Theory challenges for Flavour physics at Higgs and EW factories

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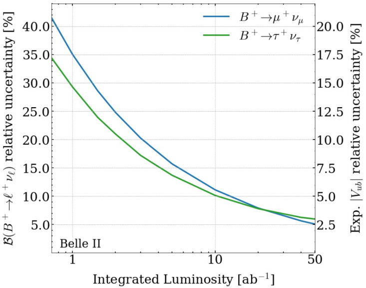
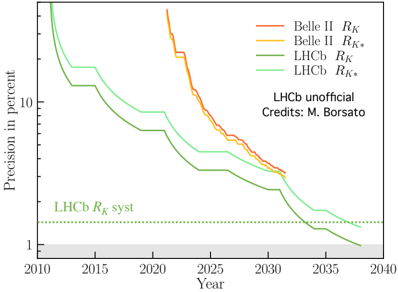
Precision Era in Flavour Physics



[Belle II Physics Book]

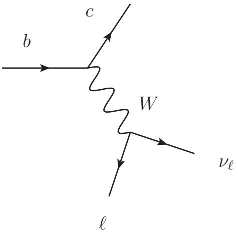


[Santimaria's Implication talk, '20]

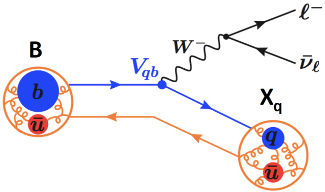
Lessons from current measurements

- New physics in flavour processes lives at scale $\Lambda > \mathcal{O}(\mathrm{TeV})$
- It is expected to be (sub)percent deviations in tree-level and loop-mediated processes
  - $\Rightarrow$ Larger effects are also possible and still not excluded by low and high energy flavour data
- The flavour structure of New physics couplings can be complex
  - $\Rightarrow$ If we are driven by the flavour puzzle, we expect new physics to affect more the 3rd generation
- Correlations between different modes are essential for model building development

The drawback of flavour



$\mu_{\text{partonic}} = m_b$



$\mu_{\text{hadronic}} = \Lambda_{\text{QCD}}$

Non-perturbative effects are calculated using various techniques

- Sum Rules and their variants still have large uncertainties, especially when predicting branching fractions
  - $\Rightarrow$ Define observables free of hadronic uncertainties
- Lattice QCD calculations exist/ are ongoing, ultimate precision is still not reached
  - $\Rightarrow$ Matter of time and computational power!

Prospects at Z factories

Channel	Belle II	LHCb-U1a	FCC-ee
B^0, $\bar{B}^0$	$\sim 5 \times 10^{10}$	$\sim 6 \times 10^{13}$	$\sim 6.2 \times 10^{11}$
$B^\pm$	$\sim 5 \times 10^{10}$	$\sim 6 \times 10^{13}$	$\sim 6.2 \times 10^{11}$
B_s^0, $\bar{B}_s^0$	$\sim 6 \times 10^{8}$	$\sim 2 \times 10^{13}$	$\sim 1.5 \times 10^{11}$
$B_c^\pm$	–	$\sim 2 \times 10^{11}$	$\sim 4 \times 10^{9}$
Λ_b, $\bar{\Lambda}_b$	–	$\sim 2 \times 10^{13}$	$\sim 1.30 \times 10^{11}$

[Archilli, Altmannshofer, '22]

- Statistics in between Belle II and LHCb, but
  - ⇒ good reconstruction efficiency
  - ⇒ good resolution on missing momentum
- b-hadrons are more boosted than at Belle II
  - ⇒ More accurate tracking reconstruction

Semileptonic decays

Leptonic $B_q \to \ell\nu$ decays

Advantages w.r.t. Semileptonic B_q decays

- Cleaner from a theoretical point of view
  - $\Rightarrow$ No form factors are needed
  - $\Rightarrow$ Standard Model decay constant are known with high precision from Lattice QCD

Caveat:

- structure dependent QED terms can be important with high statistics
  - $\Rightarrow$ Well discussed in Belle II and LHCb environment, worth re-discussing in a new environment and with new analysis strategy

Lepton Flavour universality tests

$$\frac{\mathcal{B}(B_q \to \tau\bar{\nu})}{\mathcal{B}(B_q \to \mu\bar{\nu})} = \frac{m_\tau^2[1-(m_\tau/m_{B_q})^2]^2}{m_\mu^2(1-[m_\mu/m_{B_q})^2]^2}[1+\mathcal{O}(\alpha\log(m_\tau/m_\mu))]$$

Measurement of CKM ratios

$$\frac{\mathcal{B}(B_c \to \ell\bar{\nu})}{\mathcal{B}(B \to \ell\bar{\nu})} = \frac{|V_{cb}f_{B_c}|^2}{|V_{ub}f_B|^2}$$

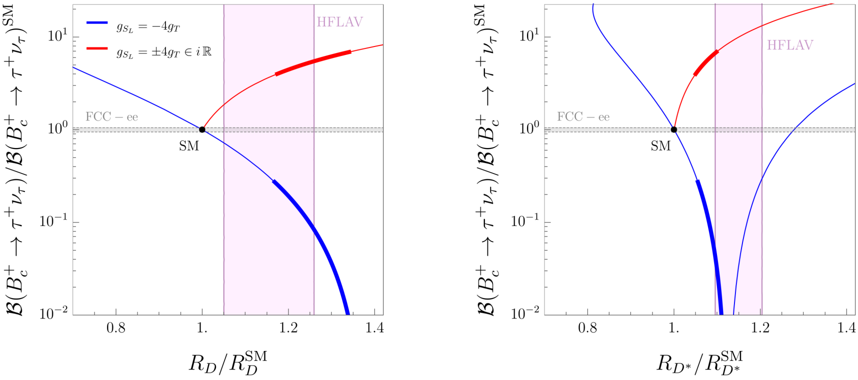
Drawbacks:

- $B_q \to \mu\nu$ is suppressed wrt $B_q \to \tau\nu$ of a factor $m_\mu^2/m_\tau^2 \sim \mathcal{O}(10^{-3})$
- $B_q \to \tau(\to \mu\nu\bar{\nu})\bar{\nu}$ is an important background to $B_q \to \mu\nu$

$\Rightarrow$ Cuts in kinematical variables should help control it [MB, Isidori, van Dyk, '16, Alonso, Kobach, Camalich, '16]

New Physics in $B_c \to \tau\bar{\nu}$

[Amhis, Hartmann, Helsens, Hill, Sumensari, '21]



$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\mu\bar{\nu})}$$

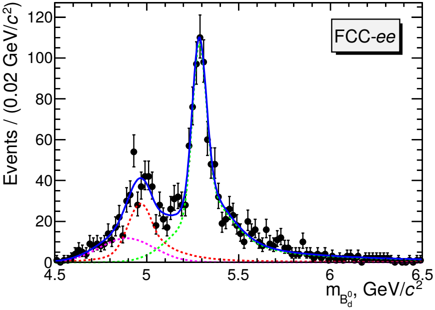
Rare decays

Modes with a τ pair in the final state

- Current constraints on $b \to s\tau\tau$ allow for large NP contributions

$$\frac{B_s \to \tau\tau|_{\rm SM}}{B_s \to \tau\tau|_{\rm exp}} \sim \mathcal{O}(10^4)$$

- Belle II and LHCb plans to reduce the gap to $\mathcal{O}(10^3)$ at the end of Upgrade II

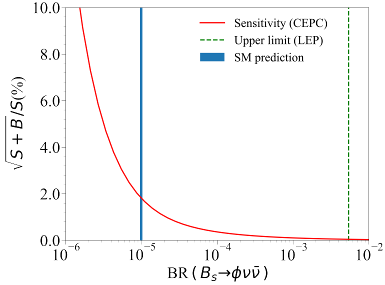


- ~ 1000 reconstructed $B \to K^*\tau\tau$
- Similar projections for $B \to K\tau\tau$
- Possible measurements of these modes, not only upper limits
- Angular coefficients are also measurable

