Flavour Physics: Current Status and Future Directions

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Flavour for New Physics at Present and Future Colliders

MITP

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Outline:

1. The problem of flavour
2. Open problems in hadronic physics
3. Beyond the LHC and Belle II

Motivation

Despite the SM successes,
there are open problems:

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Hierarchy problem

dark matter/dark energy

flavour hierarchies

neutrino masses

gravity

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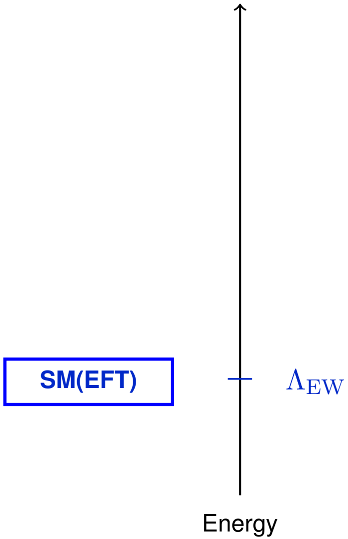

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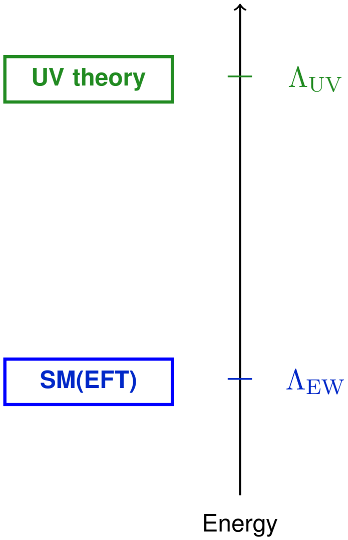

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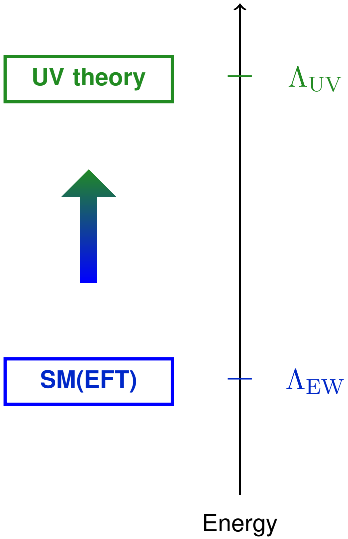


The (two) flavour problems

1. **The SM flavour problem**: The measured Yukawa pattern doesn't seem accidental

   ⇒ Is there any deeper reason for that?

2. **The NP flavour problem**: If we regard the SM as an EFT valid below a certain energy cutoff Λ, why don't we see any deviations in flavour changing processes?

   ⇒ Which is the flavour structure of BSM physics?

The SM flavour problem

$$\mathcal{L}_{\text{Yukawa}} \supset Y_u^{ij} \bar{Q}_L^i H u_R^j$$

$$Y_u \sim y_t \begin{pmatrix} & & 0.003 \\ & & 0.04 \\ & & 1 \end{pmatrix}$$

The SM flavour problem

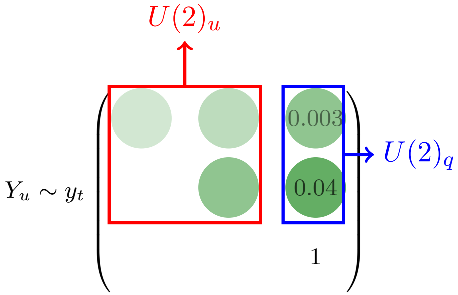
$$\mathcal{L}_{\text{Yukawa}} \supset Y_u^{ij} \bar{Q}_L^i H u_R^j$$

$$Y_u \sim y_t \begin{pmatrix} & & \\ & & \\ & & 1 \end{pmatrix}$$

Exact $U(2)^n$ limit

The SM flavour problem

$$\mathcal{L}_{\text{Yukawa}} \supset Y_u^{ij} \bar{Q}_L^i H u_R^j$$



An approximate $U(2)^n$ is acting on the light families!

