Flavour Physics at FCC-ee

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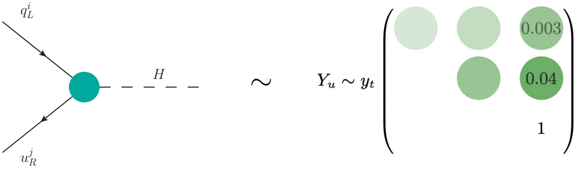
Rundgespräch

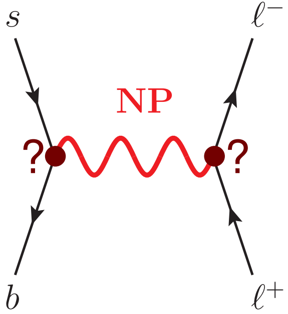
Theory Hub for Future Circular Collider e^+e^- Physics

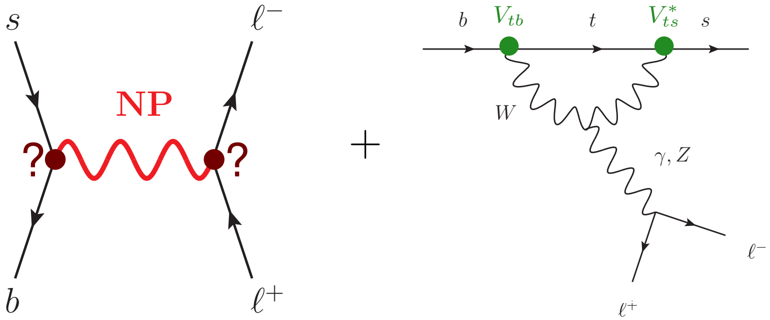
03.07.2026

Why flavour?



- Yukawas are the low-energy remnant of a UV theory
- No explanation for the hierarchical structure
  - $\Rightarrow$ Why does the third generation seems so special?
  - $\Rightarrow$ Why aren't flavour hierarchies predicted by symmetry principles?
- The UV dynamics links together the Higgs and the fermion content
- Unambiguous sign that the UV dynamics between the Higgs and fermions is non-universal


s
ℓ^-
NP
?
?
b
ℓ^+

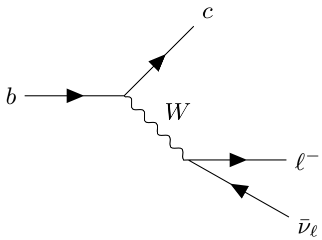


$\Rightarrow$ SM predictions for flavour-changing processes are parametrically small and therefore allow for testing heavy new physics

$\Rightarrow$ If precision was infinite, we could access all energy scales

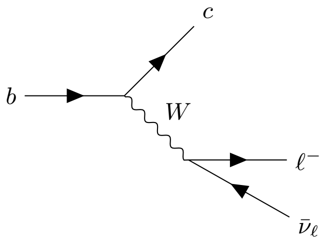
$\Rightarrow$ High control of theoretical and experimental precision is needed

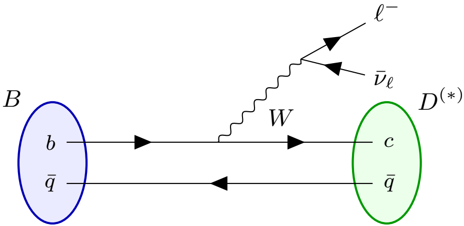
Partonic vs Hadronic picture



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

Partonic vs Hadronic picture

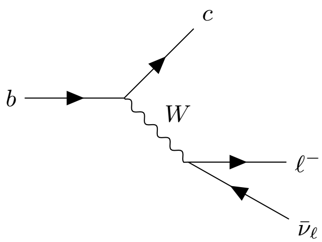


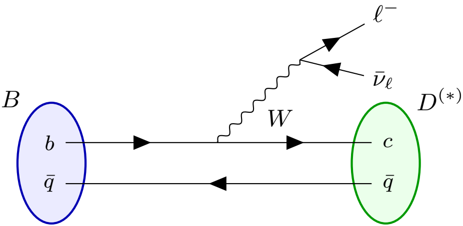


$$\mu_{\text{partonic}} = m_b$$

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

Partonic vs Hadronic picture





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

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

Predicting flavour observables requires devising non-perturbative techniques

How do we study flavour now?

LHCb

Strengths

- Huge heavy-flavour statistics: B^0, B^+, B_s, B_c, Λ_b, charm
- Excellent vertexing, tracking, and PID
- Ideal for charged final states and time-dependent measurements.

