05 - 09 June
FCC WEEK 2023

# Flavour Programme

Jernej F. Kamenik

Univerza *v Ljubljani*

Institut “Jožef Stefan”

Zoom/London
06/06/2023

# Scope of Flavour Physics

- Flavour is one of most puzzling aspects of SM ad hoc

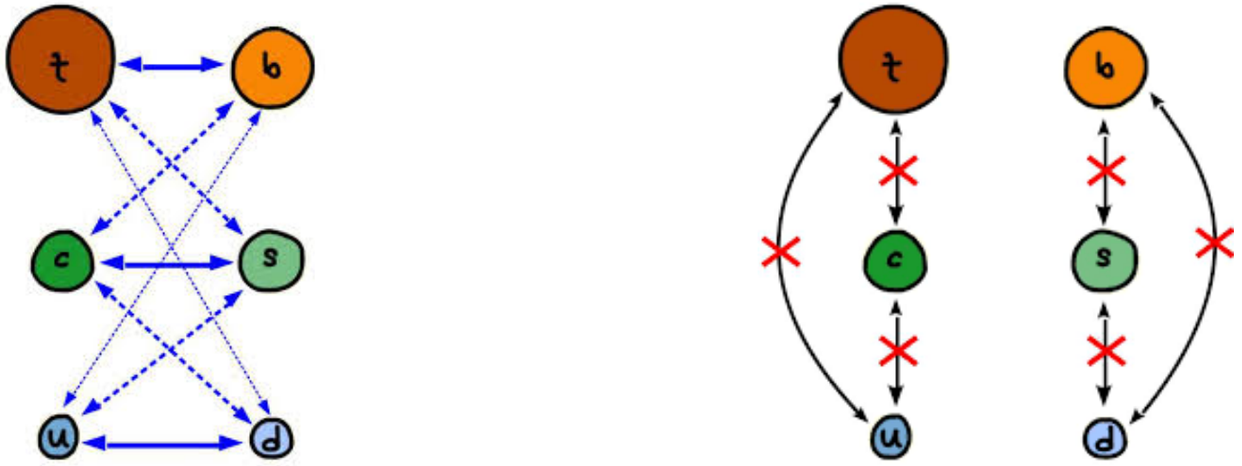
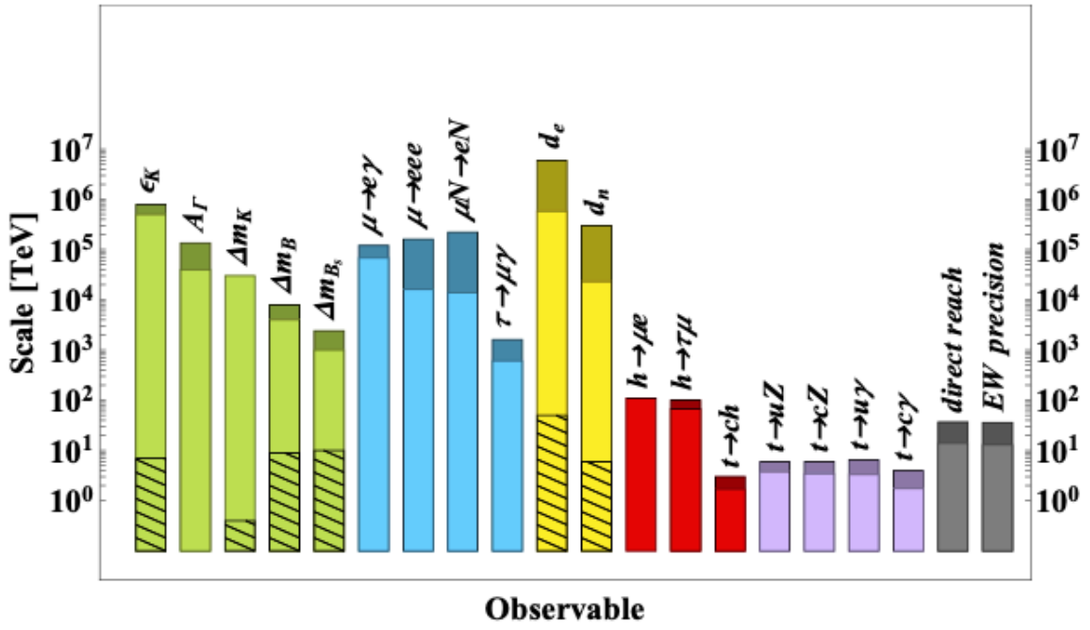



figure by
W. Altmannshofer

- strong suppression of flavor changing processes within SM
  ⇒ allows to probe deep UV dynamics




EU Strategy Update 2020
1910.11775

# Scope of Flavour Physics @ FCC(-ee)

- Flavour physics reach with O($10^{13}$) *Z* decays ($10^8$ *W*, $10^6$ Higgs, top)
  - rare decays of *c*- and *b*-hadrons and CP violation in the heavy-quark sector
  - rare (τ) lepton decays
  - rare *Z*, (*W*, *h*, *t*) decays
- In the context of ultimate potential of the LHCb upgrade and Belle II experiments.

