Overview on CEPC Flavour White Paper

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The 2022 international workshop on
the high energy Circular Electron-Positron Collider
25 Oct 2022

Why Flavour Physics?

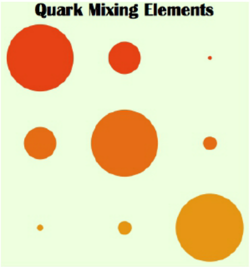
$$\mathcal{L}_{\mathrm{SM}} \supset i\bar{\psi}\not{D}\psi + \bar{\psi}_i y_{ij}\psi_j\phi$$

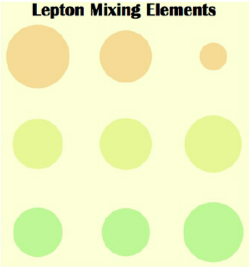
SM Flavour Puzzle
22 free parameters??

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??

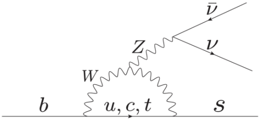
NP Flavour Puzzle (?)
Very sensitive to NP scale

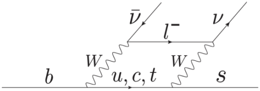
Flavour Physics × New Physics

Flavour observables are VERY sensitive to New Physics.

Leading order of FCNC is already loop level in SM.

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



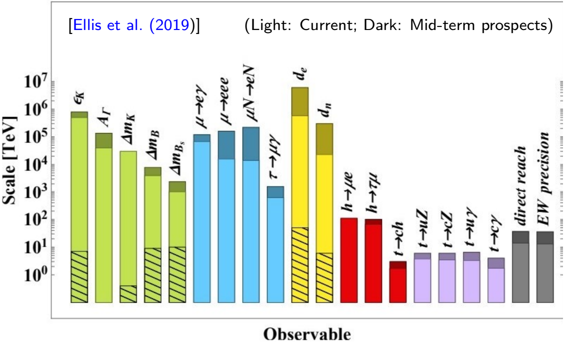


Could have tree level FCNC in BSM.

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

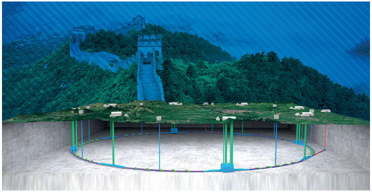
Could have new states (e.g. LFV) in BSM.

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

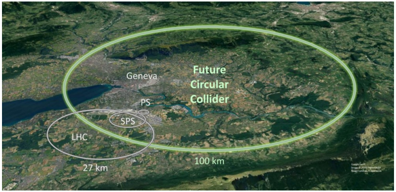


e^+e^- Collider in the Future?

CEPC (China)



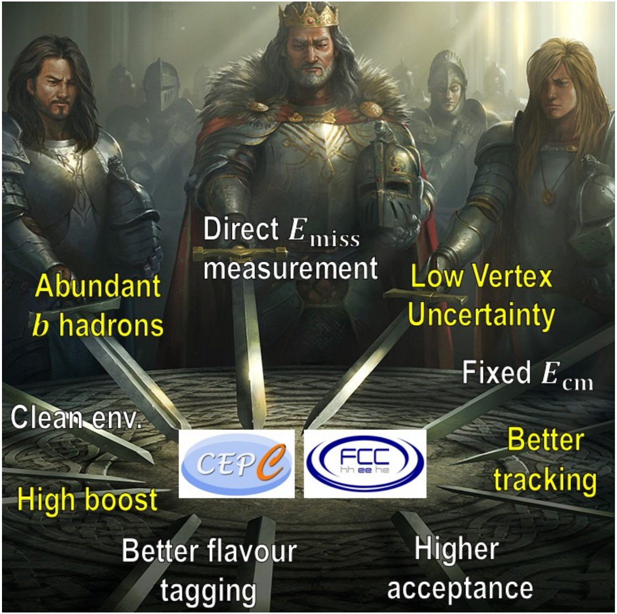
FCC-ee (Switzerland)



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 ($10^{34}\text{cm}^{-2}\text{s}^{-1}$, 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 [Anticipate to go out this year!!!]

