~ 1-2° not considered

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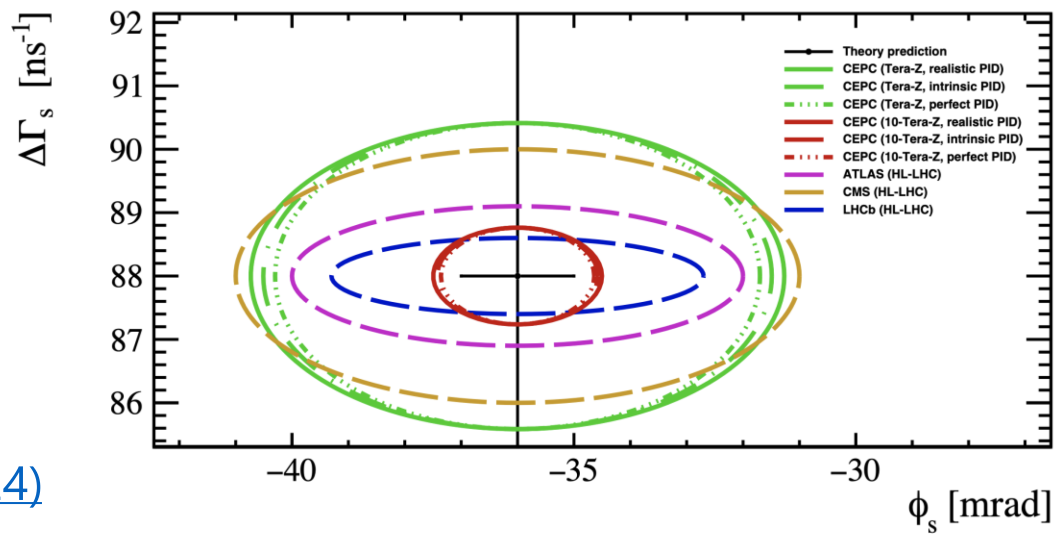
ϕ_s measurements with $B_s \to J/\psi\phi$

- Estimated resolution with 1 Tera Z
  - And comparison with LHCb 300 fb^{-1}

Table 1: Parameters table of factors to calculate the precision of ϕ_s, Γ_s and $\Delta\Gamma_s$. The terms with $*$ means that the factor is insensitive to the resolution of Γ_s and $\Delta\Gamma_s$.

	LHCb (HL-LHC)	CEPC (Tera-Z)	CEPC/LHCb
$b\bar{b}$ statics	43.2×10^{12}	0.152×10^{12}	1/284
Acceptance$\times$efficiency	7%	75%	10.7
Br	6×10^{-6}	12×10^{-6}	2
Flavour tagging*	4.7%	17.3%	3.7
Time resolution* $(\exp(-\frac{1}{2}\Delta m_s^2\sigma_t^2)^2)$	0.52	1	1.92
σ_t(fs)	45	4.7	
scaling factor ξ	0.0015	0.0021	1.4
$\sigma(\phi_s)$	3.3 mrad	4.6 mrad	



Eur. Phys. J. C 84, 859 (2024)

γ measurements with $B_s \to D_s K$

- Inputs: central values of current measurements / calculations:
- Outputs: fitted results with MC sample (preliminary)

Table 1. The latest results of parameters

Parameters	Value
$\tau(B_s^0) = 1/\Gamma_s$	1.520 ± 0.005 [ps] [4]
$\Delta\Gamma_s$	$+0.084 \pm 0.005$ [ps^{-1}] [4]
Δm_s	17.765 ± 0.006 [ps^{-1}] [4]
β_s	$0.01882^{+0.00026}_{-0.00028}$ [rad] [5]
γ	$(66.2^{+3.4}_{-3.6})^\circ$ [4]
δ	$(347.6^{+6.2}_{-6.1})^\circ$ [3]
r_{D_sK}	$0.318^{+0.035}_{-0.033}$ [3]

Fit results with 5.3% statistics

Fitted parameter	values
γ	$(66.43 \pm 3.01)^\circ$
δ	$(349.64 \pm 2.39)^\circ$
r_{D_sK}	0.314 ± 0.007

Projected to full statistics, all final states: uncertainty of γ: 0.7°

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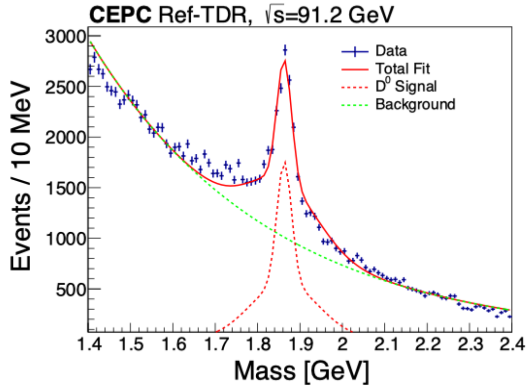
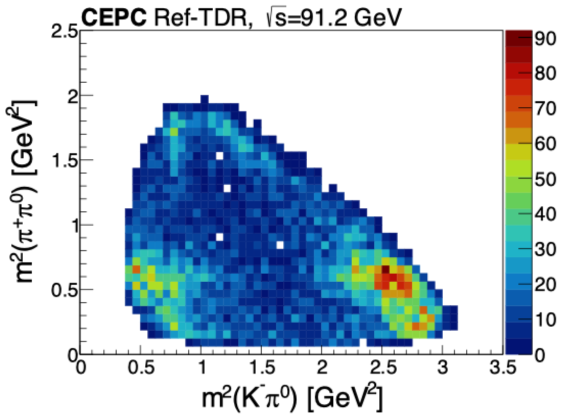
CPV searches with charm hadrons

