Status of CEPC Flavour Study

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Why Flavour Physics?

$$\mathcal{L}_{SM} \supset i\bar{\psi}\not{D}\psi + \bar{\psi}_i y_{ij} \psi_j \phi$$

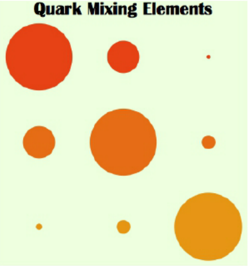
SM Flavour Puzzle

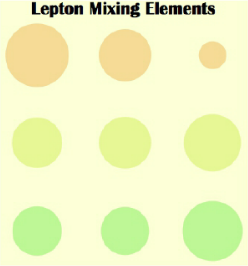
22 free parameters??

SM Flavour Puzzle

SM describes flavour sector very well (so far).
But we don't have an explanation.

- Why 3 generations?
- Why masses so different ($m_u/m_t \sim 10^{-5}$)?
- Why quark mixing so differently?
- Why lepton universal?





Why Flavour Physics?

$$\mathcal{L} \supset i\bar{\psi}\not{D}\psi + \bar{\psi}_i y_{ij}\psi_j\phi + \sum_{d\geq 5,i} \frac{c_i}{\Lambda^{d-4}}\mathcal{O}_i^d$$

SM Flavour Puzzle

22 free parameters??

NP Flavour Puzzle (?)

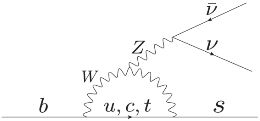
Very sensitive to NP scale

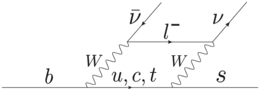
Flavour Physics × New Physics [See also: Jure, Lorenzo, Qin's talk]

Flavour observables are VERY sensitive to New Physics.

Leading order of FCNC is already loop level in SM.

- $\Gamma_{\mathrm{SM}} \propto m_f^5 / m_W^4$



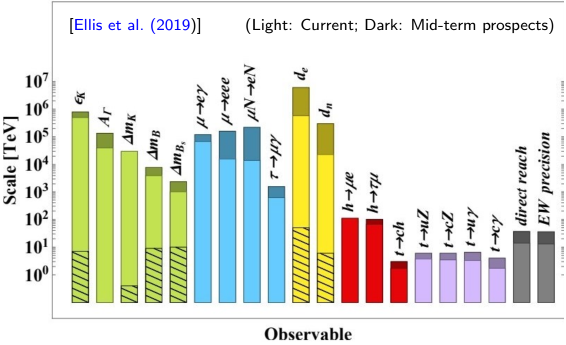


Could have tree level FCNC in BSM.

- $\Gamma_{\mathrm{BSM}} \propto m_f^5 / \Lambda_{NP}^2 m_W^2$

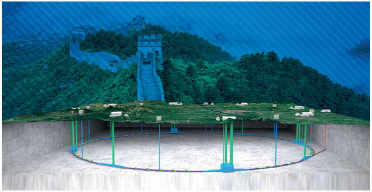
Could have new states (e.g. LFV) in BSM.

- $\Gamma_{\mathrm{BSM}} \propto m_f^5 / \Lambda_{NP}^4$

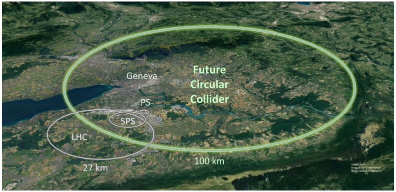


e^+e^- Collider in the Future? [See also: Zhen's talk]

CEPC (China)