S. Monteil, FCC PED Week 2023

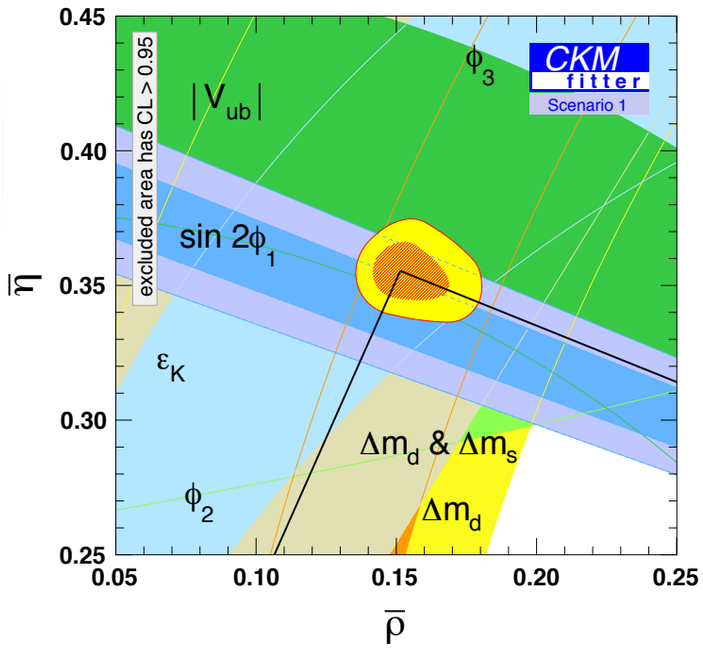
| Working point | Lumi. / IP [$10^{34}$ cm$^{-2}$.s$^{-1}$] | Total lumi. (2 IPs) | Run time | Physics goal |
|---|---|---|---|---|
| $Z$ first phase | 100 | 26 ab$^{-1}$ /year | 2 | |
| $Z$ second phase | 200 | 52 ab$^{-1}$ /year | 2 | 150 ab$^{-1}$ |

| Particle production ($10^9$) | $B^0$ / $\overline{B}^0$ | $B^+$ / $B^-$ | $B_s^0$ / $\overline{B}_s^0$ | $\Lambda_b$ / $\overline{\Lambda}_b$ | $c\bar{c}$ | $\tau^-/\tau^+$ |
|---|---|---|---|---|---|---|
| Belle II | 27.5 | 27.5 | n/a | n/a | 65 | 45 |
| FCC-*ee* | 300 | 300 | 80 | 80 | 600 | 150 |

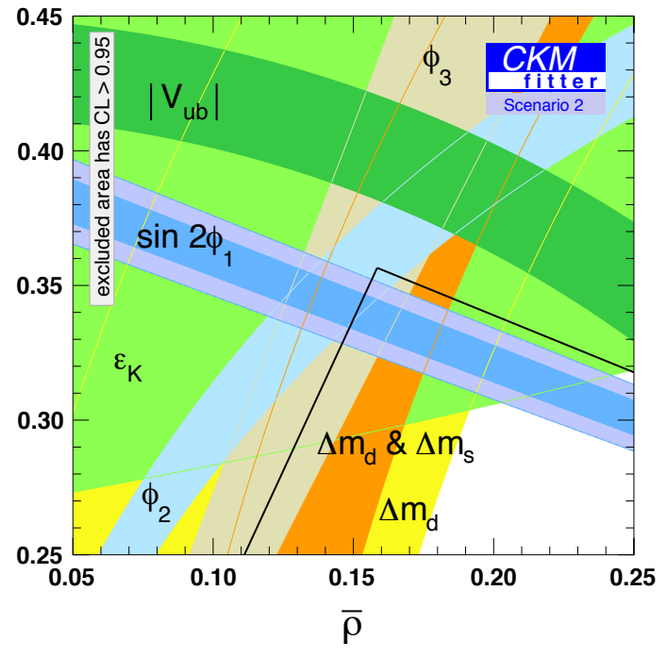
# Future flavor physics landscape: possible scenarios

