FUTURE CIRCULAR COLLIDER

30 May - 3 June

Flavour Programme

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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 lepton decays
  - rare *Z*, (*W*, *h*, *t*?) decays
- In the context of ultimate potential of the LHCb upgrade and Belle II experiments.

FCC CDR

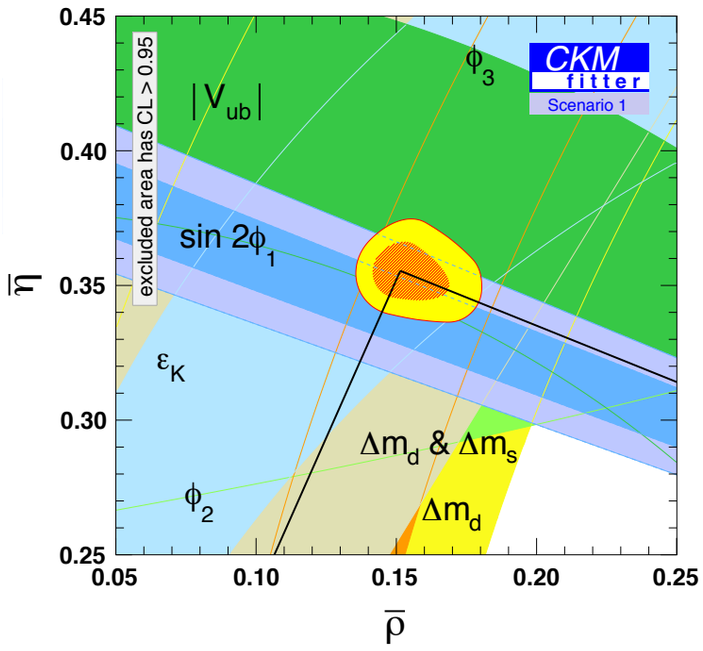
Working point	Lumi. / IP [10^{34} cm^{-2}.s^{-1}]	Total lumi. (2 IPs)	Run time	Physics goal
Z first phase	100	26 ab^{-1} /year	2	
Z second phase	200	52 ab^{-1} /year	2	150 ab^{-1}

Particle production (10^9)	B^0	B^-	B_s^0	Λ_b	$c\bar{c}$	$\tau^-\tau^+$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	400	400	100	100	800	220

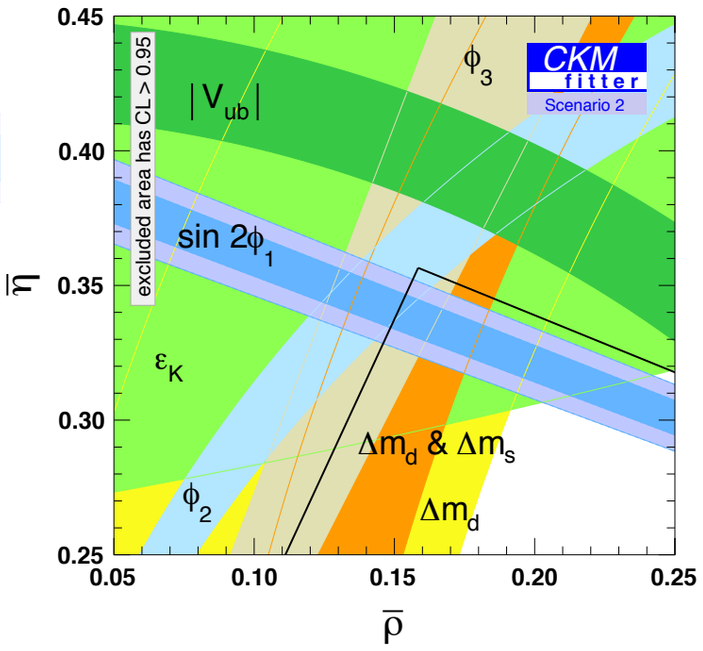
Future flavor physics landscape: possible scenarios