The NP flavour problem

$$\mathcal{L} = \boxed{\mathcal{L}_{\text{gauge}}} + \boxed{\mathcal{L}_{\text{Higgs}}}$$

Large Flavour symmetry

Three replica of the same fermion fields

$\Downarrow$

$U(3)^5$ symmetry

Flavour degeneracy is broken

The breaking is peculiar

- In the SM: accidental $U(3)^5 \to$ approx $U(2)^n$

The NP flavour problem

$$\mathcal{L} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \sum_{d,i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^d$$

Large Flavour symmetry

Three replica of the same fermion fields

$U(3)^5$ symmetry

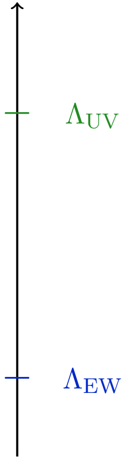
Flavour degeneracy is broken

The breaking is peculiar

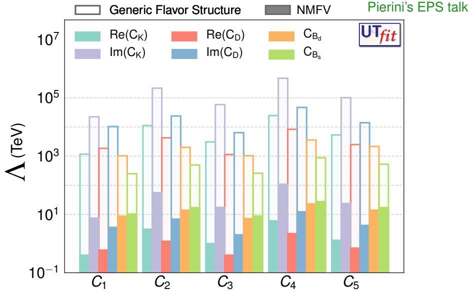
- In the SM: accidental $U(3)^5 \to$ approx $U(2)^n$
- **What happens when we switch on NP?**

The NP flavour problem

$$\mathcal{L} = \boxed{\mathcal{L}_{\text{gauge}}} + \boxed{\mathcal{L}_{\text{Higgs}}} + \boxed{\sum_{d,i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^d}$$

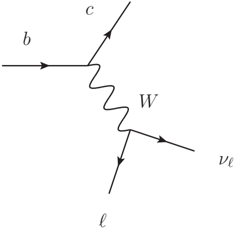


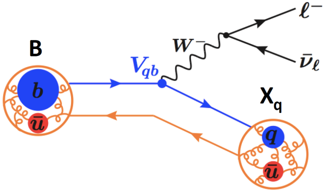
- What is the energy scale of NP?
- Why haven't observed any violation of accidental symmetries yet?



no breaking of the $U(2)^n$ flavour symmetry at low energies

Partonic vs Hadronic





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

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

Fundamental challenge to match partonic and hadronic descriptions

Open problems in hadronic physics

What are the open themes in hadronic physics?

1. Extraction of the CKM elements V_{cb} and V_{ub}

2. Non-local effects in $b \to s\ell\ell$

3. Non-leptonic decays

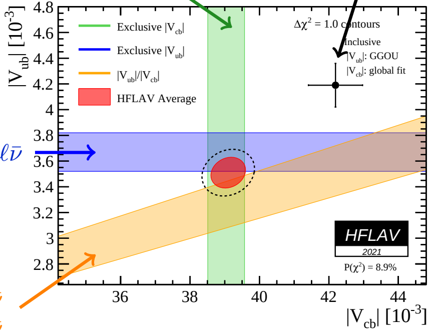
The $V_{cb} - V_{ub}$ puzzle

- Large discrepancies between inclusive and exclusive determinations
- Recent work mostly on $B \to D^*$ due to new lattice QCD form factors determinations
- When precision increases, more puzzles arise

$B \to D^{(*)}\ell\bar{\nu}$

$B \to X_{c,u}\ell\bar{\nu}$

$B \to \pi\ell\bar{\nu}$



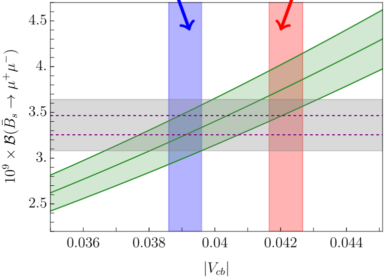
$\Lambda_b \to p\ell\bar{\nu}/\Lambda_b \to \Lambda_c\ell\bar{\nu}$

$B_s \to K\ell\bar{\nu}/B \to D\ell\bar{\nu}$

- $|V_{cb}|$ is a fundamental parameter
  - $\mathcal{B}(B_s \to \mu^+\mu^-) \sim |V_{cb}|^2$
  - $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) \sim |V_{cb}|^4$