**WA**

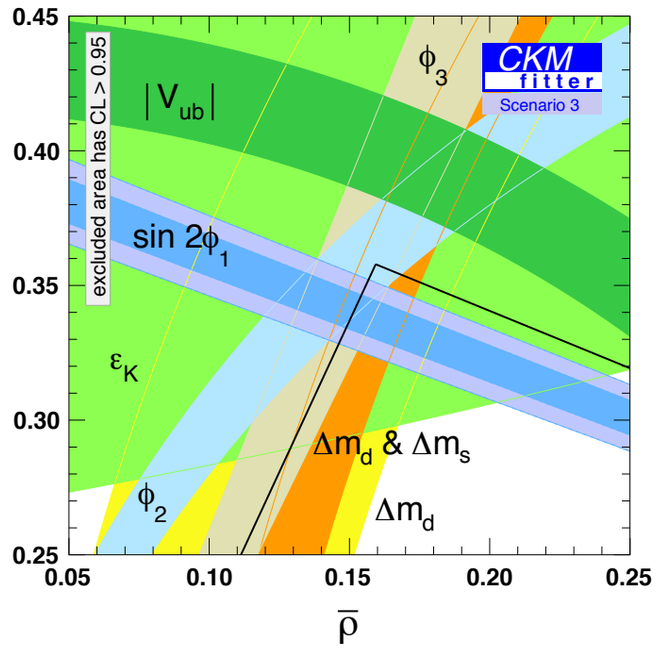
**Now**




**50 ab$^{-1}$ Belle II**

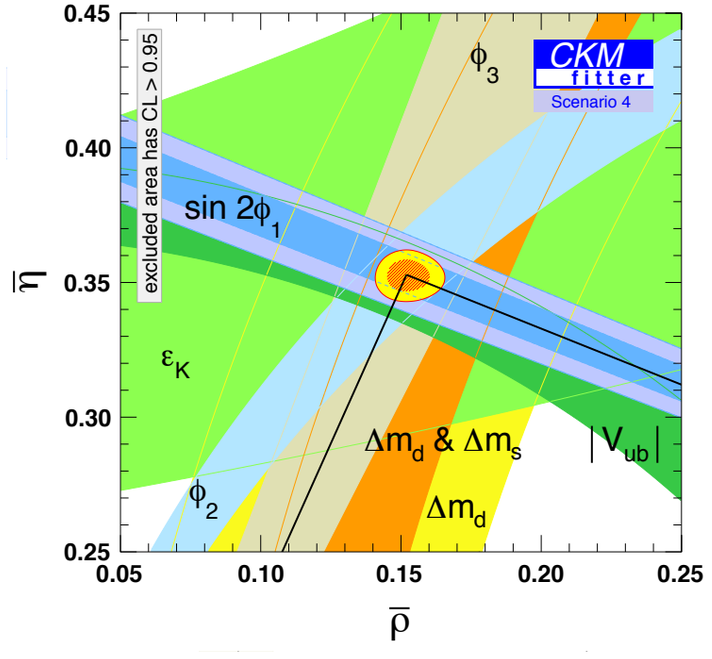



**50 ab$^{-1}$ Belle II + LHCb**

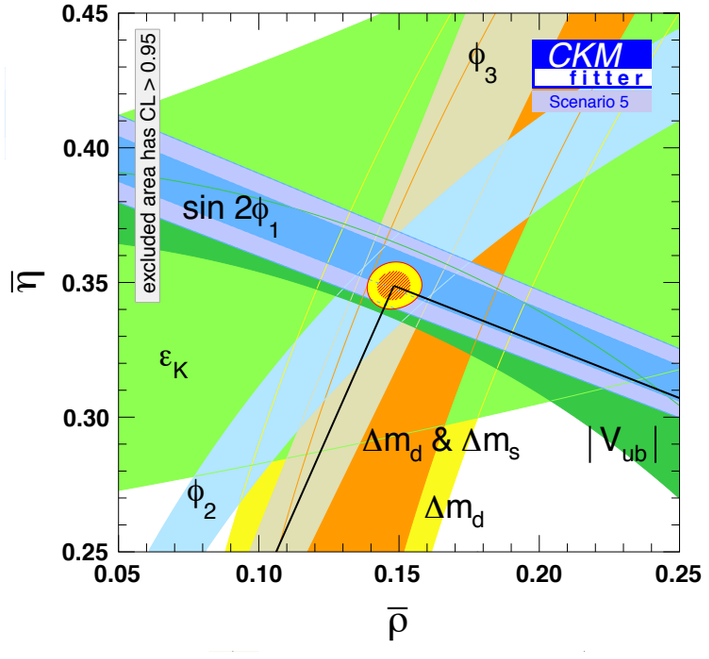



**SM-like**

**50 ab$^{-1}$ Belle II**




**50 ab$^{-1}$ Belle II + LHCb**




+ discoveries or bounds from high-$p_T$ LHC searches

# Mandate of Flavour Physics Group

with Gino Isidori

- identify key topics and observables
  (extensive and focused primarily on FCC-ee)
- propose new benchmark measurements
  (interface with exp. groups - detector requirements, exp. reach)
- project requirements and feasibility of precision calculations
  (i.e. EM/EW corrections, lattice QCD)

# Mandate of Flavour Physics Group

with Gino Isidori

- identify key topics and observables
  (extensive and focused primarily on FCC-ee)
- propose new benchmark measurements
  (interface with exp. groups - detector requirements, exp. reach)
- project requirements and feasibility of precision calculations
  (i.e. EM/EW corrections, lattice QCD)

## Interface with other working groups:

- Flavor of Higgs interactions ( $h \to \bar{f} f'$ , CPV, …)
- top-quark as a probe of flavor ( $V_{tx}$, CPV, LFU)
- Flavor at high $p_T$ (CKM from *W* decays, FCNC *Z* decays, …)

# Mandate of Flavour Physics Group

with Gino Isidori

- identify key topics and observables ⬅
  (extensive and focused primarily on FCC-ee)
- propose new benchmark measurements ⬅
  (interface with exp. groups - detector requirements, exp. reach)
- project requirements and feasibility of precision calculations
  (i.e. EM/EW corrections, lattice QCD)

## Interface with other working groups:

- Flavor of Higgs interactions ( $h \to \bar{f} f'$ , CPV, …)
- top-quark as a probe of flavor ( $V_{tx}$, CPV, LFU)
- Flavor at high $p_T$ (CKM from *W* decays, FCNC *Z* decays, …)