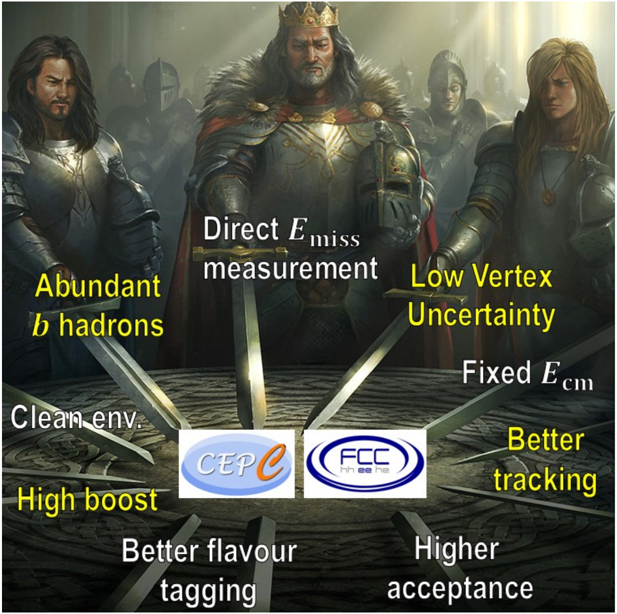
FCC-ee (Switzerland)



Nominal CEPC operation scheme.

Operation mode	Z factory	WW threshold	Higgs factory	$t\bar{t}$
$\sqrt{s}$ (GeV)	91.2	160	240	360
Run time (year)	2	1	10	5
Instantaneous luminosity ($10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, per IP)	191.7	26.6	8.3	0.83
Integrated luminosity (ab^{-1}, 2 IPs)	100	6	20	1
Event yields	3×10^{12}	1×10^{8}	4×10^{6}	5×10^{5}

What is good?



White: compared to LHCb; Yellow: compared to B-factories

Estimated b-hadron yields

Hadrons	Belle II	LHCb (300 fb^{-1})	CEPC ($10^{12} Z$)
B^0, $\bar{B}^0$	5.4×10^{10}	$\sim 3 \times 10^{13}$	1.2×10^{11}
$B^{\pm}$	5.7×10^{10}	$\sim 3 \times 10^{13}$	1.2×10^{11}
B_s, $\bar{B}_s$	6.0×10^{8}	$\sim 1 \times 10^{13}$	3.1×10^{10}
$B_c^{\pm}$	-	$\sim 2 \times 10^{11}$	1.8×10^{8}
Λ_b, $\bar{\Lambda}_b$	-	$\sim 2 \times 10^{13}$	2.5×10^{10}

[Li et al. (2022)]

(Cannot cover all contributions, only present a portion of them)

CEPC Flavour White Paper

Contents

Fully Neutral Final States [Wang et al. (2022)]

- Measuring BR($B^0_{(s)} \to \pi^0\pi^0 \to 4\gamma$)

  uncert.($B^0 \to \pi^0\pi^0 \to 4\gamma$) $\sim$ 0.45%

  uncert.($B^0_s \to \pi^0\pi^0 \to 4\gamma$) $\sim$ 4.5%

  [Not observed]

- Measuring BR($B^0_{(s)} \to \eta^0\eta^0 \to 4\gamma$)

  uncert.($B^0 \to \eta^0\eta^0 \to 4\gamma$) $\sim$ 18%

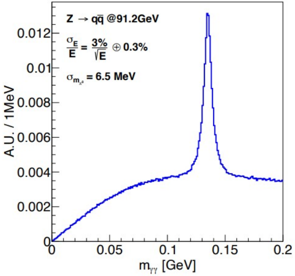
  [Not observed]

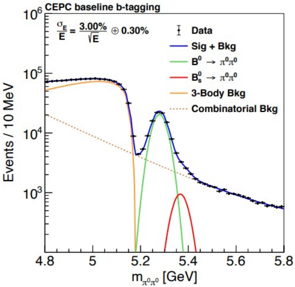
  uncert.($B^0_s \to \eta^0\eta^0 \to 4\gamma$) $\sim$ 0.95%

  [Not observed]

- Benefit from: Cleanness, ECAL resolution, High eff. and purity flavour tagging, ...

Testing charmless 2-body decays, $|V_{ub}|$, hadron physics, ...