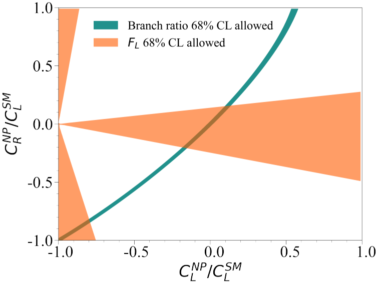
[Kamenik, Monteil, Semkiv, Vale Silva, '17]

Modes with neutrinos in the final state

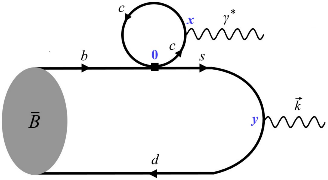
- Modes with neutrinos are important to distinguish among heavy new physics states
- Expected sensitivity at Belle II on $B \to K^{(*)} \nu \bar{\nu} \sim \mathcal{O}(10\%)$
- If the reconstruction efficiencies don't change, we can expect to reduce the sensitivity to $\mathcal{O}(2-3\%)$



[Li, Ruan, Wang, Wang, '22]



Data driven determination of non perturbative physics



- The computation of non-perturbative effects in the resonant region is of utmost importance
- These effects are universal among the three generations
- Data driven methods allow for the extraction of non-perturbative parameters
- Can we learn something more?

- Large data samples allow precise measurement of $B^0 \to K^* e^+ e^-$ branching ratio and angular distribution
- The comparison with corresponding muon mode determines the size of the non perturbative physics
- It also provides a test of LFU

Decay mode	$B^0 \to K^* e^+ e^-$
Belle II	~ 2000
LHCb Upgrade	~ 20000
FCC-ee	~ 50000

Charm decays

Charm physics

- At FCC-ee, $\sim 6 \times 10^{11}$ $c\bar{c}$ pairs are expected

Channel	Z-factory
D^0	$\sim 70 \times 10^{10}$
$D^{\pm}$	$\sim 30 \times 10^{10}$
D_s^0	$\sim 10 \times 10^{10}$
Λ_c	$\sim 10 \times 10^{10}$

- Roughly a factor 10 more statistics than Belle II
- LHCb Upgrade II overcomes this estimates largely
- FCC-ee can contribute in modes with neutrino in the final states

$D \to h\nu\bar{\nu}$

- Short distance contribution is suppressed by CKM and coupling $Z \to \nu\bar{\nu}$

- Long distance contributions from light-resonances can be accounted for in naive factorisation using non-leptonic data

  $\Rightarrow$ they are also estimated to be very small **[Burdmana, Golowichb, Hewettc, Pakvasad, '02]**

$$\mathcal{B}(D \to h\nu\bar{\nu}) \sim 10^{-13} - 10^{-15}$$

[Bause, Gisbert, Golz, Hiller, '20]