# Outline

1 Leptonic and semileptonic b decays

2 Rare leptonic and semileptonic b decays

3 CPV in b decays and mixing

4 Tau physics

5 Charm physics

6 Flavour @ high-pT

# Outline

1 Leptonic and semileptonic b decays

2 Rare leptonic and semileptonic b decays

3 CPV in b decays and mixing

4 Tau physics

5 Charm physics

6 Flavour @ high-pT

# 1 Leptonic and semileptonic b decays

- Traditionally focused on CKM ($|V_{cb}|$ & $|V_{ub}|$) extraction
  - Ultimate $|V_{ub}|$ precision possible with $B \to \pi l \nu$ and $B_s \to K l \nu$
- Projected statistics @ FCC-ee motivate precision tests of LFU

see also Ho et al., 2212.02433

  - Leptonic decays ($B_{u,c} \to \mu\nu, \tau\nu$) theoretically cleaner compared to exclusive semileptonic decays

$$Br(B^- \to \tau^- \bar{\nu}(\gamma))_{\rm SM} = 1.13(1) \times 10^{-4} \left(\frac{f_B}{0.2{\rm GeV}}\right)^2 \left(\frac{|V_{ub}|}{4 \times 10^{-3}}\right)^2$$

$$\left[\frac{\Gamma(B^+ \to \tau^+ \nu)}{\Gamma(B_c^+ \to \tau^+ \nu)}\right]_{SM*} = 0.782 \left|\frac{V_{ub} f_B}{V_{cb} f_{B_c}}\right|^2$$

$$\left[\frac{\Gamma(B \to \mu\nu)}{\Gamma(B \to \tau\nu)}\right]_{\rm SM} \simeq \frac{m_\mu^2 [1 - (m_\mu/m_B)^2]^2}{m_\tau^2 [1 - (m_\tau/m_B)^2]^2} (1 + \mathcal{O}(\alpha \log m_\tau/m_\mu))$$

see also Amhis et al., 2105.13330 Zheng et al., 2007.08234

- Differential LFU tests with inclusive semileptonic decays ($B \to X_c\, \mu\nu, \tau\nu$)

see e.g. Ligeti, Luke & Tackmann, 2112.07685

# Outline

1 Leptonic and semileptonic b decays

2 Rare leptonic and semileptonic b decays

3 CPV in b decays and mixing

4 Tau physics

5 Charm physics

6 Flavour @ high-pT

# 2 Rare leptonic and semileptonic b decays

- Rare *b*-hadron decays to taus
  - Partly motived by current intriguing exp. situation in rare & semitauonic *B* decays

    see e.g. Capdevilla et al., 1712.01919 Buttazzo et al., 1706.07808
  - Possibly large NP effects predicted in motivated BSM models

    see e.g. Bauer et al., 2110.10698
    - FCC-ee (unique) probe of SM predictions for $B \to [K^{(*)}]\ \tau^+\tau^-$

      see e.g. Li & Liu, 2012.00665
    - Complete kinematical reconstruction yields access to angular observables, tau polarization

      J.F.K. et al., 1705.11106
- FCC statistics allow to contemplate time-dependent (CPV) studies with rare (semi)leptonic decays - unique new window to CPV

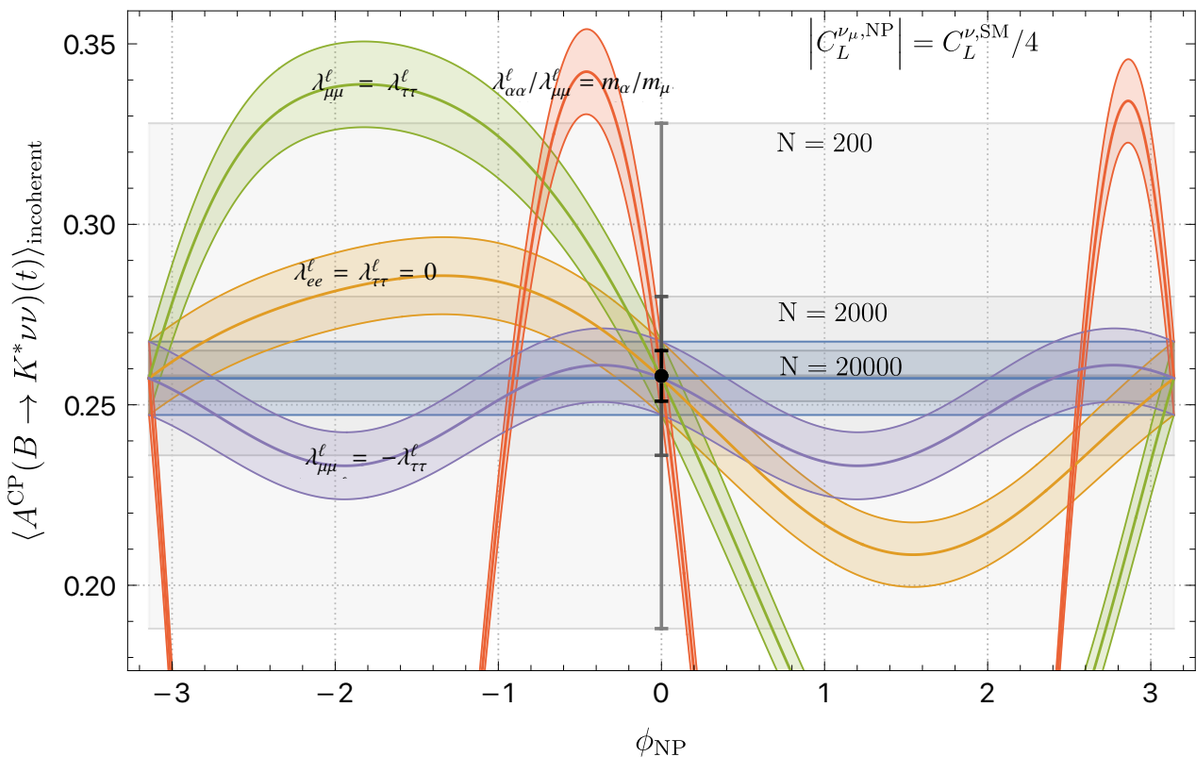
  see Fleisher et al., 2212.09575, 1709.04735, 1303.3820 Descotes-Genon, Novoa-Brunet, Vos, 2008.08000