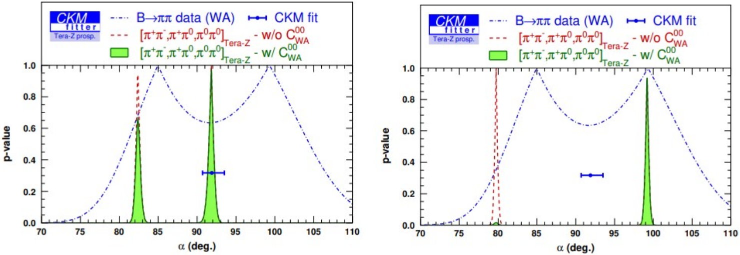
CKM elements: $\alpha(\phi_2)$ in UT [Wang et al. (2022)]

See also: [Charles et al. (2017); Abada et al. (2019); Chang et al. (2017); Monteil and Wilkinson (2021); Hsiao and Geng (2015)]

- Isopsin anaylsis of $B \to \pi\pi$
- Measuring $\alpha(\phi_2)$ from $B^0 \to \pi^0\pi^0 \to 4\gamma$

  uncert.$(\alpha) \sim 0.4^\circ$
- Removed mirror solutions!!!

$a^{00}_{CP} = 0.95$; $a^{00}_{CP} = 0.53$

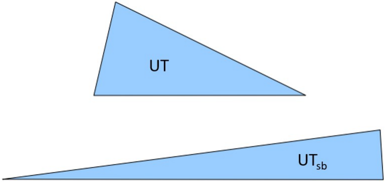


Current determination of α is limited by direct CP asymmetry of $B^0 \to \pi^0\pi^0$

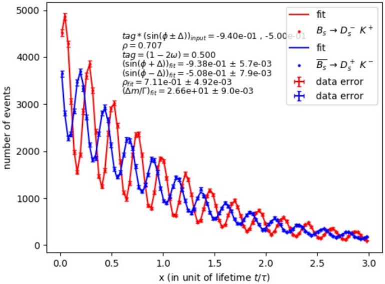
CKM elements: UT_{sb} angles [Aleksan et al. (2022, 2021)]

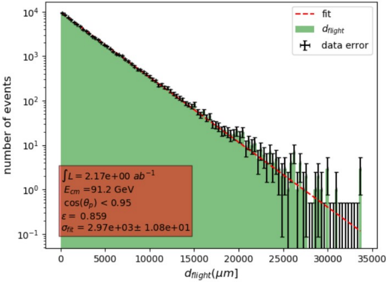
See also: [Aaij et al. (2013, 2015); Xiao et al. (2014)]

- Measuring α_s from $\bar{B}_s(B_s) \to D_s^{\pm} K^{\mp}$
  uncert.$(\alpha_s) \sim 0.4^{\circ}$
- Measuring β_s from $\bar{B}_s(B_s) \to J/\psi\phi$
  uncert.$(\beta_s) \sim 0.035^{\circ}$
- Measuring γ_s from $B^{\pm} \to \bar{D}^0(D^0)K^{\pm}$
  uncert.$(\gamma_s) \sim \mathcal{O}(1^{\circ})$



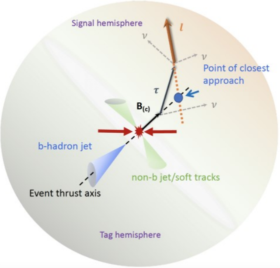
Challenging because UT_{sb} is relatively flat



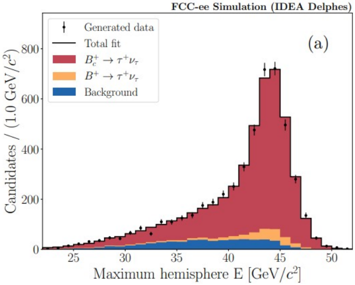


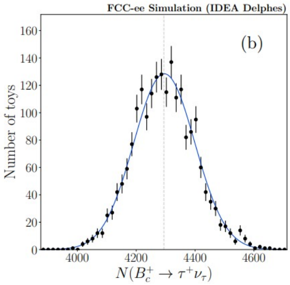
Charged (Pseudo)Scalar Decays [Zheng et al. (2020); Amhis et al. (2021)]

- Measuring $B_c \to \tau\nu$
  uncert.(BR) $\sim \mathcal{O}(10^{-4})$ **[Not observed]**
  uncert.($|V_{cb}|$) $\sim \mathcal{O}(1\%)$
- Benefit from: Knowing PV, E_{cm}, abundant B_c, ...