WA

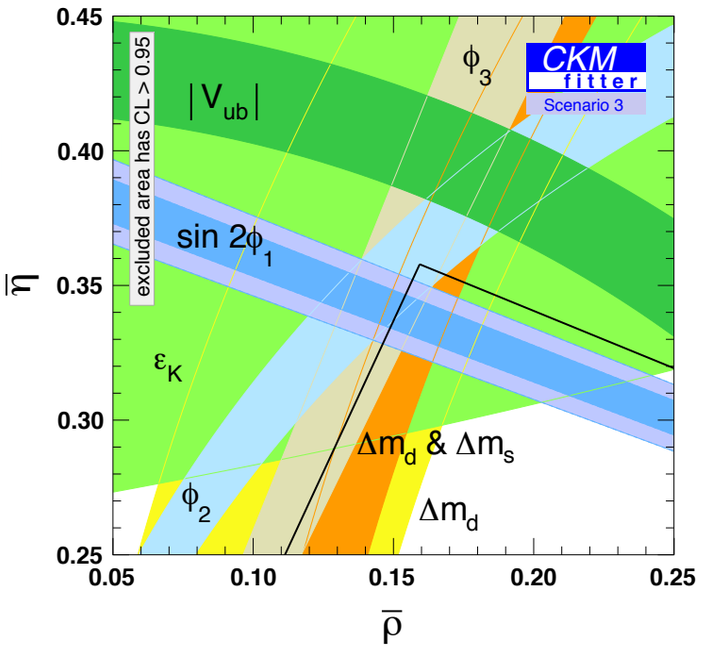
Now



50 ab^{-1} Belle II

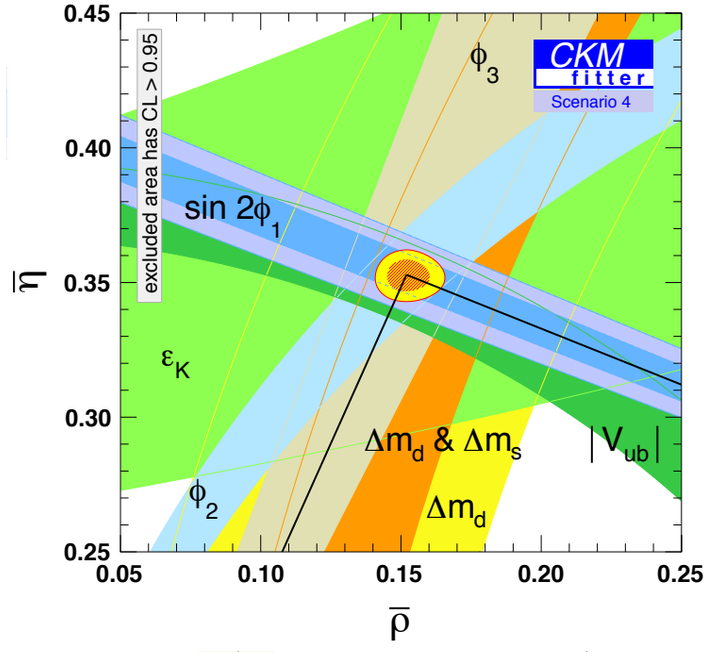


50 ab^{-1} Belle II + LHCb



SM-like

50 ab^{-1} Belle II



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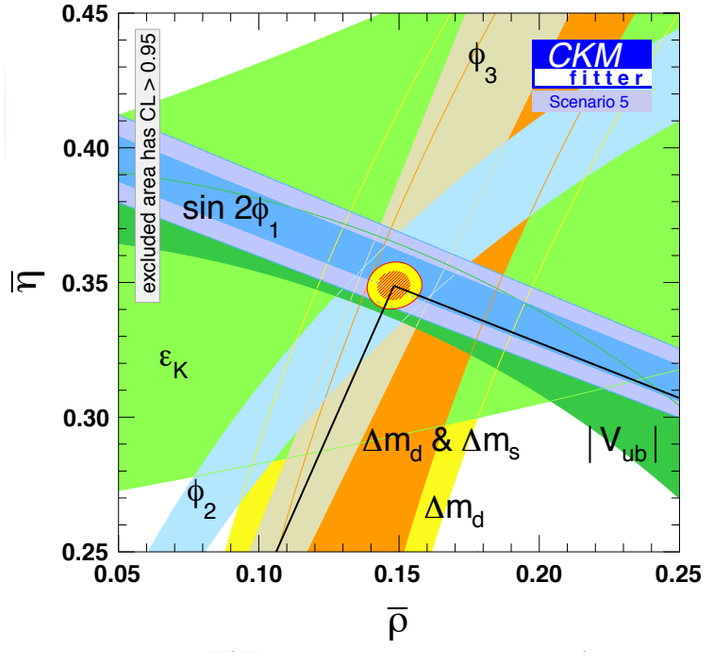