# 2 Rare leptonic and semileptonic b decays

- Rare *b*-hadron decays to neutrinos
  - Belle II expected to measure SM rates of $B \to K^{(*)}\nu\nu$
  - FCC-ee statistics could allow for unique probes into CP nature of these decays via (time dependent/integrated) CP asymmetries

Descotes-Genon, et al., 2208.10880

- *Example*: time-integrated decay CP asymmetry



# 2 Rare leptonic and semileptonic b decays

- Rare *b*-hadron decays to neutrinos
  - Belle II expected to measure SM rates of $B \to K^{(*)}\nu\nu$
  - FCC-ee statistics could allow for unique probes into CP nature of these decays via (time dependent/integrated) CP asymmetries
- Rare (semi)leptonic $b \to d$ transitions $B \to [\pi,\varrho]\ [l^+l^-,\tau^+\tau^-]$
  - Challenging backgrounds (even from other rare *B* decays)
- LFV *B* decays will remain statistics dominated SM null-probes
  - Special theoretical interest in semi-taunic modes $B \to [h]\ l^+\ \tau^-$

# Outline

1 Leptonic and semileptonic b decays

2 Rare leptonic and semileptonic b decays

3 CPV in b decays and mixing

4 Tau physics

5 Charm physics

6 Flavour @ high-pT

# 3 CPV in b decays and mixing

- Determination of CKM phase angle $\gamma$ from $B \to D\ K$ decays
  - Tiny theoretical uncertainty in SM $|\delta\gamma| \lesssim \mathcal{O}(10^{-7})$

Brod and Zupan, 1308.5663

- Measurements of $\varphi_s$ from studies of $B_s \to \varphi\psi$, $B_s \to \varphi\varphi$, etc. could challenge current theory uncertainties
  - Potentially interesting new CPV probes: $B_s \to D_s\ K$ decays
  - Theoretical x-checks needed

Aleksan, Oliver and Perez, 2107.05311, 2107.02002

- Mixing induced semileptonic charge asymmetries

$$a_{\rm fs} = \frac{\Gamma(\bar{B}_q^0 \to B_q^0 \to f) - \Gamma(B_q^0 \to \bar{B}_q^0 \to \bar{f})}{\Gamma(\bar{B}_q^0 \to B_q^0 \to f) + \Gamma(B_q^0 \to \bar{B}_q^0 \to \bar{f})}$$

  - Can experimental sensitivity reach SM theory predictions?

$$a_{\rm fs}^{s,{\rm SM},2015} = (2.22 \pm 0.27) \cdot 10^{-5} \qquad a_{\rm fs}^{d,{\rm SM},2015} = (-4.7 \pm 0.6) \cdot 10^{-4}$$