Testing $|V_{cb}|$, f_{B_c}, LFUV
BSM (e.g. 2HDM, Leptoquark)





Neutral Current $b \to s\tau\tau$ measurements [Li and Liu (2021); Miralles (2021)]

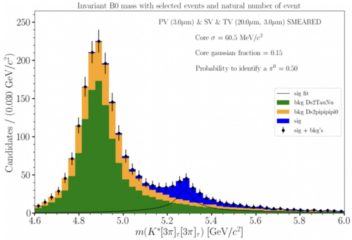
See also: [Kamenik et al. (2017); Monteil and Wilkinson (2021)]

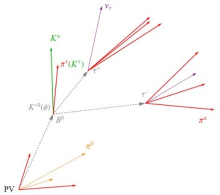
- Measuring BR($B^0 \to K^{*0}\tau^+\tau^-$), BR($B_s \to \phi\tau^+\tau^-$), BR($B^+ \to K\tau^+\tau^-$)

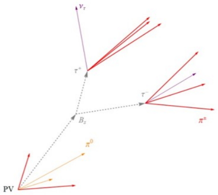
  uncert.$\sim \mathcal{O}(10^{-7} - 10^{-6})$**[Not observed]**
- Measuring BR($B_s \to \tau^+\tau^-$)

  uncert.$\sim \mathcal{O}(10^{-5})$**[Not observed]**
- Benefit from: Vertexing, Known E_{cm}, Clean Env., ...

Testing 3$^{\text{rd}}$ generation FCNC NP (e.g. τ FCNC LFUV)







Ulta-rare (and LFV) decays [Monteil and Wilkinson (2021); Chrzaszcz et al. (2021)]

See also: Lorenzo's Talk, [Descotes-Genon et al. (2021)]

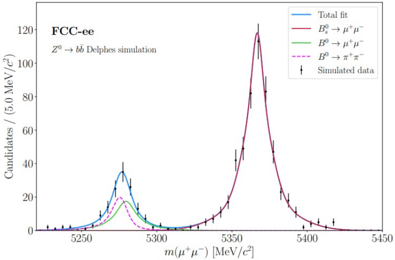
- Measuring BR($B_s^0 \to \mu^+\mu^-$), BR($B^0 \to \mu^+\mu^-$)

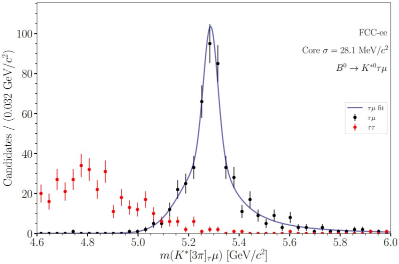
  BR($B^0 \to \mu^+\mu^-$) affected by $B^0 \to \pi^+\pi^-$ **mis-ID**

- Benefit from: Low mis-ID rate

Potentially also measuring $B_s^0 \to \mu^+\mu^-$ Lifetime, CP asymmetries

- Measuring LFV decays: $B^0 \to K^{*0}\tau\mu$

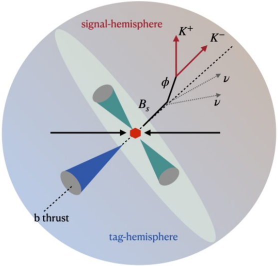




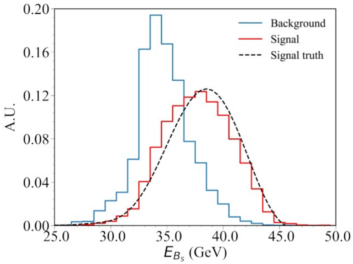
Di-neutrino Final State [Li et al. (2022)]