Contents

Fully Neutral Final States [Wang et al. (2022)] [See also Y. Wang's Talk]

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

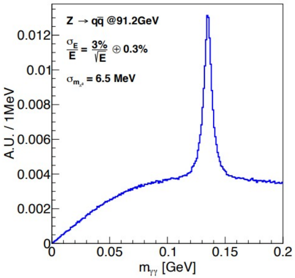
  uncert.($B^0 \to \eta^0\eta^0 \to 4\gamma$) $\sim$ 18%
  [Not observed]

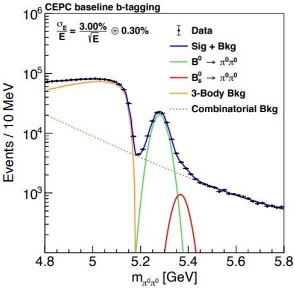
  uncert.($B^0_s \to \eta^0\eta^0 \to 4\gamma$) $\sim$ 0.95%

  [Not observed]

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

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





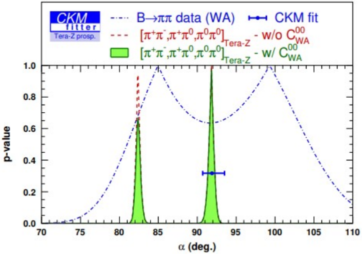
CKM elements: $\alpha(\phi_2)$ in UT [Wang et al. (2022)] [See also Y. Wang's Talk]

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

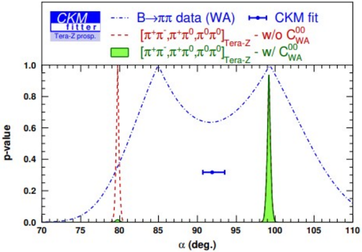
- Isopsin anaylsis of $B \to \pi\pi$
- Measuring $\alpha(\phi_2)$ from $B^0 \to \pi^0\pi^0 \to 4\gamma$

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

$a_{CP}^{00} = 0.95$;



$a_{CP}^{00} = 0.53$

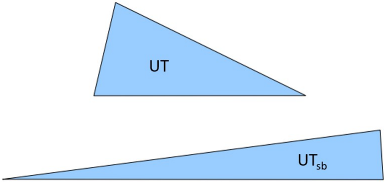


Current determination of α is limited by direct CP asymmetry of $B^0 \to \pi^0\pi^0$

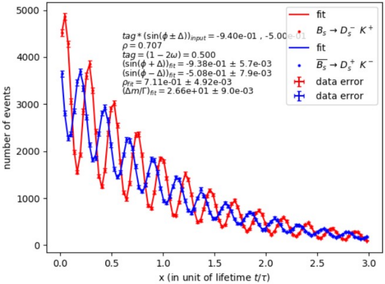
CKM elements: UT_{sb} angles [Aleksan et al. (2022, 2021)]

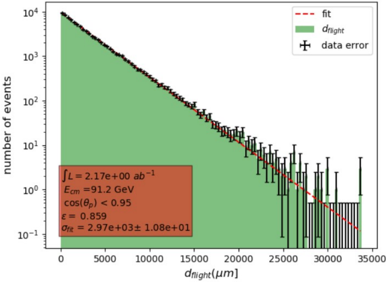
See also: [Aaij et al. (2013, 2015); Xiao et al. (2014)]

- 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.$(\gamma_s) \sim \mathcal{O}(1^\circ)$



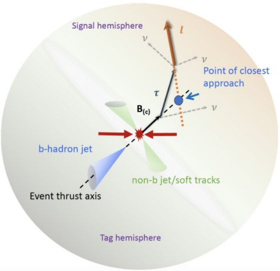
Challenging because UT_{sb} is relatively flat



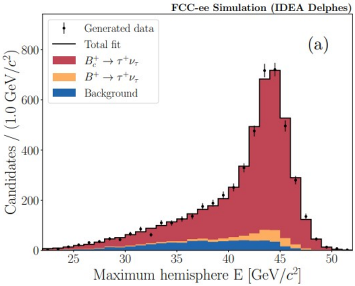


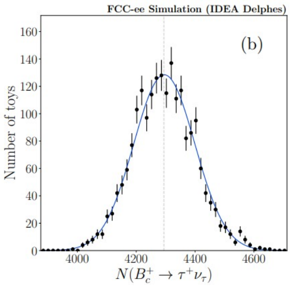
Charged (Pseudo)Scalar Decays [Zheng et al. (2020); Amhis et al. (2021)]

- 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)]

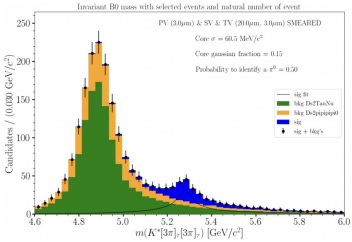
See also: [Kamenik et al. (2017); Monteil and Wilkinson (2021)]

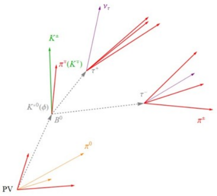
- Measuring $\mathrm{BR}(B^0 \to K^{*0}\tau^+\tau^-)$, $\mathrm{BR}(B_s \to \phi\tau^+\tau^-)$, $\mathrm{BR}(B^+ \to K\tau^+\tau^-)$