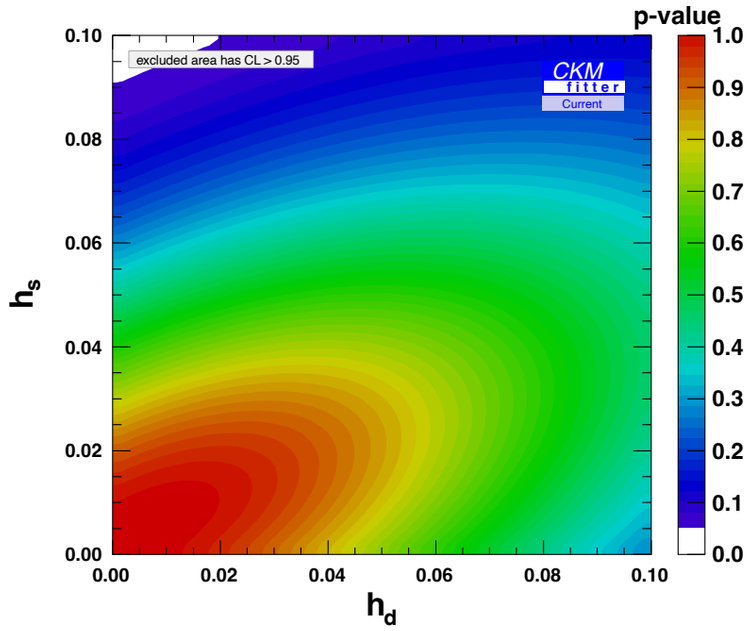
Artuso, Borissov & Lenz, 1511.09466

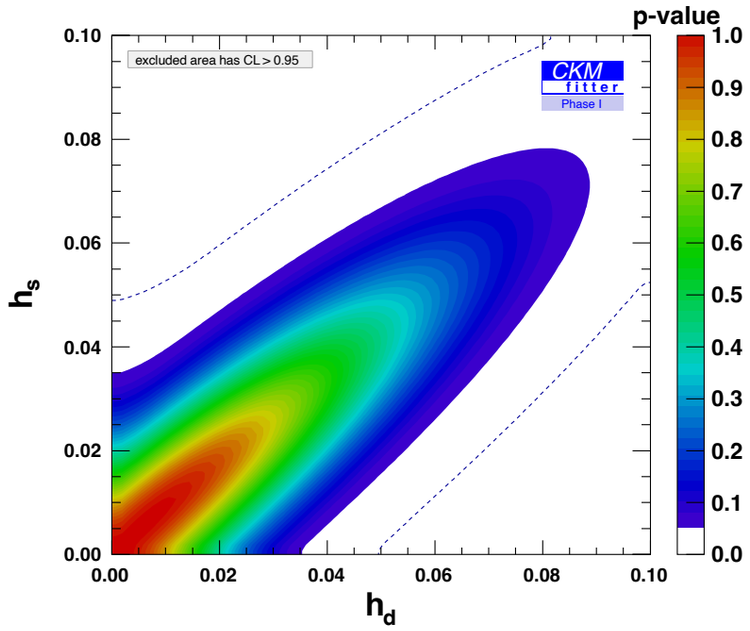
# 3 CPV in b decays and mixing

Charles et al., 2006.04824

- Projections of NP reach - $B_{d,s}$ mixing $M_{12} = \left(M_{12}\right)_{\rm SM} \times \left(1 + h_{d,s}\, e^{2i\sigma_{d,s}}\right)$

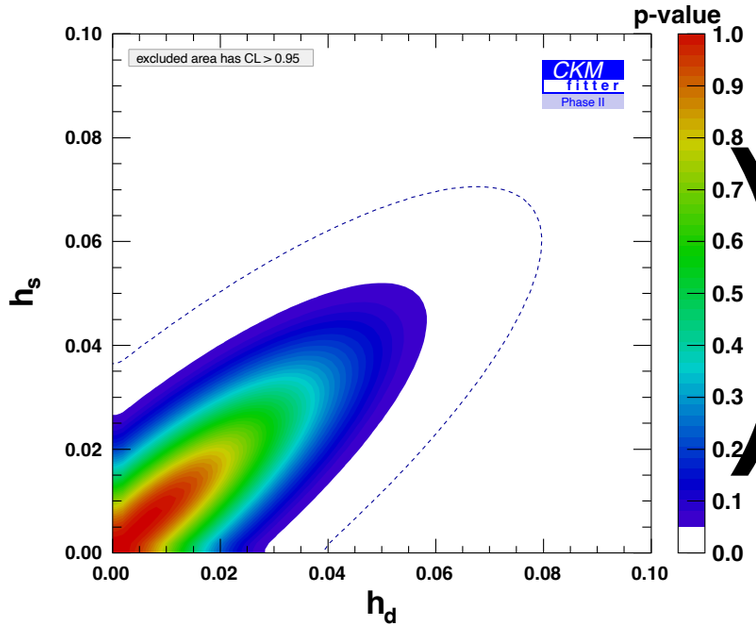
Now

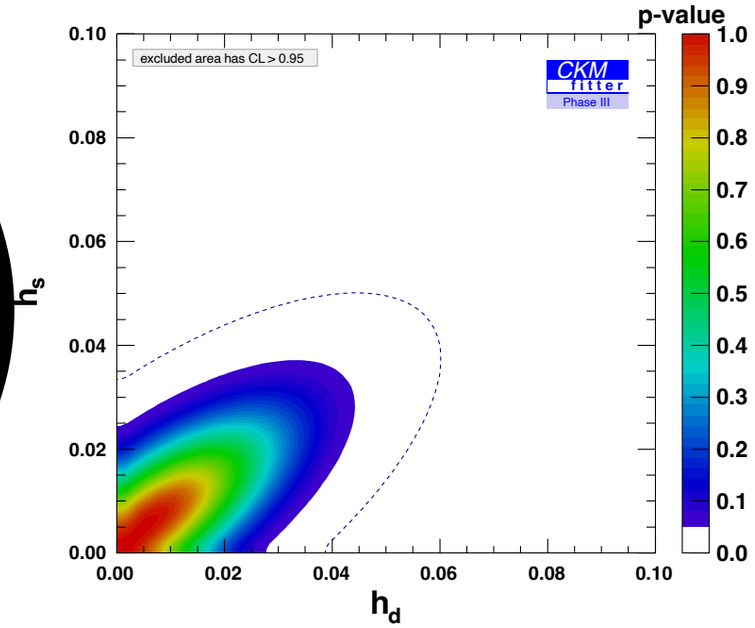



LHCb 50/fb, Belle II 50/ab

( LHCb 300/fb, Belle II 250/ab




**FCC-ee**

# Outline

1 Leptonic and semileptonic b decays

2 Rare leptonic and semileptonic b decays

3 CPV in b decays and mixing

4 Tau physics

5 Charm physics

6 Flavour @ high-pT

# 4 Tau physics

- Partially motivated also by current flavour anomalies

  Allwicher, Isidori & Selimovic, 2109.03833
  Feruglio, Paradisi & Pattori, 1705.00929