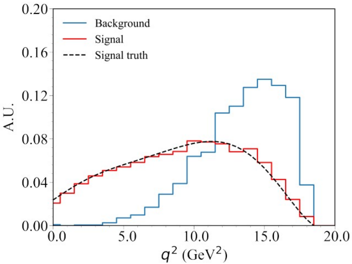
See also: [Batell et al. (2011); Dror et al. (2017)]

- Measuring $\mathrm{BR}(B_s \to \phi\nu\nu)$ uncert. $\sim \mathcal{O}(1\%)$
- Benefit from: Abundant B_s, E_{cm}, Vertexing, ... $\implies$ Deduce E_B



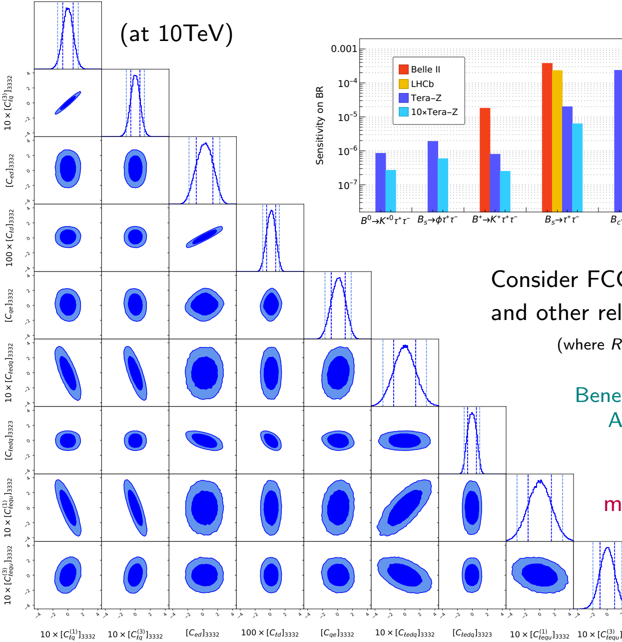
Useful for extracting CKM elements:
Clean theoretical predictions
Potentially constraint BSM,
which acts as E_{miss} (e.g. Dark Photon, ALP [Ongoing], ...)

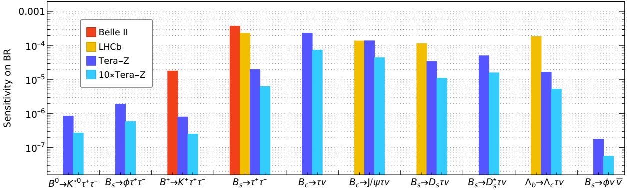




Lepton Flavour Universality [Ho et al. (2022)] , See also: Shanzhen's talk

(at 10TeV)





Consider FCCC ($R_{J/\psi}$, $R_{D_s^{(*)}}$, R_{Λ_c}), FCNC and other related measurements together.

(where $R_{H_c} = \dfrac{Br(H_b \to H_c \tau\nu)}{Br(H_b \to H_c \mu\nu)}$ for FCCC)

Benefit from: $E_{\rm cm}$, Clean Env., Abundant b-hadrons, ...

Constraint of NP up to multi-TeV when Wilson Coeff. are about $\mathcal{O}(1)$

τ Physics [Dam (2019)]

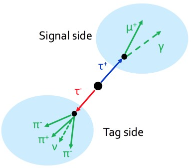
See also: Lorenzo, Alberto's talk, [Dam (2021); Pich (2014); Celis et al. (2014); Calibbi and Signorelli (2018)]

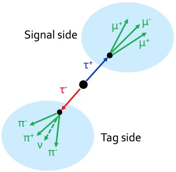
Z factory produces $\sim \mathcal{O}(10^{10})$ $\tau^+\tau^-$ pairs from $Z \to \tau^+\tau^-$

- Measuring BR($\tau \to \ell\nu\bar{\nu}$)
  Improvement: $\sim \mathcal{O}(10^2)$
- Measuring τ lifetime
  Improvement: $\sim \mathcal{O}(10^3)$