- CEPC generally do not have advantages in statistics for charm hadrons compare to LHCb
- However, CEPC can have much higher efficiency with π^0s

Decays	LHCb (6 fb^{-1})	LHCb (300 fb^{-1})	CEPC (4 Tera Z)
D^{*+}	4.7×10^{12}	2.4×10^{14}	4.6×10^{11}
D^0 from D^{*+}	3.2×10^{12}	1.6×10^{14}	3.1×10^{11}
$D^{*+}\to(D^0\to K^-K^+)\pi^+$	1.6×10^{10}	6.5×10^{11}	1.3×10^{9}
$D^{*+}\to(D^0\to \pi^-\pi^+)\pi^+$	4.6×10^{9}	2.3×10^{11}	4.5×10^{8}
$D^{*+}\to(D^0\to K^-\pi^+)\pi^+$	1.6×10^{11}	6.3×10^{12}	1.2×10^{10}
$D^{*+}\to(D^0\to \pi^-\pi^+\pi^0)\pi^+$	4.8×10^{10}	2.4×10^{12}	4.6×10^{9}
$D^{*+}\to(D^0\to K^-\pi^+\pi^0)\pi^+$	4.6×10^{11}	2.3×10^{13}	4.4×10^{10}
Reco. & Sel. $D^0\to K^-K^+$	5.8×10^{7} [147]	2.9×10^{9}	1.3×10^{8}
Reco. & Sel. $D^0\to \pi^-\pi^+$	1.8×10^{7} [147]	9×10^{8}	4.5×10^{7}
Reco. & Sel. $D^0\to K^-\pi^+$	5.2×10^{8} [147]	2.6×10^{10}	1.2×10^{9}
Reco. & Sel. $D^0\to \pi^-\pi^+\pi^0$	2.5×10^{6} [148]	1.2×10^{8}	4.6×10^{8}
Reco. & Sel. $D^0\to K^-\pi^+\pi^0$	1.9×10^{7} [148]	9.6×10^{8}	4.4×10^{9}





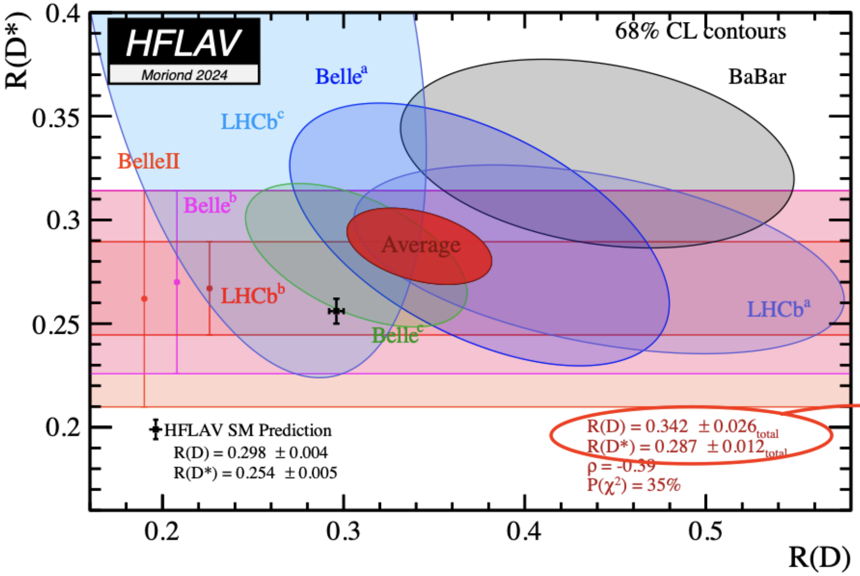
LFU tests in B decays

- Gauge interactions are flavour blind: the SM predicts Lepton Flavour Universality (LFU) EW interactions ⇒ any deviation from LFU would be a clear indication of NP

Example: LFU tests in semileptonic (charged-current) B decays

$$\boxed{R_{D^{(*)}} \equiv \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)},\ \ell = e,\, \mu}$$

CEPC can achieve a precision below 1%



R_{H_c}	SM Value	Tera-Z	4×Tera-Z	10×Tera-Z
$R_{J/\psi}$	0.289	4.3×10^{-2}	2.1×10^{-2}	1.4×10^{-2}
R_{D_s}	0.393	4.1×10^{-3}	2.1×10^{-3}	1.3×10^{-3}
$R_{D_s^*}$	0.303	3.3×10^{-3}	1.6×10^{-3}	1.0×10^{-3}
R_{Λ_c}	0.334	9.8×10^{-4}	4.9×10^{-4}	3.1×10^{-4}