- Charged current mediated leptonic decays
  - Expect ultimate exp. precision on LFU ratio $\frac{\Gamma(\tau \to e\nu\bar{\nu})}{\Gamma(\tau \to \mu\nu\bar{\nu})}$
    - Theoretical work needed to go beyond $10^{-3}$ relative precision
- Charged current mediated semi-leptonic modes ($|V_{us}|$, $\alpha_s$)
  - Potentially interesting inclusive $\tau \to X\,\nu$ measurement
    + hadronic moments
- LFV $\tau$ decays will remain statistics dominated SM null-probes

# Outline

1 Leptonic and semileptonic b decays

2 Rare leptonic and semileptonic b decays

3 CPV in b decays and mixing

4 Tau physics

5 Charm physics

6 Flavour @ high-pT

# 5 Charm physics

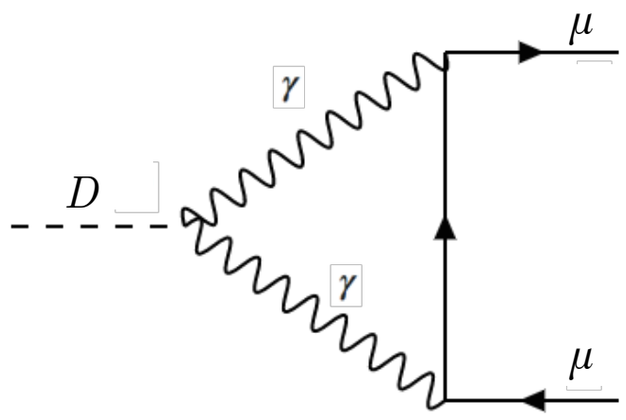
- CPV in radiative charm decays
  - theoretically related to $\Delta A_{CP}$ (currently only measurement of CPV in charm sector)

see e.g.
Isidori and J. F. K., 1205.3164

- Study of rare $D \to [\pi, \varrho]\ \nu\nu$
  - complementary to rare semileptonic K decays

see e.g.
Fajfer et al., 2305.13851

- Purely radiative $D \to \gamma\gamma$ decay
  - needed for SM prediction of $D \to \mu\mu$



# Outline

1 Leptonic and semileptonic b decays

2 Rare leptonic and semileptonic b decays

3 CPV in b decays and mixing

4 Tau physics

5 Charm physics

6 Flavour @ high-pT

# 6 Flavour @ high-pT

- Exploiting large statistics of Z, W, h @ FCC-ee
  - Measurement of $|V_{cb}|$ at 0.4% precision from $W \to j_b j_c$

M.-H. Schune, FCC PE Workshop 2020

  - Direct probes of Z and h FCNCs

J.F.K. et al., 2306.xxxxx

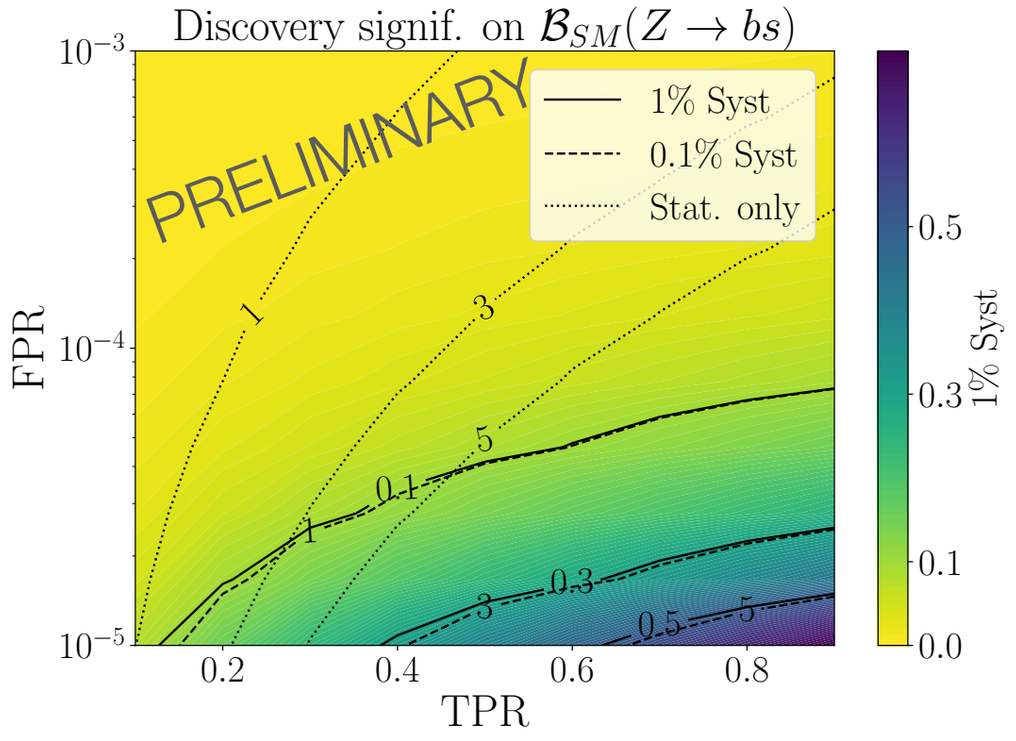
$$\mathcal{L} \supset g^L_{sb}(\bar{s}_L \gamma_\mu b_L) Z^\mu + g^R_{sb}(\bar{s}_R \gamma_\mu b_R) Z^\mu + y_{sb}(\bar{s}_L b_R) h + y_{bs}(\bar{b}_L s_R) h + \text{h.c.}\,,$$