+ discoveries or bounds from high-p_T LHC searches

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)

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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, …)

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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

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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
  - 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 ($B \to X_c\ \mu\nu, \tau\nu$)

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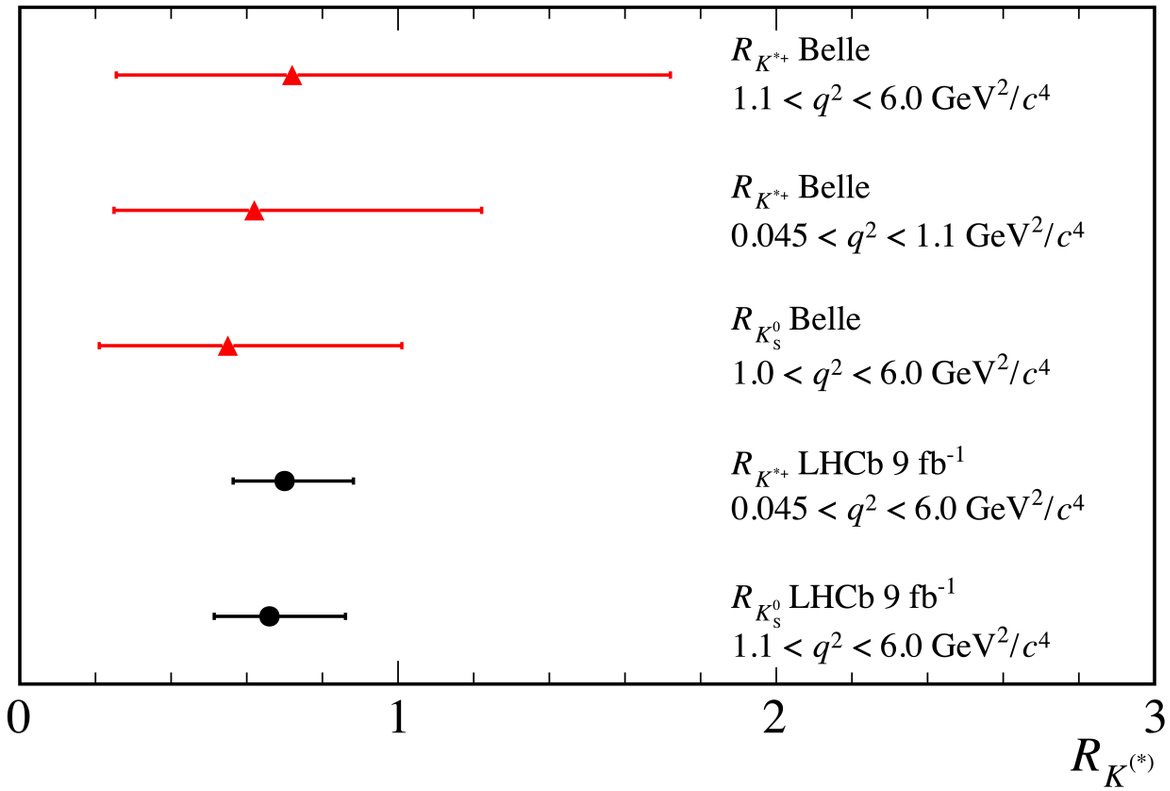
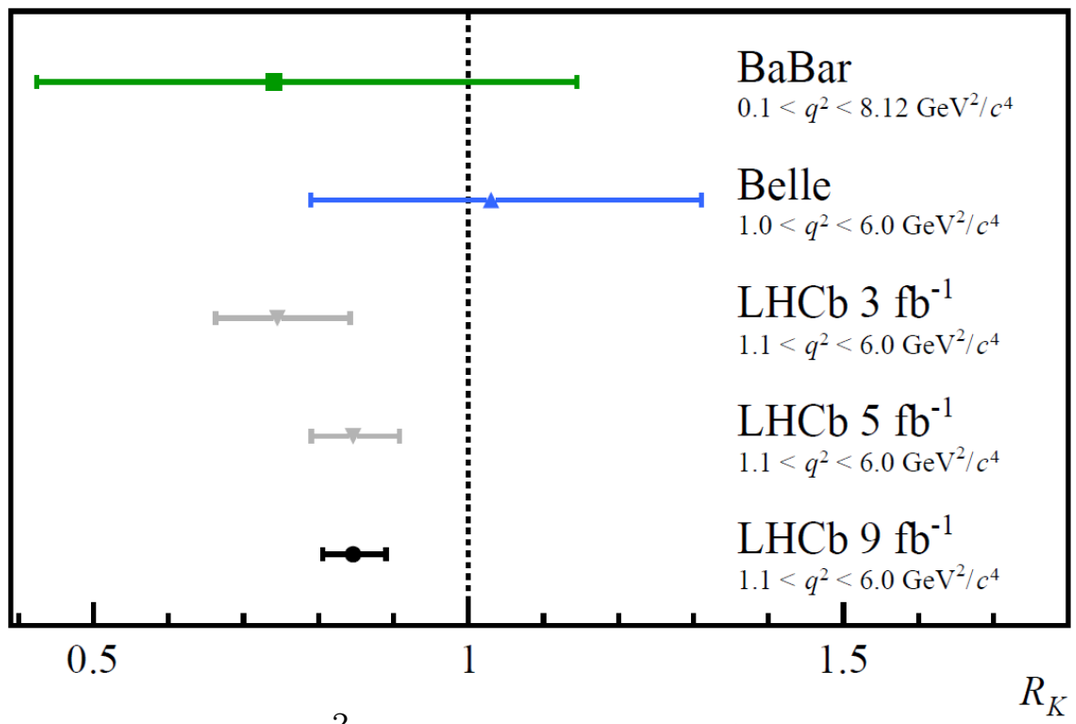
2 Rare leptonic and semileptonic b decays