Current precision: ~5-10%
World average still somewhat in tension with the SM prediction

Physics Goal 2: Rare & Forbidden Decays

CEPC's clean environment and particle-flow detectors excel at reconstructing elusive processes:

- Flavour-changing neutral currents (FCNC):
  - Search for $b \to s$ transitions suppressed in the Standard Model, e.g., $B_s \to \phi \nu\nu$ (aiming for 2% precision), $B \to K\tau\tau$, and $B_s \to \tau\tau$. Sensitivity to branching ratios as low as 10^{-7}.
- Lepton flavour violation (LFV):
  - Hunt for absolute forbidden decays like $\tau \to \mu\gamma$ (target: BR 10^{-10}), $Z \to e\mu$. These "smoking guns" for new physics are inaccessible at hadron colliders due to backgrounds.
- Baryon/lepton number violation:
  - Probe decays like $B^+ \to \pi^- \ell^+ \ell^+$ or $\Lambda_b \to \pi^- \ell^+$ that challenge fundamental symmetries.

FCNC b hadronic decays

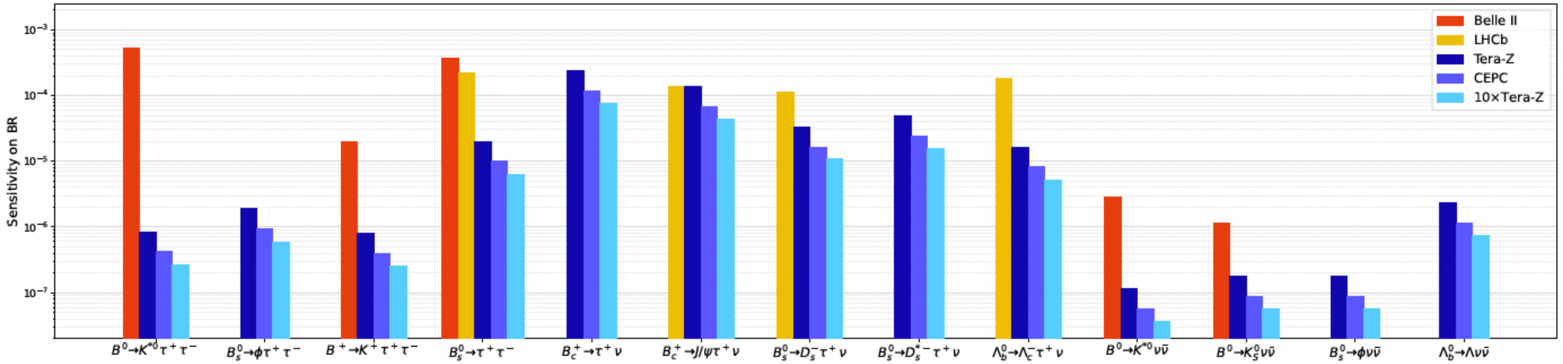
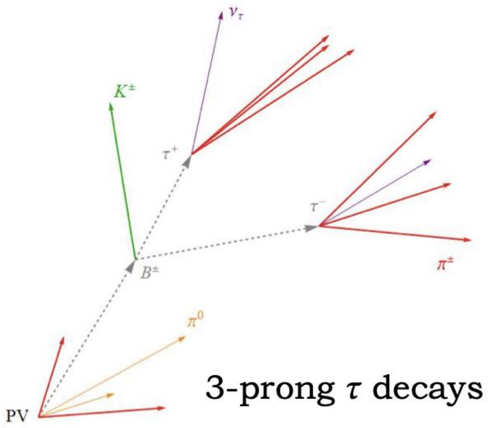
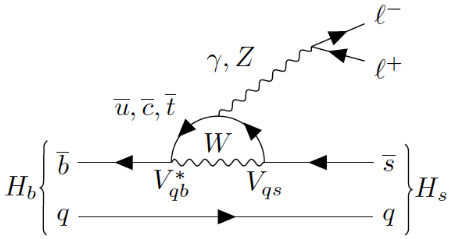
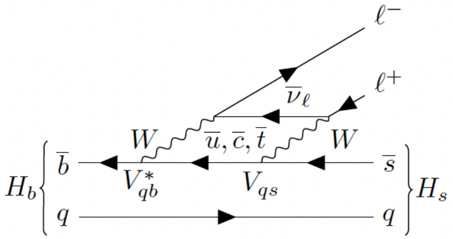


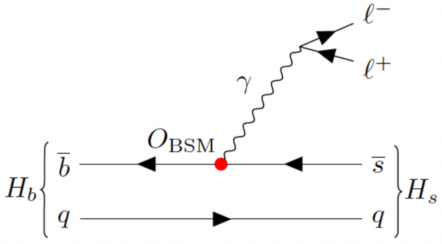
Figure 16: Projected sensitivities of measuring the $b \to s\tau\tau$ [85], $b \to s\nu\bar{\nu}$ [36, 86] and $b \to c\tau\nu$ [39, 68] transitions at the Z pole. The sensitivities at Belle II @ 50 ab^{-1} [7, 87] and LHCb Upgrade II [18, 57] have also been provided as a reference. Note that LHCb sensitivities are generated by combining the analyses of $\tau^+ \to \pi^+\pi^-\pi^-(\pi^0)\nu$ and $\tau \to \mu\nu\bar{\nu}$. This plot is taken from Ref. [39], with additional $b \to s\nu\bar{\nu}$ modes included.