- Non-vanishing in SM

$$\mathcal{B}(Z \to bs) = (4.2 \pm 0.7) \times 10^{-8}\,,$$

$$\mathcal{B}(h \to b\bar{s}) = (2.7 \pm 0.5) \times 10^{-7}$$

- could probe SM Z-FCNCs
- complementary to rare b-decays



# 6 Flavour @ high-pT

- Exploiting large statistics of Z, W, h @ FCC-ee
  - Measurement of $|V_{cb}|$ at 0.4% precision from $W \to j_b j_c$

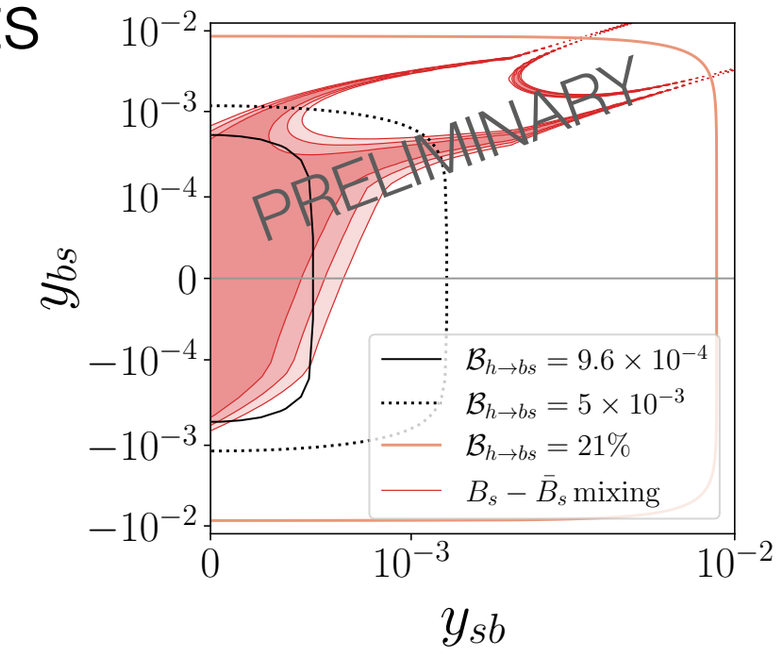
M.-H. Schune, FCC PE Workshop 2020

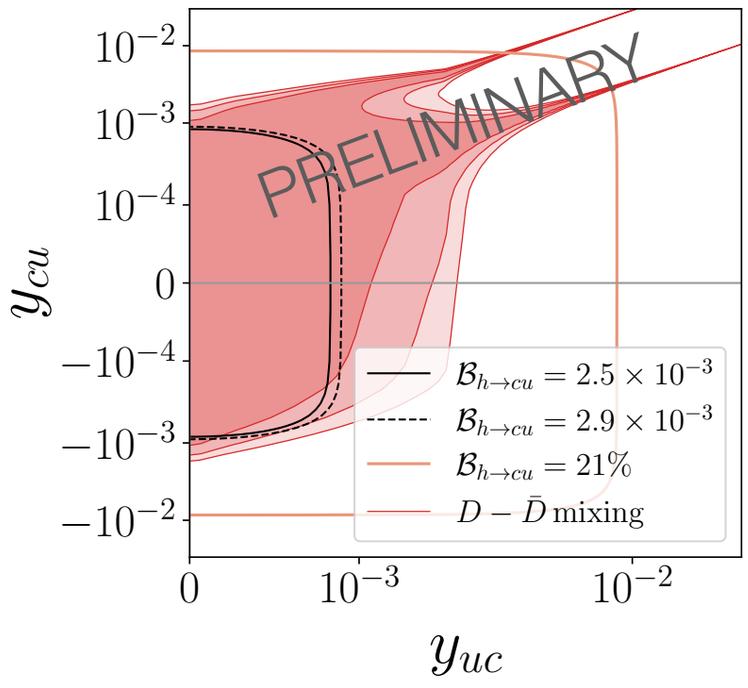
  - Direct probes of Z and h FCNCs

J.F.K. et al., 2306.xxxxx

$$\mathcal{L} \supset g^L_{sb}(\bar{s}_L \gamma_\mu b_L) Z^\mu + g^R_{sb}(\bar{s}_R \gamma_\mu b_R) Z^\mu + y_{sb}(\bar{s}_L b_R) h + y_{bs}(\bar{b}_L s_R) h + \text{h.c.}\,,$$

- Direct Higgs measurements competitive with meson mixing constraints



# Conclusions

- FCC-ee could be a powerful and competitive probe of flavour physics beyond current experimental programs

- Effort underway to understand exp. precision with which rare decays of c- and b-hadrons and CP violation in heavy-quark sector & LFV processes could be measured

- Less explored areas in scope of FCC-ee,-hh include flavour studies using top decays, spectroscopy, quarkonium physics & flavor conversion @ high-$p_T$

see e.g.
Descotes-Genon et al., 2303.07521
Faroughy et al., 2209.01222
J.F.K. et al., 1808.00964