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





$$R_H \equiv \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{\mathrm{d}\mathcal{B}(B \to H\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{\mathrm{d}\mathcal{B}(B \to He^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2}$$

2 Rare leptonic and semileptonic b decays

- Rare *b*-hadron decays to taus
  - Partly motived by current intriguing exp. situation in rare *B* decays
  - FCC-ee (unique) probe of SM predictions for $B \to [K^{(*)}]\ \tau^+\tau^-$

$$R^{\mu\tau}_{K^+} = 0.87 \pm 0.02 \quad , \quad R^{\mu\tau}_{K^0} = 0.87 \pm 0.02 \ , \quad 15\ \mathrm{GeV}^2 < q^2 < 22\ \mathrm{GeV}^2$$

$$R^{\mu\tau}_{K^{*+}} = 2.44 \pm 0.09 \ , \quad R^{\mu\tau}_{K^{*0}} = 2.45 \pm 0.08 \ , \quad 15\ \mathrm{GeV}^2 < q^2 < 19.2\ \mathrm{GeV}^2.$$

  - Complete kinematical reconstruction yields access to angular observables, tau polarization

J.F.K. et al., 1705.11106

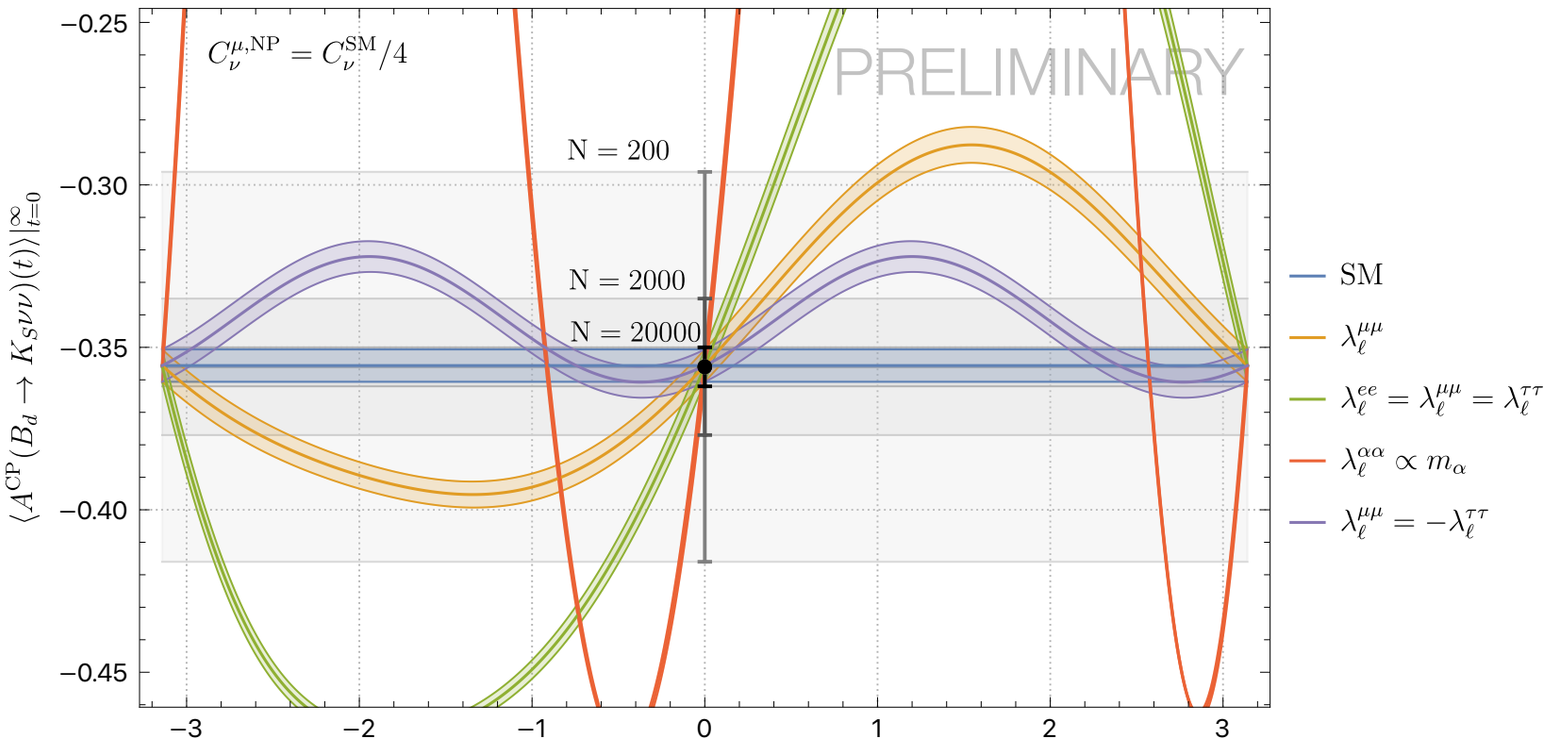
- FCC statistics allow to contemplate time-dependent (CPV) studies with rare (semi)leptonic decays

see also R. Fleisher et al., 1709.04735, 1303.3820
S. Descotes-Genon, M. Novoa-Brunet, K. 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) CP asymmetries

- Example: time-integrated decay CP asymmetry



in preparation with S. Descotes-Genon, S. Fajfer & **M. Novoa-Brunet**

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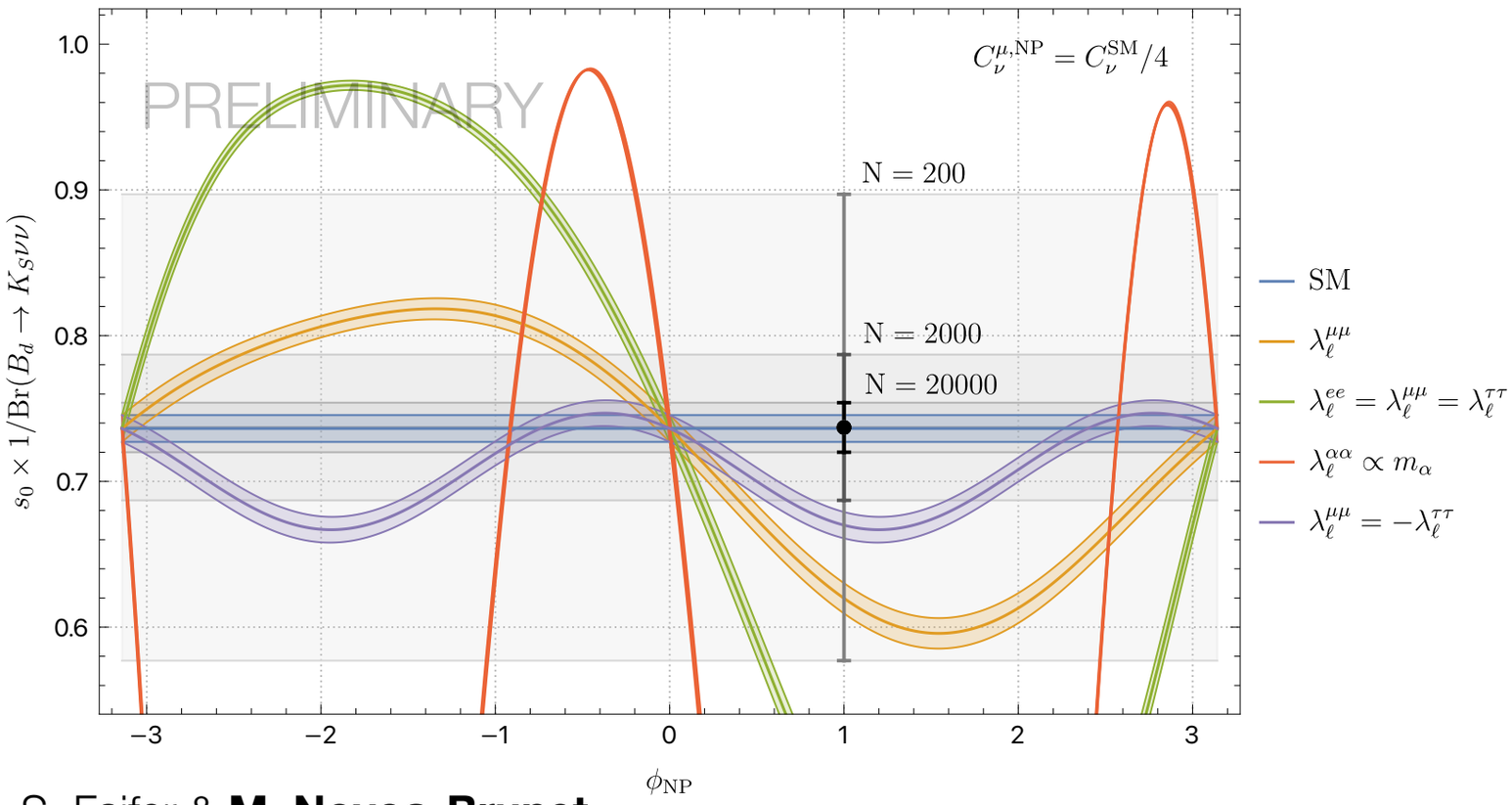
- Example: time-dependent decay CP asymmetry