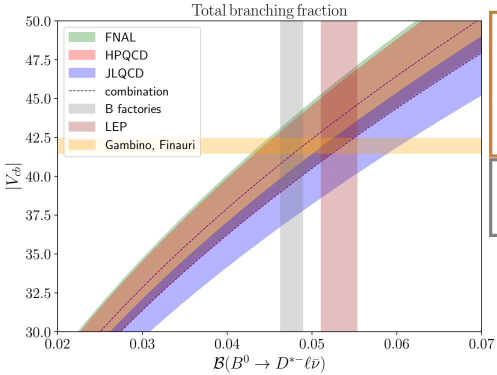
exclusive

inclusive



Exclusive V_{cb} from $B \to D^*$

MB, A. Jüttner, '23 + WIP



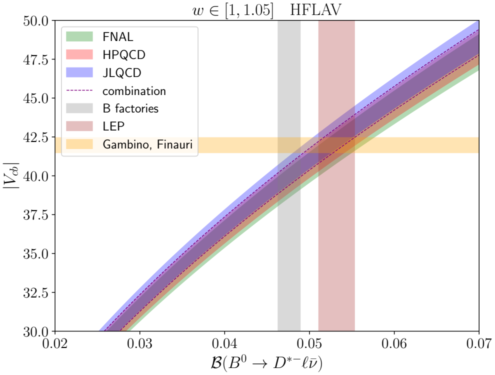
Experiment	BF (rescaled) [%]	Parameters	
ALEPH	5.56 +/- 0.27 +/- 0.33	input	parameters
OPAL incl	6.13 +/- 0.28 +/- 0.57	input	parameters
OPAL excl	5.17 +/- 0.20 +/- 0.36	input	parameters
DELPHI incl	4.96 +/- 0.14 +/- 0.35	input	parameters
DELPHI excl	5.23 +/- 0.20 +/- 0.42	input	parameters
CLEO	6.17 +/- 0.19 +/- 0.37	input	parameters
BELLE untagged	4.90 +/- 0.02 +/- 0.16	input	parameters
BELLE tagged	4.95 +/- 0.11 +/- 0.22	input	parameters
BABAR untagged	4.52 +/- 0.04 +/- 0.33	input	parameters
BABAR tagged	5.26 +/- 0.16 +/- 0.31	input	parameters
Average	**5.06 +/- 0.02 +/- 0.12**	**chi2/dof = 16.0/9 (CL = 0.0661)**	

- Shape information shifts the total branching fraction prediction

Thanks to C. Schwanda for the averages!

Exclusive V_{cb} close to zero-recoil

MB, A. Jüttner, '23 + WIP



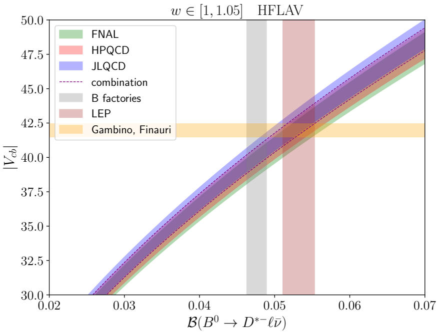
- Combination of Belle and Belle II angular distribution data
  - Only the zero-recoil bin
  - In that region, one form factor dominates
- Which branching ratio should we use?

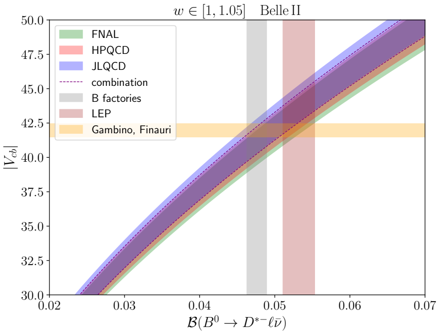
B factories: $|V_{cb}| = 40.07 \pm 0.86$

LEP: $|V_{cb}| = 42.37 \pm 1.09$

Exclusive V_{cb} close to zero-recoil

MB, A. Jüttner, '23 + WIP





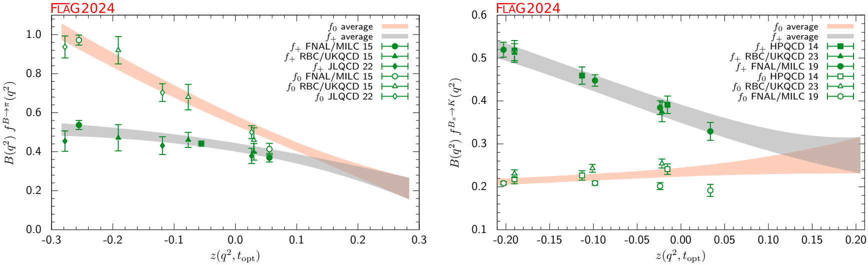
B factories: $|V_{cb}| = 40.07 \pm 0.86$