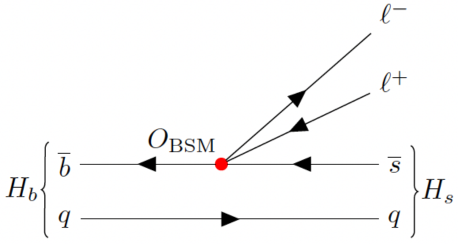


3-prong τ decays









prospects of LFV sensitivity in the τ and Z decays

Measurement	Current [126]	FCC [115]	Tera-Z Prelim. [127]	Comments
Lifetime [sec]	$\pm 5 \times 10^{-16}$	$\pm 1 \times 10^{-18}$		from 3-prong decays, stat. limited
$\mathrm{BR}(\tau \to \ell\nu\bar{\nu})$	$\pm 4 \times 10^{-4}$	$\pm 3 \times 10^{-5}$		$0.1\times$ the ALEPH systematics
$\mathrm{m}(\tau)$ [MeV]	± 0.12	$\pm 0.004 \pm 0.1$		$\sigma(p_{\text{track}})$ limited
$\mathrm{BR}(\tau \to 3\mu)$	$< 2.1 \times 10^{-8}$	$\mathcal{O}(10^{-10})$	same	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
$\mathrm{BR}(\tau \to \mu\gamma)$	$< 4.4 \times 10^{-8}$	$\sim 2 \times 10^{-9}$	$\mathcal{O}(10^{-10})$	$Z \to \tau\tau\gamma$ 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
$\mathrm{BR}(Z \to \tau\mu)$	$< 1.2 \times 10^{-5}$	$\mathcal{O}(10^{-9})$	same	$\tau\tau$ bkg, $\sigma(p_{\text{track}})$ & $\sigma(E_{\text{beam}})$ limited
$\mathrm{BR}(Z \to \tau e)$	$< 9.8 \times 10^{-6}$	$\mathcal{O}(10^{-9})$		$\tau\tau$ bkg, $\sigma(p_{\text{track}})$ & $\sigma(E_{\text{beam}})$ limited
$\mathrm{BR}(Z \to \mu e)$	$< 7.5 \times 10^{-7}$	$10^{-8} - 10^{-10}$	$\mathcal{O}(10^{-9})$	PID limited

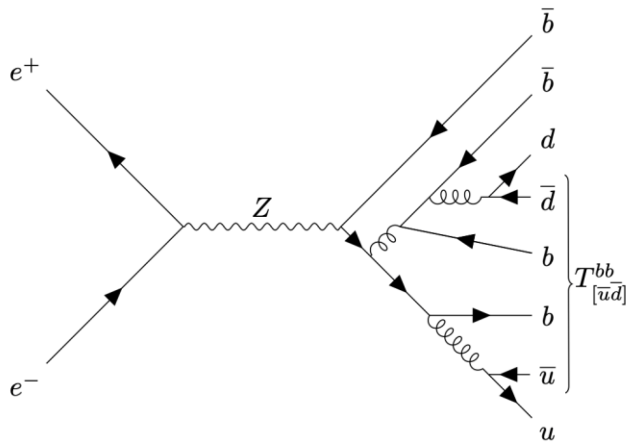
Physics Goal 3: Exotic Hadrons & Spectroscopy

With 10^{11} *b*-hadrons and charm particles, CEPC will map the "heavy-flavour zoo":