$h_c \to F$	$\mathcal{B}_{\text{LU}}^{\text{max}}$ $[10^{-7}]$	$\mathcal{B}_{\text{cLFC}}^{\text{max}}$ $[10^{-6}]$	$\mathcal{B}^{\text{max}}$ $[10^{-6}]$	$N_{\text{LU}}^{\text{max}}/\eta_{\text{eff}}$	$N_{\text{cLFC}}^{\text{max}}/\eta_{\text{eff}}$	$N^{\text{max}}/\eta_{\text{eff}}$
$D^0 \to \pi^0$	6.1	3.5	13	47 k (395 k)	270 k (2.3 M)	980 k (8.3 M)
$D^+ \to \pi^+$	25	14	52	77 k (650 k)	440 k (3.7 M)	1.6 M (14 M)
$D_s^+ \to K^+$	4.6	2.6	9.6	6 k (50 k)	34 k (290 k)	120 k (1.1 M)
$D^0 \to \pi^0\pi^0$	1.5	0.8	3.1	11 k (95 k)	64 k (540 k)	230 k (2.0 M)
$D^0 \to \pi^+\pi^-$	2.8	1.6	5.9	22 k (180 k)	120 k (1.0 M)	450 k (3.8 M)
$D^0 \to K^+K^-$	0.03	0.02	0.06	0.2 k (1.9 k)	1.3 k (11 k)	4.8 k (40 k)
$\Lambda_c^+ \to p^+$	18	11	39	14 k (120 k)	82 k (700 k)	300 k (2.6 M)
$\Xi_c^+ \to \Sigma^+$	36	21	76	28 k (240 k)	160 k (1.4 M)	590 k (5.0 M)
$D^0 \to X$	15	8.7	32	120 k (980 k)	660 k (5.6 M)	2.4 M (21 M)
$D^+ \to X$	38	22	80	120 k (1.0 M)	680 k (5.8 M)	2.5 M (21 M)
$D_s^+ \to X$	18	10	38	24 k (200 k)	140 k (1.1 M)	500 k (4.2 M)

NP contributions should be easily found with FCC-ee statistics

τ decays

Status of τ physics

Channel	LEP	Belle II	FCC-ee
$\tau^+\tau^-$	$\sim 10^5$	$\sim 45 \times 10^9$	$\sim 170 \times 10^9$

Advantages of a Z factory: higher boost of the τs

- Easier lifetime measurement
- better quality of identification of final state particles

Status:

- only modest improvement by Belle II
- branching fraction LEP measurements are unchallenged

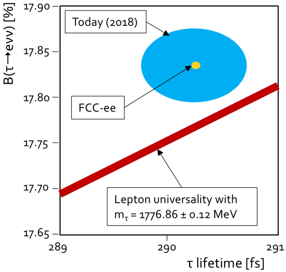
Leptonic branching fractions:

$$\Gamma_{\ell\to\ell'} \equiv \Gamma[\ell \to \ell' \nu_{\ell'} \bar{\nu}_\ell] = \frac{G_{\ell\ell'}^2 m_\ell^5}{193\pi^3} f(m_{\ell'}/m_\ell)(1+\delta_{\mathrm{RC}}^{\ell\ell'})$$

- Electroweak corrections to $G_{\ell\ell'}$ are known
- QED corrections are known up to α_{EM}^3 **[Fael, Schönwald, Steinhauser, '20]**
  - $\Rightarrow$ match the expected precision at FCC-ee $\sim \mathcal{O}(10^{-6})$
- Measurement of LFU ratios possible below the $\mathcal{O}(0.1\%)$

τ properties

[Dam, '18]



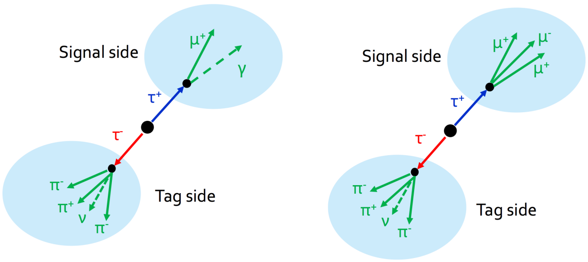
- Red band obtained under hypothesis of universality
- Only limitation is the measurement of the τ mass
  - $\Rightarrow$ no substantial improvement at FCC-ee

Summary

- The possibilities for flavour physics at the e^+e^- machines are numerous
- High statistics and detector efficiency allow to have large statistics in many channels
- There are questions open that need to be addressed:
  - QED effects need to be estimated at equal precision as the experimental sensitivity
  - Backgrounds can be estimated theoretically to propose interesting cuts to experimental analysis
  - High sensitivity helps for data-driven determination of non-perturbative quantities
- Collaboration of theory and experimental community is of utmost importance!

Appendix

Charged Lepton Flavour Violation



- Sensitivity on the same level of the ones at Belle II