LEP: $|V_{cb}| = 42.37 \pm 1.09$

B factories: $|V_{cb}| = 41.24 \pm 1.15$

LEP: $|V_{cb}| = 43.60 \pm 1.35$

A few words on exclusive V_{ub}

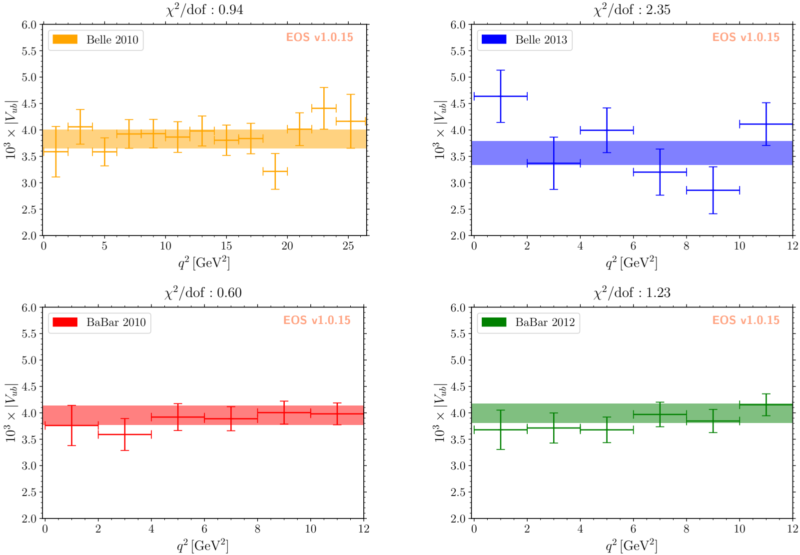


- There are tensions in the lattice determinations of f_0
- f_+ and f_0 are correlated through the kinematic constraint

$$f_+(q^2 = 0) = f_0(q^2 = 0)$$

- The chiral continuum extrapolation using the helicity base or the "lattice" base has some tricky points and checks are ongoing

V_{ub} from $B \to \pi \ell \bar{\nu}$



Not inflating uncertainties reveals a few tensions

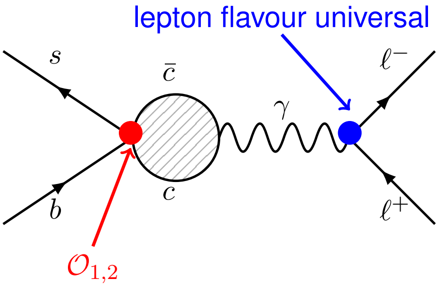
Charm-loop effects in $b \to s\ell^+\ell^-$

$$\mathcal{H}_{\text{eff}} = -4\frac{G_F}{\sqrt{2}}V_{tb}V_{ts}^*\left[-\mathcal{C}_1\mathcal{O}_1 - \mathcal{C}_2\mathcal{O}_2 + \mathcal{C}_7\mathcal{O}_7 + \mathcal{C}_9\mathcal{O}_9 + \mathcal{C}_{10}\mathcal{O}_{10}\right]$$

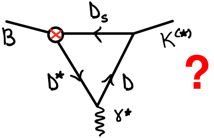
$$\mathcal{O}_1 = (\bar{s}\gamma^\mu P_L b)\,(\bar{c}\gamma_\mu c) \qquad \mathcal{O}_2 = (\bar{s}\gamma^\mu T^a P_L b)\,(\bar{c}\gamma_\mu T^a c)$$

$$\mathcal{O}_9 = (\bar{s}\gamma^\mu P_L b)\,(\bar{\ell}\gamma_\mu \ell) \qquad \mathcal{O}_{10} = (\bar{s}\gamma^\mu P_L b)\,(\bar{\ell}\gamma_\mu\gamma_5 \ell)$$

$$\mathcal{O}_7 = (\bar{s}\sigma^{\mu\nu} P_R b)\,F_{\mu\nu}$$



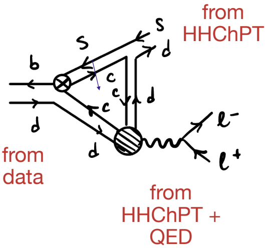
$$C_9 \to C_9^{\text{eff}}(q^2) = C_9 + C_9^{\text{LD}}(q^2)$$