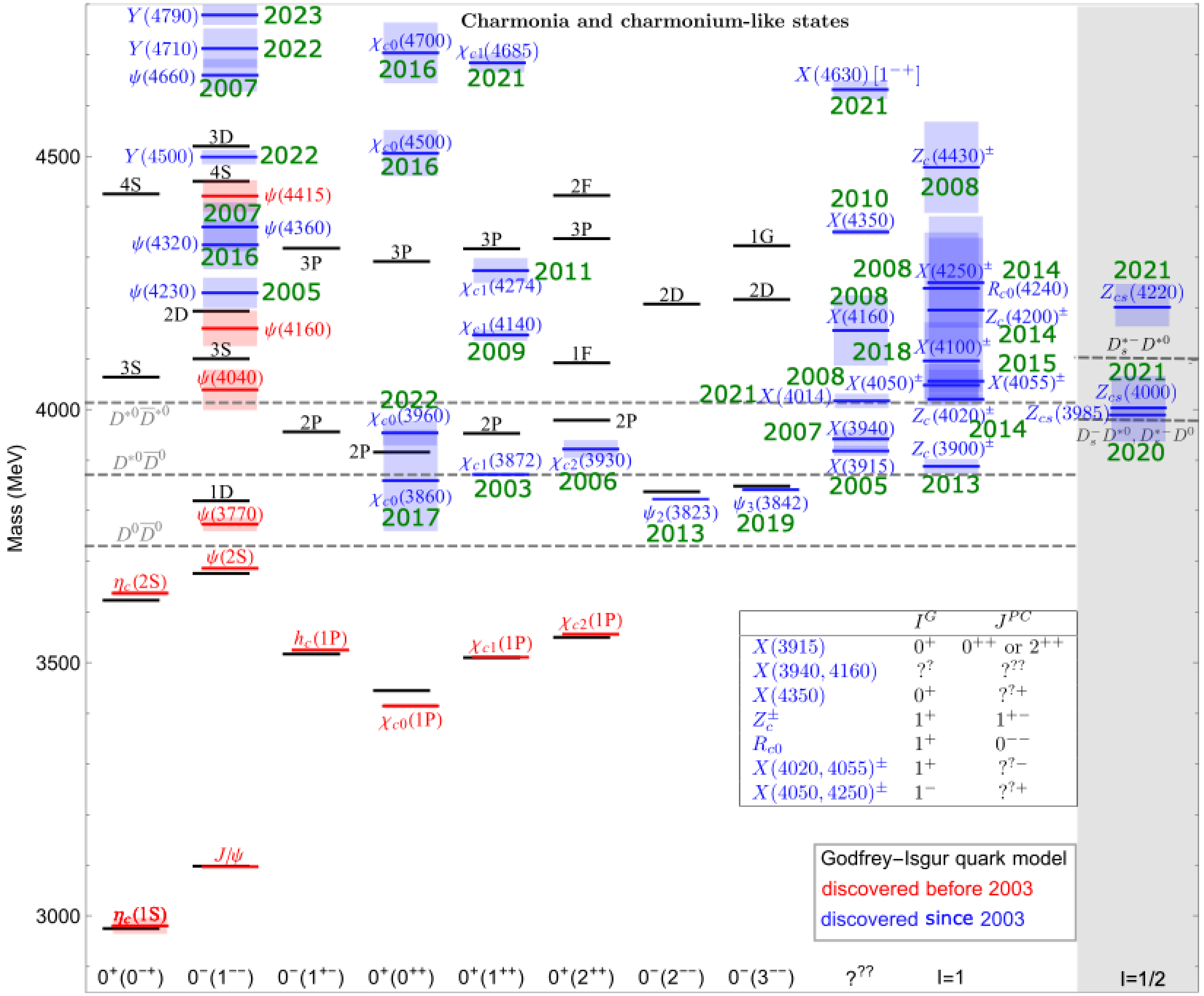
- Discover tetraquarks (T_{cc}, T_{bb}) pentaquarks (P_c), and doubly heavy baryons (Ξ_{cc}, Ξ_{bb}), predicted by QCD but rarely observed.
- Study production mechanisms of charmonium-like states (e.g., *X(3872)*) via $Z \rightarrow qq$ or B-decay chains.
- Precision spectroscopy of conventional *b*/*c*-mesons and baryons (e.g., Λ_b, B_c), including excited states.

Spectroscopy and Exotics - prospects

- A lot of states, guaranteed discovery at CEPC?
- *Z→bbbb*, *bbcc*, *cccc* processes may give rise to highly exotic species



- Need more theory inputs for simulation



	I^G	J^{PC}
$X(3915)$	0^+	0^{++} or 2^{++}
$X(3940, 4160)$	$?^?$	$?^{??}$
$X(4350)$	0^+	$?^{?+}$
$Z_c^\pm$	1^+	1^{+-}
R_{c0}	1^+	0^{--}
$X(4020, 4055)^\pm$	1^+	$?^{?-}$
$X(4050, 4250)^\pm$	1^-	$?^{?+}$

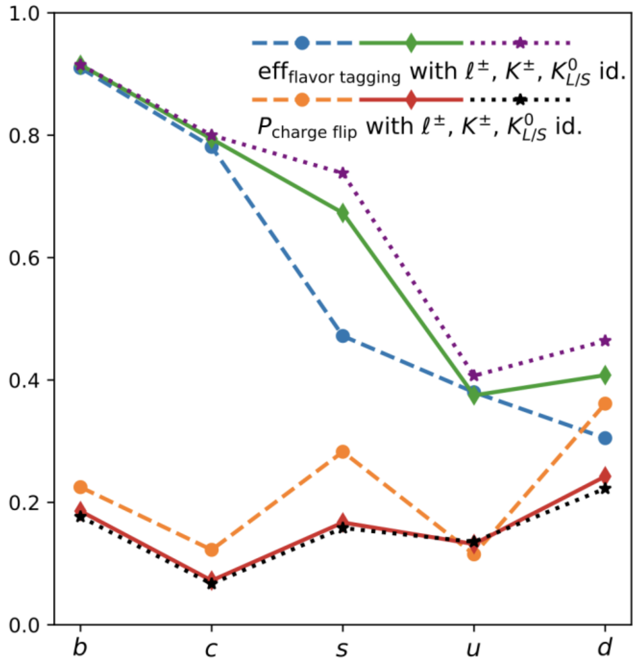
Physics Goal 4: WW & Higgs & Top Quark Flavour Physics