Observable	Present value $\pm$ error	FCC-ee stat.	FCC-ee syst.
m_τ (MeV)	1776.86 ± 0.12	0.004	0.1
$\mathcal{B}(\tau \to e\bar{\nu}\nu)$ (%)	17.82 ± 0.05	0.0001	0.003
$\mathcal{B}(\tau \to \mu\bar{\nu}\nu)$ (%)	17.39 ± 0.05	0.0001	0.003
τ_τ (fs)	290.3 ± 0.5	0.001	0.04

- Measuring BR($\tau \to 3\mu$) and BR($\tau \to \mu\gamma$)
  Improvement: $\sim \mathcal{O}(10 - 10^2)$





Decay	Present bound	FCC-ee sensitivity
$Z \to \mu e$	0.75×10^{-6}	10^{-10}–10^{-8}
$Z \to \tau\mu$	12×10^{-6}	10^{-9}
$Z \to \tau e$	9.8×10^{-6}	10^{-9}
$\tau \to \mu\gamma$	4.4×10^{-8}	2×10^{-9}
$\tau \to 3\mu$	2.1×10^{-8}	10^{-10}

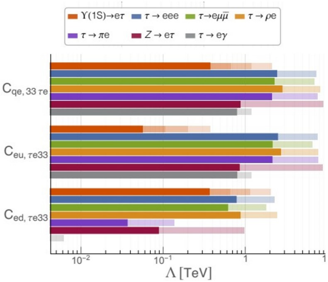
Flavour Physics From Z Decays See also Lorenzo's talk,

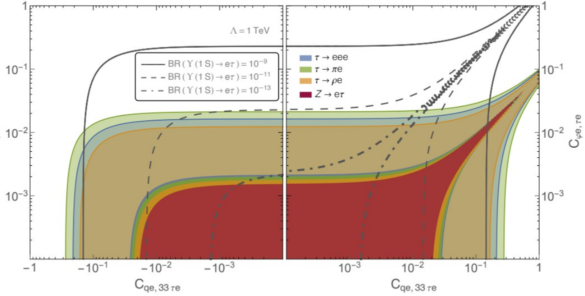
[Calibbi et al. (2021, 2022); Dam (2019)]

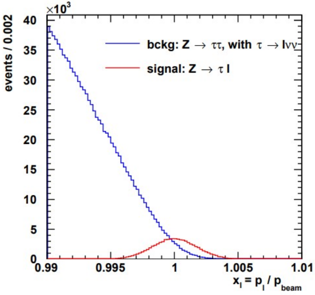
- Measuring $\mathrm{BR}(Z \to \ell\ell')$ with $(\ell \neq \ell')$

  Limits $\sim \mathcal{O}(10^{-8} - 10^{-10})$

Z decays can well constrain operators involve top quarks.







Other Opportunities

Exotic Hadrons:

- From b-hadron decays/ Direct $Z \to b\bar{b}, c\bar{c}$

  $\mathrm{BR}(Z \to T^{\{cc\}}_{[\bar{q}\bar{q}']} + X) \sim \mathcal{O}(10^{-6})$, $\mathrm{BR}(Z \to \Xi^{+}_{cc} + X) \sim 1 \times 10^{-5}$,
  $\mathrm{BR}(Z \to \Sigma^{+}_{cc} + X) \sim 5 \times 10^{-5}$ [Qin et al. (2021)]

Charm-Physics:

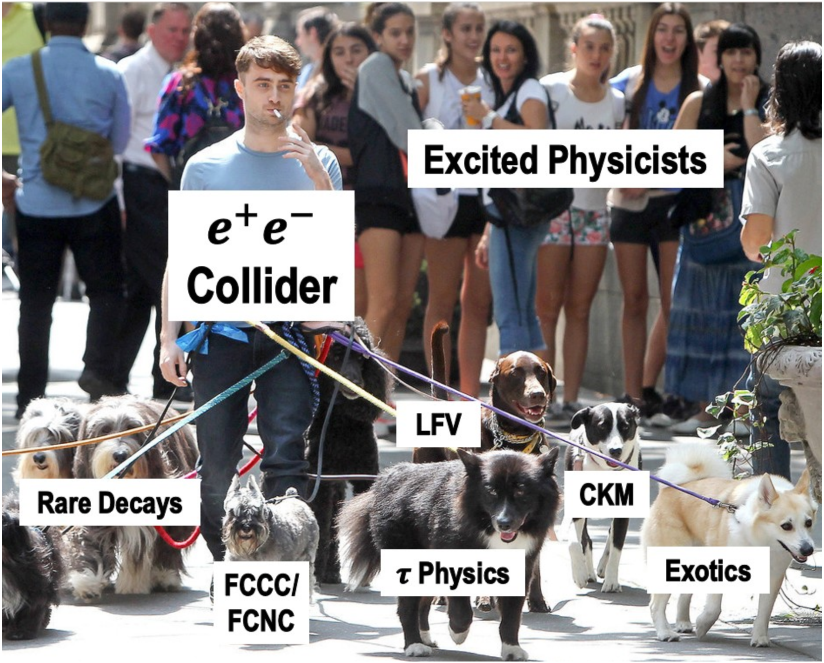
- $\mathrm{BR}(Z \to c\bar{c}) \sim 12\%$ v.s. $\mathrm{BR}(Z \to b\bar{b}) \sim 15\%$
- Similar to those of b-physics (e.g. CKM, FCNC, ...) [Bause et al. (2021)]

W-Decays ($e^+e^- \to W^+W^-$) at $\sqrt{s} \sim 160$ GeV:

- Direct measurement of CKM elements

  $|V_{cb}|$ based on flavour tagging, $|V_{cs}|$ [Charles et al. (2020)], ...
- Similar to those of Z decays

Flavour Physics in Higgs & Top ??? [König and Neubert (2015); Shi and Zhang (2019)]


Excited Physicists
e^+e^- Collider
LFV
Rare Decays
CKM
FCCC/ FCNC
τ Physics
Exotics

Reference I

Aaij, R. et al. (2013). Observations of $B_s^0 \to \psi(2S)\eta$ and $B_{(s)}^0 \to \psi(2S)\pi^+\pi^-$ decays. *Nucl. Phys. B*, 871:403–419.

Aaij, R. et al. (2015). Study of $\eta - \eta'$ mixing from measurement of $B_{(s)}^0 \to J/\psi\eta^{(\prime)}$˜decay rates. *JHEP*, 01:024.

Abada, A. et al. (2019). FCC Physics Opportunities: Future Circular Collider Conceptual Design Report Volume 1. *Eur. Phys. J. C*, 79(6):474.

Aleksan, R., Oliver, L., and Perez, E. (2021). Study of CP violation in $B^\pm$ decays to $\overline{D^0}(D^0)K^\pm$ at FCCee.

Aleksan, R., Oliver, L., and Perez, E. (2022). CP violation and determination of the bs flat unitarity triangle at an FCC-ee. *Phys. Rev. D*, 105(5):053008.

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

Reference II

Batell, B., Pospelov, M., and Ritz, A. (2011). Multi-lepton Signatures of a Hidden Sector in Rare B Decays. *Phys. Rev. D*, 83:054005.

Bause, R., Gisbert, H., Golz, M., and Hiller, G. (2021). Rare charm $\boldsymbol{c} \to \boldsymbol{u}\,\boldsymbol{\nu}\bar{\boldsymbol{\nu}}$ dineutrino null tests for e^+e^- machines. *Phys. Rev. D*, 103(1):015033.

Calibbi, L., Li, T., Marcano, X., and Schmidt, M. A. (2022). Indirect constraints on lepton-flavour-violating quarkonium decays.

Calibbi, L., Marcano, X., and Roy, J. (2021). Z lepton flavour violation as a probe for new physics at future e^+e^- colliders.

Calibbi, L. and Signorelli, G. (2018). Charged Lepton Flavour Violation: An Experimental and Theoretical Introduction. *Riv. Nuovo Cim.*, 41(2):71–174.

Reference III

Celis, A., Cirigliano, V., and Passemar, E. (2014). Model-discriminating power of lepton flavor violating τ decays. *Phys. Rev. D*, 89(9):095014.

Chang, P., Chen, K.-F., and Hou, W.-S. (2017). Flavor Physics and CP Violation. *Prog. Part. Nucl. Phys.*, 97:261–311.