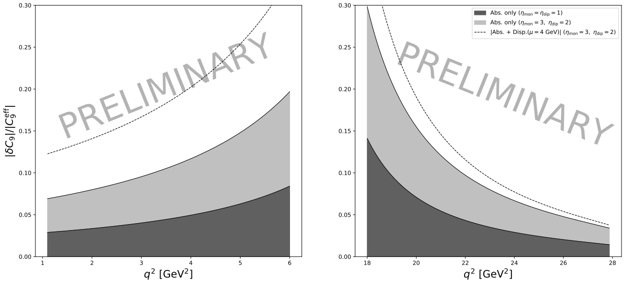
[Ciuchini, Fedele, Franco, Paul, Silvestrini, Valli, '22]

Models for the rescattering

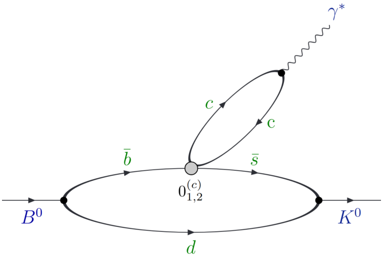
G. isidori, Z. Polonsky, A.Tinari, '24 + WIP



- Use of heavy hadron chiral perturbation theory + data + QED to determine the various vertices
- Better reliability at maximum q^2
- The tower of all possible combinations of states is accounted for by multiplicity factors based on the respective branching ratio
- Relative phases and how various contributions add up depend on unknown relative phases



News from the lattice



$$H^\mu(\mathbf{q}) \sim \int_{E_0}^{\infty} \frac{dE}{2\pi} \frac{\rho^\mu(E,\mathbf{q})}{E - m_B - i\epsilon}$$

⇒ Spectral densities are connected to correlation functions

$$C^\mu(t,\mathbf{q}) \sim \int_{E_0}^{\infty} \frac{dE}{2\pi} e^{-Et} \rho^\mu(E,\mathbf{q})$$

One has to solve a very complicated inverse problem

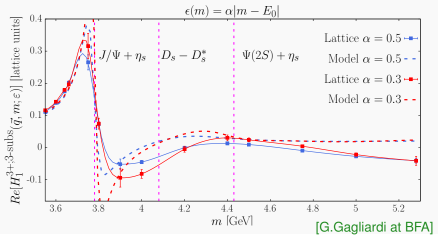
News from the lattice

Solution: **smeared correlators**

$$H^{\mu}(\mathbf{q}) \sim \int_{E_0}^{\infty} \frac{dE}{2\pi} \frac{\rho^{\mu}(E,\mathbf{q})}{E - m_B - i\epsilon} = \lim_{\epsilon \to 0} \int_{E_0}^{\infty} \frac{dE}{2\pi} \mathcal{K}_{\epsilon}(E,\mathbf{q}) \rho^{\mu}(E,\mathbf{q})$$

- The smearing makes the problem solvable in a finite volume
- This technique has been successfully applied to various problems like $g-2$ computation, inclusive semileptonic D decays

$B_s \to \eta_s \ell^+ \ell^-$



[G.Gagliardi at BFA]

- Extend to $B \to K\ell^+\ell^-$
- Attempt the $\epsilon \to 0$ limit
- Include more ensembles
- Perform non-perturbative renormalisation

The $B_{(s)} \to D^*_{(s)} K(\pi)$ decays

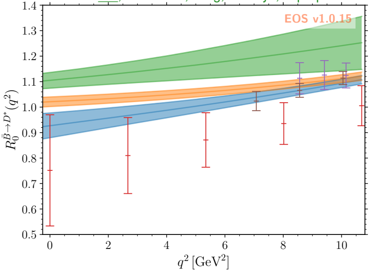
Why?