Higher-energy CEPC runs extend flavour studies:

- Higgs flavour violation:
  - Search for $H \to b\bar{s}$, $H \to c\bar{u}$, or $H \to \tau\mu$ decays at the Higgs factory (240 GeV). Jet-origin identification via ML could constrain branching ratios to 10^{-3}.
- Top quark FCNC:
  - At the $t\bar{t}$ threshold (360 GeV), probe anomalous $t \to cZ$ or $t \to cH$ decays, sensitive to new physics in top-Higgs couplings.
- CKM elements from WW threshold:
  - Resolve long-standing tensions in CKM matrix elements (e.g., $|V_{cb}|$, $|V_{ub}|$) by combining data from B/D meson decays and on-shell W boson decays at the WW threshold. Target precision for $|V_{cb}|$ reaches 0.1–0.4%.

Jet origin identification

- Full Simulated vvH, Higgs to two jets sample at CEPC baseline configuration, reconstructed with deep learning techniques
- Jets identified as the category with highest likelihood
- 5 quarks+antiquarks + gluon



True \ Predicted	b	$\bar{b}$	c	$\bar{c}$	s	$\bar{s}$	u	$\bar{u}$	d	$\bar{d}$	G
b	0.745	0.163	0.033	0.025	0.004	0.003	0.002	0.003	0.002	0.002	0.017
$\bar{b}$	0.170	0.737	0.026	0.033	0.003	0.004	0.003	0.002	0.002	0.003	0.018
c	0.015	0.014	0.743	0.055	0.036	0.031	0.025	0.009	0.009	0.018	0.043
$\bar{c}$	0.016	0.015	0.056	0.739	0.032	0.037	0.009	0.026	0.017	0.010	0.043
s	0.003	0.002	0.020	0.018	0.543	0.102	0.030	0.080	0.063	0.045	0.092
$\bar{s}$	0.003	0.003	0.018	0.020	0.102	0.542	0.084	0.028	0.045	0.062	0.094
u	0.002	0.003	0.020	0.011	0.044	0.131	0.367	0.055	0.080	0.174	0.111
$\bar{u}$	0.003	0.003	0.011	0.019	0.132	0.043	0.062	0.356	0.178	0.081	0.111
d	0.003	0.003	0.012	0.019	0.112	0.092	0.082	0.207	0.277	0.079	0.112
$\bar{d}$	0.003	0.003	0.020	0.012	0.092	0.112	0.219	0.076	0.079	0.272	0.113
G	0.015	0.014	0.024	0.024	0.052	0.052	0.043	0.041	0.034	0.034	0.667

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Flavour violating Higgs decay & Top FCNC

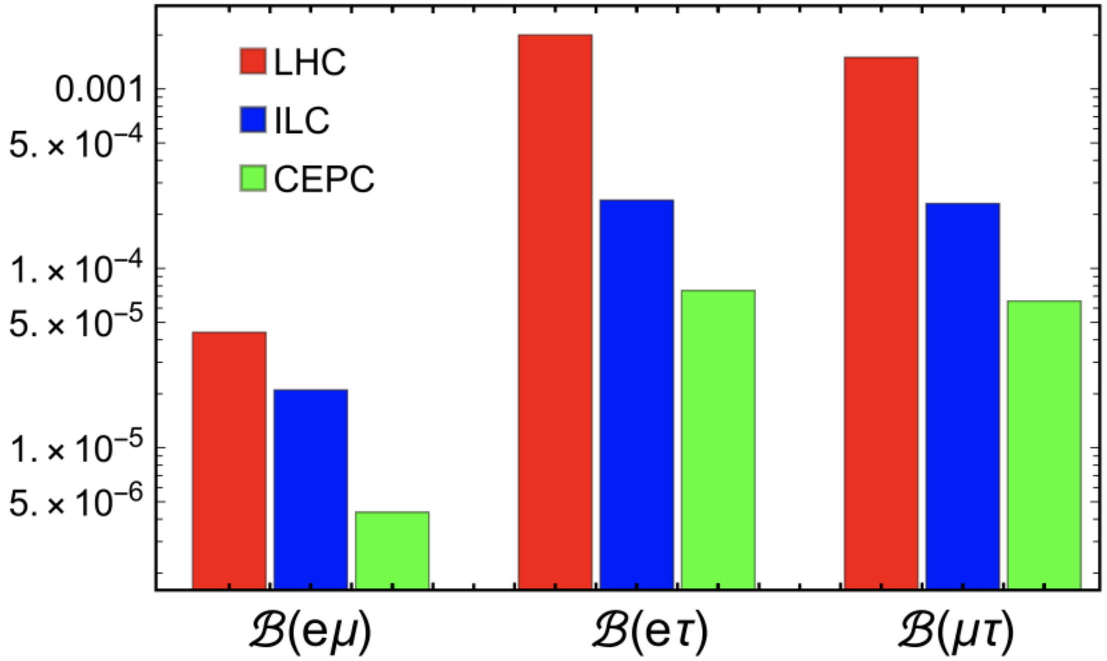
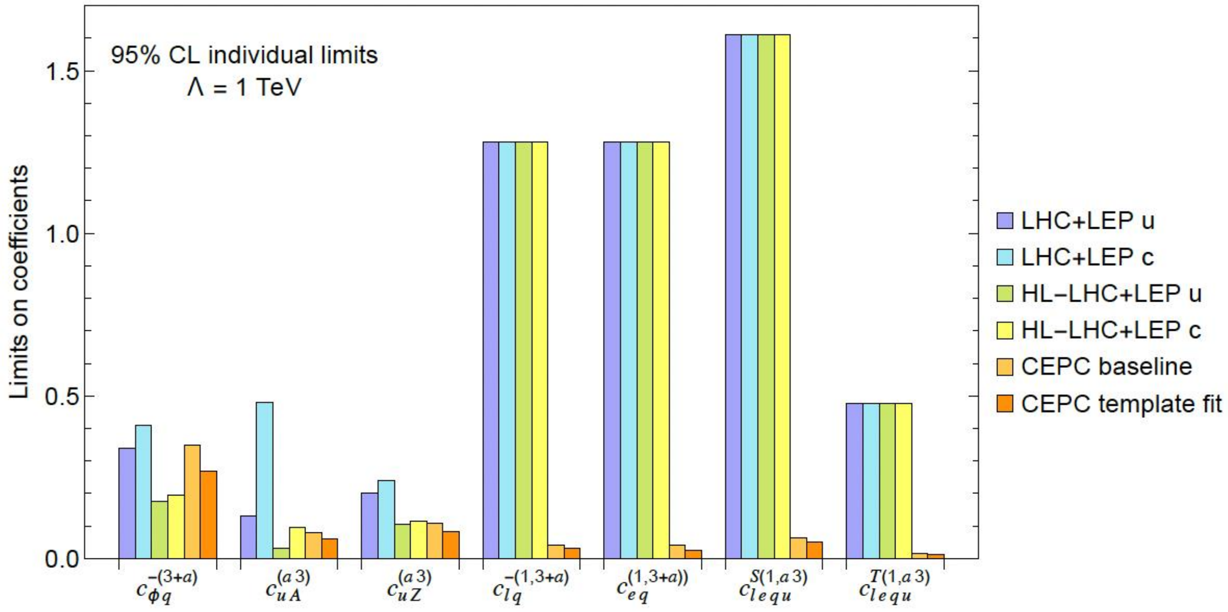