$$d\Gamma(B_d \to K_S\,\nu\bar{\nu}) - d\Gamma(\bar{B}_d \to K_S\,\nu\bar{\nu}) \propto$$

$$e^{-\Gamma t}[(G_0 - \bar{G}_0)\cos(x\Gamma t) + s_0 \sin(x\Gamma t)]$$



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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) 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
  - Especial theoretical interest in semi-taunic modes $B \to [h]\ l^+\ \tau^-$

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

J. Brod and J. Zupan, 1308.5663

- Measurements of φ_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

R. Aleksan, L. Oliver and E. Perez, 2107.05311, 2107.02002

  - Theoretical x-checks needed

- 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

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- Partially motivated also by current LFU anomalies

L. Allwicher, G. Isidori and N. Selimovic, 2109.03833
F. Feruglio, P. Paradisi & A. 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 ($|V_{us}|$, α_s)
  - Potentially interesting inclusive $\tau \to X\ \nu$ measurement + hadronic moments
- LFV τ decays will remain statistics dominated SM null-probes

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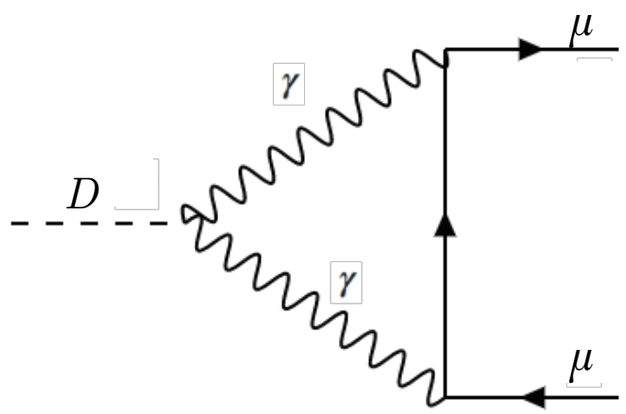
- CPV in radiative charm decays
  - theoretically related to ΔA_{CP} (currently only measurement of CPV in charm sector)

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

- Study of rare $D \to [\pi,\, \varrho]\ \nu\nu$
  - can be related to rare semileptonic K decays in flavor alignment models

see e.g.
Gedalia et al., 1202.5038

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



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

  see next talk by S. Monteil

- Less explored areas include flavour studies using top & Higgs decays, spectroscopy, quarkonium physics, flavor conversion @ high-p_T