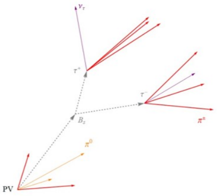
  uncert.$\sim \mathcal{O}(10^{-7} - 10^{-6})$**[Not observed]**
- Measuring $\mathrm{BR}(B_s \to \tau^+\tau^-)$

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

Testing 3rd generation FCNC NP (e.g. τ FCNC LFUV)







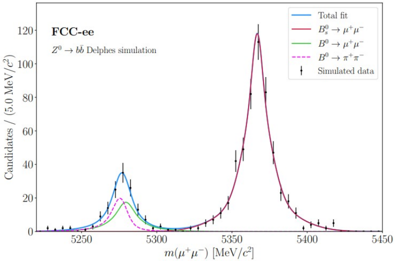
Ulta-rare (and LFV) decays [Monteil and Wilkinson (2021); Chrzaszcz et al. (2021)]

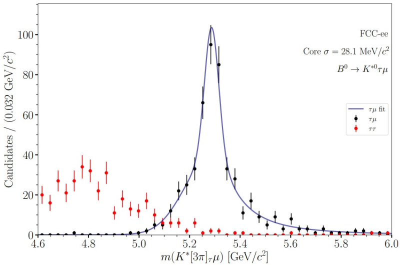
See also: [Monteil and Wilkinson (2021); Descotes-Genon et al. (2021)]

- Measuring BR($B_s^0 \to \mu^+\mu^-$), BR($B^0 \to \mu^+\mu^-$)
  Limit of BR($B_s^0 \to \mu^+\mu^-$): $\sim \mathcal{O}(10^{-10})$
  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: $B^0 \to K^{*0}\tau\mu$

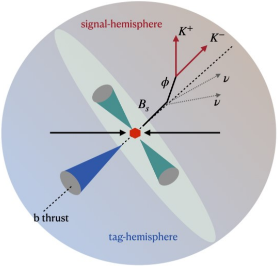




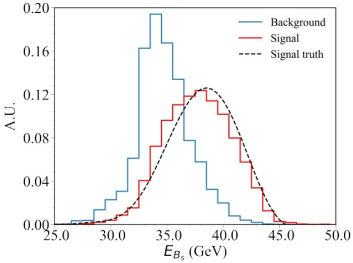
Di-neutrino Final State [Li et al. (2022)]

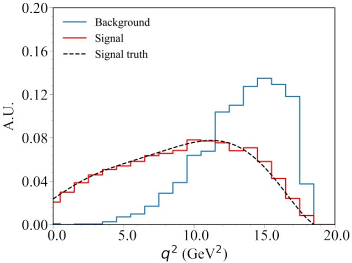
See also: [Batell et al. (2011); Dror et al. (2017)]

- 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



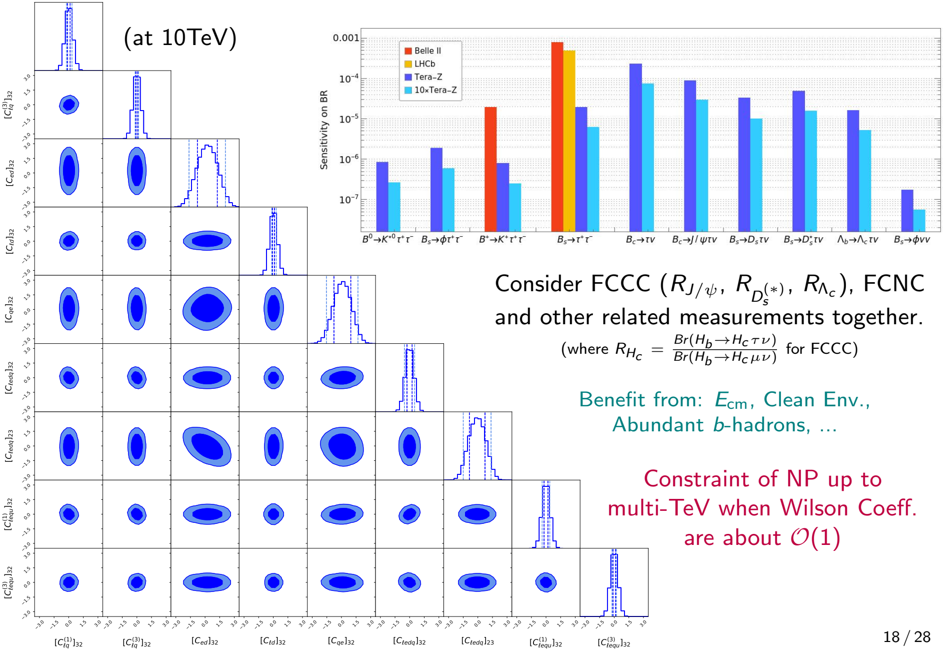
Useful for extracting CKM elements:
Clean theoretical predictions
Potentially constraint BSM,
which acts as E_{miss} (e.g. Dark Photon, ALP [Ongoing], ...)