Fig. 34. (color online) Projected upper limits on the LFV Higgs decays at the LHC, ILC and CEPC. The figure is updated from [255].



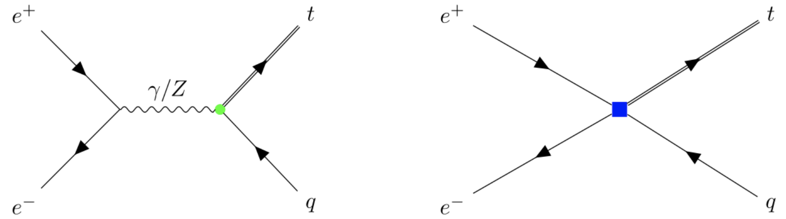


Fig. 35. (color online) Illustrative Feynman diagrams for the FCNC single top production $e^-e^+ \to t(\bar{t})j$. The green dot and blue square represent two-fermion FCNC and four-fermion (two-lepton two-quark) contact operators, respectively.

CKM element from W decay

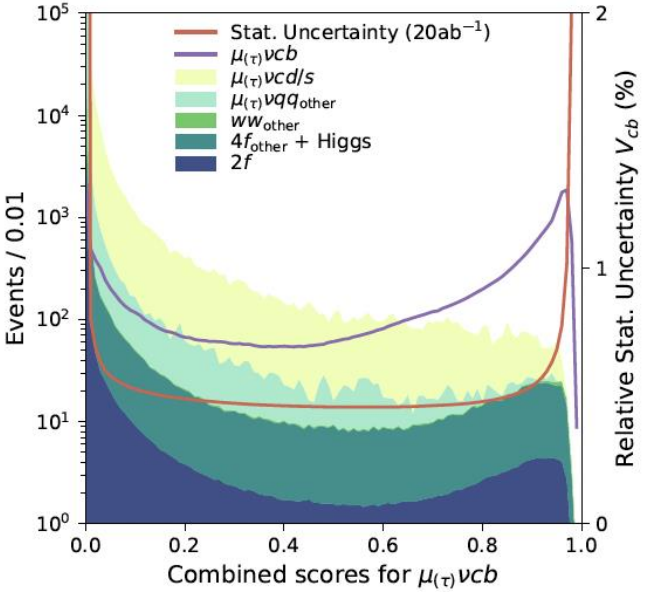
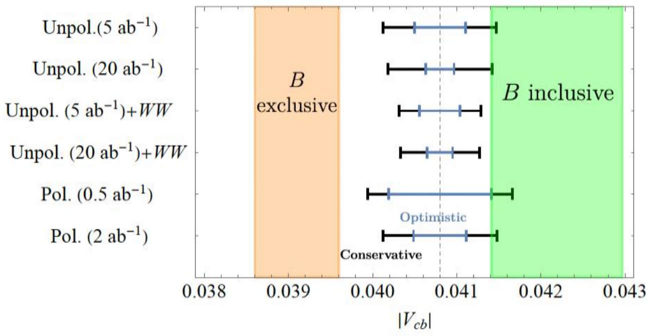


Figure 4. The BDT score distribution of signal and backgrounds in: the muon channel (left) and electron channel (right). The red curve indicates the projected statistical relative sensitivity estimated from eq. (4.1) assuming a luminosity of 20 ab^{-1}.