Charles, J., Deschamps, O., Descotes-Genon, S., and Niess, V. (2017). Isospin analysis of charmless B-meson decays. *Eur. Phys. J. C*, 77(8):574.

Charles, J., Descotes-Genon, S., Ligeti, Z., Monteil, S., Papucci, M., Trabelsi, K., and Vale Silva, L. (2020). New physics in B meson mixing: future sensitivity and limitations. *Phys. Rev. D*, 102(5):056023.

Chrzaszcz, M., Suarez, R. G., and Monteil, S. (2021). Hunt for rare processes and long-lived particles at FCC-ee. *Eur. Phys. J. Plus*, 136(10):1056.

Reference IV

Dam, M. (2019). Tau-lepton Physics at the FCC-ee circular e^+e^- Collider. *SciPost Phys. Proc.*, 1:041.

Dam, M. (2021). The \texttau challenge at FCC-ee.

Descotes-Genon, S., Novoa-Brunet, M., and Vos, K. K. (2021). The time-dependent angular analysis of $B_d \to K_S \ell\ell$, a new benchmark for new physics. *JHEP*, 02:129.

Dror, J. A., Lasenby, R., and Pospelov, M. (2017). Dark forces coupled to nonconserved currents. *Phys. Rev. D*, 96(7):075036.

Ellis, R. K. et al. (2019). Physics Briefing Book: Input for the European Strategy for Particle Physics Update 2020.

Ho, T. S. M., Jiang, X.-H., Kwok, T. H., Li, L., and Liu, T. (2022). Testing Lepton Flavor Universality at Future Z Factories.

Hsiao, Y. K. and Geng, C. Q. (2015). Direct CP violation in Λ_b decays. *Phys. Rev. D*, 91(11):116007.

Reference V

Kamenik, J. F., Monteil, S., Semkiv, A., and Silva, L. V. (2017). Lepton polarization asymmetries in rare semi-tauonic $b \to s$ exclusive decays at FCC-*ee*. *Eur. Phys. J. C*, 77(10):701.

König, M. and Neubert, M. (2015). Exclusive Radiative Higgs Decays as Probes of Light-Quark Yukawa Couplings. *JHEP*, 08:012.

Li, L. and Liu, T. (2021). $\mathrm{b} \to \mathrm{s}\tau^+\tau$ physics at future Z factories. *JHEP*, 06:064.

Li, L., Ruan, M., Wang, Y., and Wang, Y. (2022). The analysis of $B_s \to \phi\nu\bar{\nu}$.

Miralles, T. (2021). Study of $B^0 \to K^{*0}\ \tau^+\tau$ at FCC-ee.

Monteil, S. and Wilkinson, G. (2021). Heavy-quark opportunities and challenges at FCC-ee. *Eur. Phys. J. Plus*, 136(8):837.

Pich, A. (2014). Precision Tau Physics. *Prog. Part. Nucl. Phys.*, 75:41–85.

Reference VI

Qin, Q., Shen, Y.-F., and Yu, F.-S. (2021). Discovery potentials of double-charm tetraquarks. *Chin. Phys. C*, 45(10):103106.

Shi, L. and Zhang, C. (2019). Probing the top quark flavor-changing couplings at CEPC. *Chin. Phys. C*, 43(11):113104.

Wang, Y., Descotes-Genon, S., Deschamps, O., Li, L., Chen, S., Zhu, Y., and Ruan, M. (2022). Prospects for $B^0_{(s)} \to \pi^0\pi^0$ and $B^0_{(s)} \to \eta\eta$ modes and corresponding CP asymmetries at Tera-Z.

Xiao, Z.-J., Li, Y., Lin, D.-T., Fan, Y.-Y., and Ma, A.-J. (2014). $\overline{b}^0_s \to (\pi^0\eta^{(\prime)}, \eta^{(\prime)}\eta^{(\prime)})$ decays and the effects of next-to-leading order contributions in the perturbative qcd approach. *Phys. Rev. D*, 90:114028.

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.