Lepton Flavour Universality [See also X.H. Jiang's Talk]

(at 10TeV)



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

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

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

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

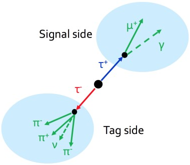
τ Physics [Dam (2019)]

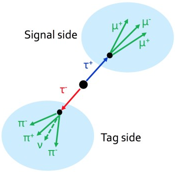
See also: [Dam (2021); Pich (2014); Celis et al. (2014); Calibbi and Signorelli (2018)]

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

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





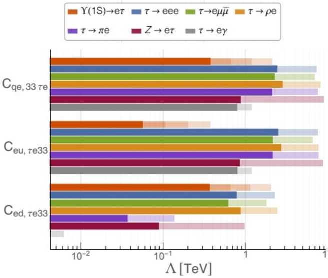
Decay	Present bound	FCC-ee sensitivity
$Z \to \mu e$	0.75×10^{-6}	10^{-10}–10^{-8}
$Z \to \tau\mu$	12×10^{-6}	10^{-9}
$Z \to \tau e$	9.8×10^{-6}	10^{-9}
$\tau \to \mu\gamma$	4.4×10^{-8}	2×10^{-9}
$\tau \to 3\mu$	2.1×10^{-8}	10^{-10}

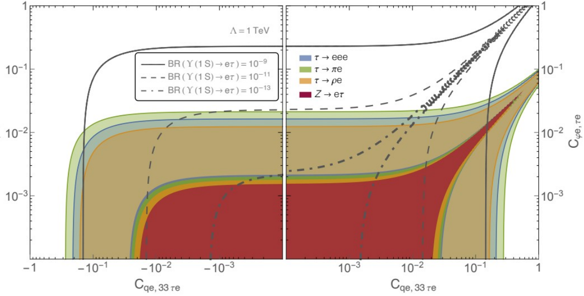
Flavour Physics From Z Decays [Calibbi et al. (2021, 2022); Dam (2019)]

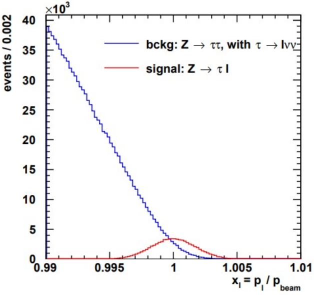
- Measuring $\mathrm{BR}(Z \to \ell\ell')$ with $(\ell \neq \ell')$

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

Z decays can well constrain operators involve top quarks.







Other Opportunities

Exotic Hadrons [See also F.K. Guo's Talk]:

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

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

Charm-Physics:

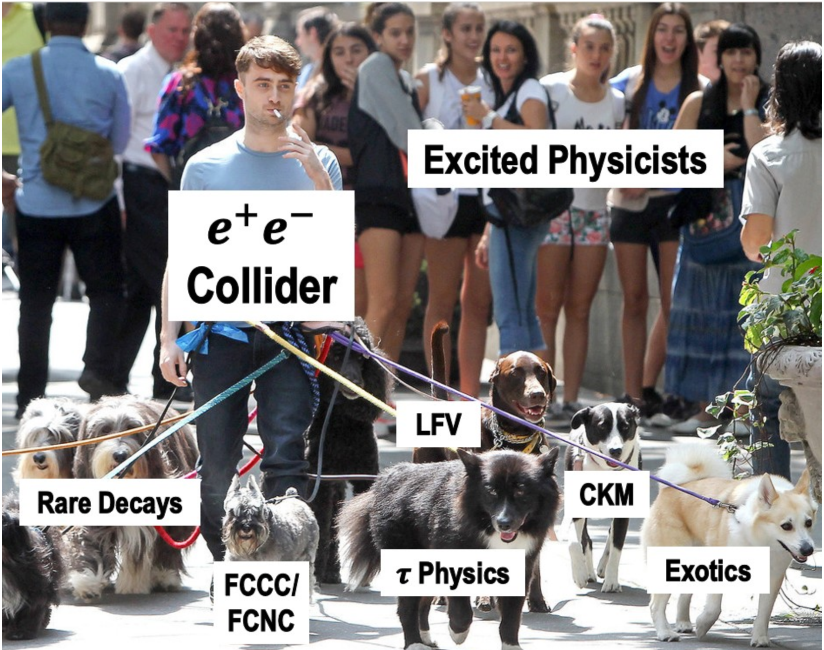
- $\text{BR}(Z \to c\bar{c}) \sim 12\%$ v.s. $\text{BR}(Z \to b\bar{b}) \sim 15\%$
- Similar to those of b-physics (e.g. CKM, FCNC, ...) [Bause et al. (2021)]

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.

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