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Measurement of CKM element $|V_{cb}|$ from W boson decays at the future Higgs factories

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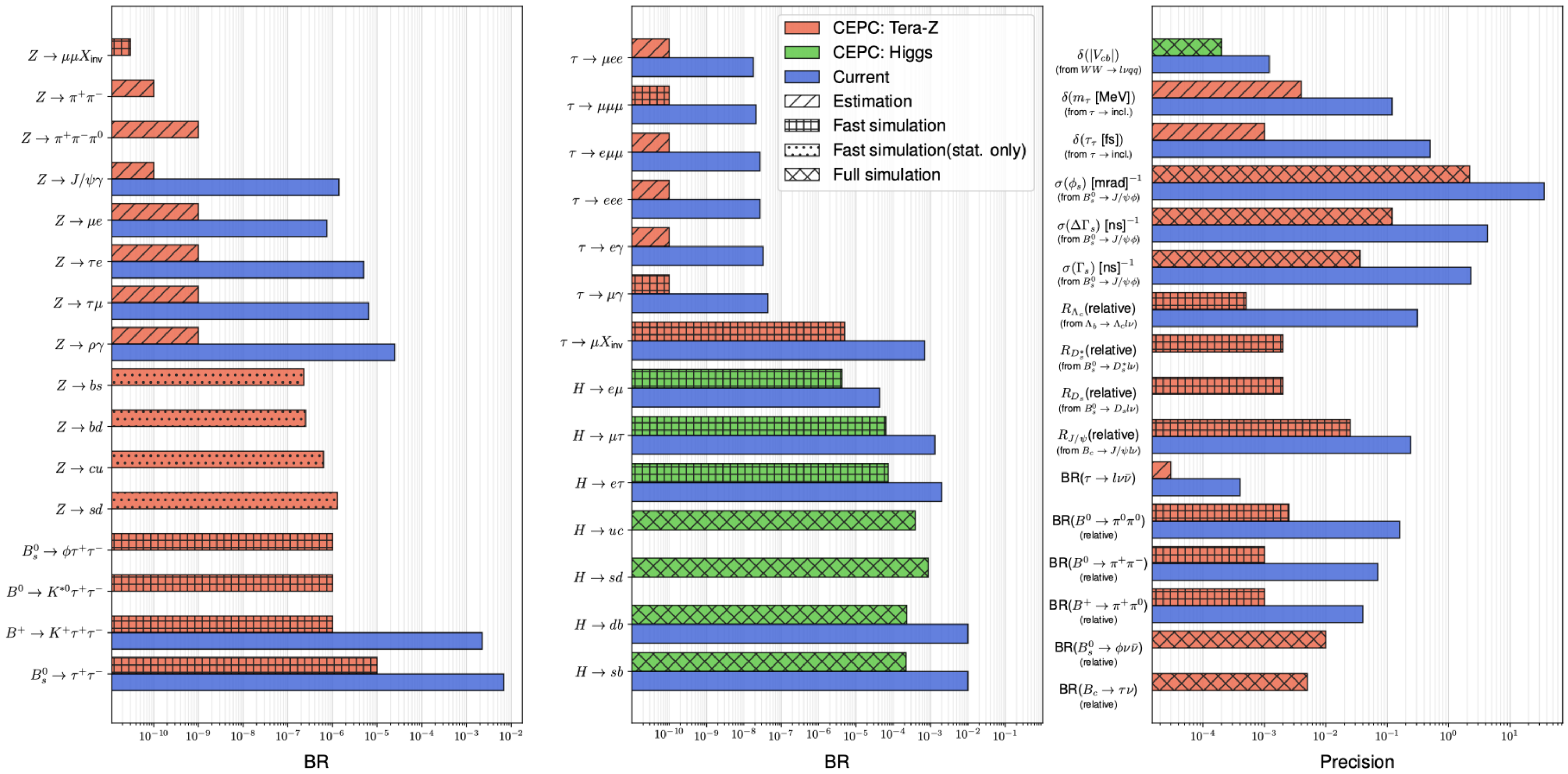
Summary of flavour benchmark channels



Summary

- We demonstrated the potential of studying flavour physics @ CEPC
- O(10^{12}) Z decays would enable us to study many processes with a much higher precision than (or inaccessible to) other experiments
- WW, Higgs, top runs extended the flavour program
- Extremely rich physics program results in stringent requirements on the detector performance, to be addressed by intensive study on detector design, key tech R&D, and algorithms development

- Will explore more possibilities in the next stage feasibility studies

Thanks!