$\Rightarrow$ crucial inputs to extract fragmentation fractions from data

$$\mathcal{A}(\bar{B}^0_q \to D^{*+}_q L^-) = -i \frac{G_F}{\sqrt{2}} V^*_{uq_2} V_{cb} a_1(D^{*+}_q L^-) f_L$$
$$\times A_0^{\bar{B}_q \to D^*_q}(M_L^2) 2 M_{D^*_q} \varepsilon^*(\lambda = 0) \cdot q$$

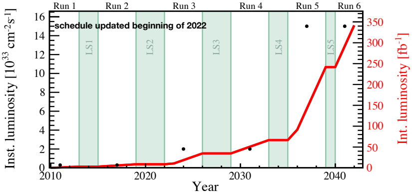
- Currently a 4σ descrepancy
  MB, Huber, Gubernari, Jung, van Dyk, '20
- Initiated further works on power correction
  M.L. Piscopo, A. Rusov, '23

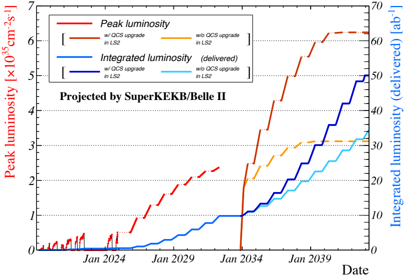
MB, Gubernari, Jung, van Dyk, in preparation



- New form factor analyses suggest a 15% downward shift in the scalar form factor
- This would reduce the tension with experimental data
- This is just for $B \to D^*$, $B \to D$ is unchanged at the current status

Beyond the LHC and Belle II





- Both the LHCb and Belle II programs are supported by not only unprecedented datasets, but also by software and analysis improvements
- What can be yet improved?

FCC-ee flavour opportunities

FCC: combines some of the best features of pp colliders and B factories

- High statistics
- Relatively clean environment due to high boost of b quarks

Particle production (10^9)	$B^0/\overline{B}^0$	B^+/B^-	$B_s^0/\overline{B}_s^0$	$B_c^+/\overline{B}_c^-$	$\Lambda_b/\overline{\Lambda}_b$	$c\bar{c}$	$\tau^+\tau^-$
Belle II	27.5	27.5	n/a	n/a	n/a	65	45
FCC-ee	620	620	150	4	130	600	170

$\Rightarrow$ unique opportunity to study flavour under all possible angles

$\Rightarrow$ all possible decay modes are accessible

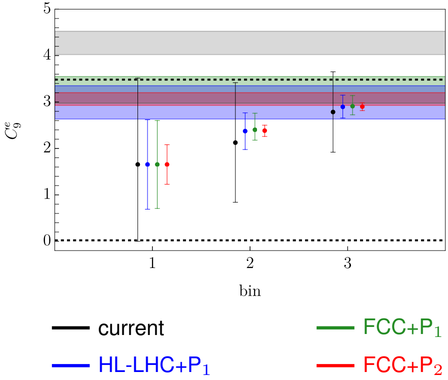
$B \to K^* e^+ e^-$ at FCC-ee

MB, C. Cornella, J. Davighi, '25

- Reconstruction is as good as for muons

  $\Rightarrow$ estimated around $\sim 80\%^*$ in all phase space

- The statistical error is below 1% and half of what is expected from HL-LHC



- Only $\mathcal{B}(B \to K^* e^+ e^-)$
- High Lumy projections: $\sigma_{\rm stat} = \sigma_{\rm syst}$
- Theory projections:

$$\mathrm{P}_1 : \sigma_{F_i} \to \sigma_{F_i}/2\,,$$
$$\mathrm{P}_2 : \sigma_{F_i} \to \sigma_{F_i}/5\,,$$

- Only with P_2 we can fully exploit the FCC-ee statistics

*estimates from $B \to K^* \tau^+ \tau^-$ studies confirmed by ad hoc simulations by S. Monteil

Conclusions

- Flavour physics is a powerful test for new physics living at different energy scales
- We have a lot of puzzles to solve, but this is just a sign of the advancements in both theory and experiments
- One of the most urgent puzzle to resolve concerns V_{cb} and V_{ub}
- Precise SM predictions are the key to unveiling potential NP signals
- The excellent experimental prospects, on the short and long term, combining with theory and experimental advancements

Appendix