Limitations

- Hadronic environment: large backgrounds
- Limited missing-momentum reconstruction
- Electrons, photons, and fully neutral modes are challenging

Belle II

Strengths

- Clean $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ environment
- Known initial state momentum
- Powerful for missing energy, photons, inclusive modes, and τ physics

Limitations

- No access to B_s, B_c, and heavy baryons
- Much smaller heavy-flavour statistics than LHCb

Projections for early 2040s

2503.24346, ESPP

Experiment Assumed data sample	**ATLAS** $3000\,\mathrm{fb}^{-1}$	**CMS** $3000\,\mathrm{fb}^{-1}$	**LHCb** $300\,\mathrm{fb}^{-1}$	**Belle II** $50\,\mathrm{ab}^{-1}$
Semileptonic B decays				
$\lvert V_{ub}\rvert$	—	—	1%	1.2%
$\lvert V_{cb}\rvert$	—	—	—	1.0%
$R(D)$, $R(D^*)$	—	—	3.3%, 3.0%	1.4%, 1.0%
Leptonic B decays				
$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ $[10^{-9}]$	$(0.33 - 0.40)$	0.22	0.16	—
$\mathcal{B}(B^0 \to \mu^+\mu^-)$ $[10^{-10}]$	$(0.32 - 0.48)$	0.12	0.12	—
$\mathcal{B}(B^+ \to \tau^+\nu_\tau)$	—	—	—	6%
$\mathcal{B}(B^+ \to \mu^+\nu_\mu)$	—	—	—	5%
Flavour-changing neutral current $b \to s\ell\ell$ decays				
$P_5'(B^0 \to K^{*0}\mu^+\mu^-)$ $[10^{-3}]$	$(47 - 82)$	23	12	—
$\mathcal{B}(B^{+,0} \to K^{+,*0}\nu\bar{\nu})$	—	—	—	8%, 23%
$\mathcal{B}(B^{+,0} \to K^{+,*0}\tau^+\tau^-)$ $[10^{-4}]$	—	—	—	< 0.9, < 1.5
Flavour-changing neutral current $b \to s\gamma$ decays				
$\mathcal{B}(B \to X_s\gamma; E_\gamma > 1.6\,\mathrm{GeV})$	—	—	—	$(4.7 - 8.8)\%$
Lepton flavour violation in τ decays				
$\mathcal{B}(\tau^+ \to \mu^+\gamma)$ $[10^{-8}]$	—	—	—	< 0.7
$\mathcal{B}(\tau^+ \to \mu^+\mu^+\mu^-)$ $[10^{-8}]$	$< (0.13 - 0.64)$	< 0.39	< 0.26	$< (0.02 - 0.17)$

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$\mathcal{O}(5)$ improvement

$\mathcal{O}(10)$ improvement

Flavourful opportunities at FCC-ee

Particle production (10^9)	$B^0/\bar{B}^0$	B^+/B^-	$B_s^0/\bar{B}_s^0$	B_c^+/B_c^-	$\Lambda_b/\bar{\Lambda}_b$	$c\bar{c}$	$\tau^+\tau^-$
Belle II, $50\,\mathrm{ab}^{-1}$	27.5	27.5	n/a	n/a	n/a	65	–
LHCb, $300\,\mathrm{fb}^{-1}$	3.6×10^5	3.6×10^5	1.2×10^5	1.2×10^3	1.2×10^5	7.1×10^5	–
FCC-ee, $6 \times 10^{12}\ Z$	740	740	180	4	160	720	200

Advantages:

- $\Rightarrow$ Combines some of the best features of pp colliders and B factories
- $\Rightarrow$ Relatively high production cross section ($\mathcal{B}(Z \to bb) \sim 15\%$)
- $\Rightarrow$ Very boosted topologies allow for a good vertex reconstruction

Detector requirements:

- $\Rightarrow$ Particle identification
- $\Rightarrow$ Vertex Locator
- $\Rightarrow$ Good calorimeter

Flagship opportunities

Flagship opportunities

$B \to K^* \nu\bar{\nu}$

Flagship opportunities

$B \to K^* \nu \bar{\nu}$

$B \to K^{(*)} \tau\tau$

$B \to K^* ee$

$B_s \to \tau\tau$

Flagship opportunities

$B \to K^* \nu \bar{\nu}$

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$B_s \to \tau\tau$

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Flagship opportunities

$B \to K^* \nu \bar{\nu}$

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polarised Λ_b

Flagship opportunities

- $B \to K^* \nu\bar{\nu}$
- $B \to K^{(*)}\tau\tau$
- $B \to K^* ee$
- $B_s \to \tau\tau$
- $B_c \to \tau\nu$
- **polarised** Λ_b
- τ **properties**
- **EWPO**

Flagship opportunities

$B \to K^* \nu \bar{\nu}$

$B \to K^{(*)} \tau\tau$

$B \to K^* ee$

$B_s \to \tau\tau$

$B_c \to \tau\nu$

polarised Λ_b

τ **properties**

EWPO

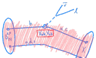
+ many other modes!

What are the theory challenges for the coming years?

- It is hard to say in general terms
- The same theoretical challenges that are already very pressing are also important for FCC-ee
- In the long run, the key player for precise flavour prediction will be Lattice QCD
  - $\Rightarrow$ For many observables we still have $\sim 10\%$ precision but we know how to improve
  - $\Rightarrow$ New avenues stemming from spectral reconstruction techniques are now feasible
  - $\Rightarrow$ For some quantities like decay constants, we are already at the $\%$ frontier and the next step is a full QED+QCD LQCD calculation
- Analytic/EFT methods remain essential to complement lattice inputs and control QED radiation in realistic Monte Carlo simulations

Lattice QCD progress

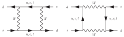
From A. Juttner, ESPP Open Symposium



Inclusive semileptonic $B_{(s)}$ and $D_{(s)}$ decay

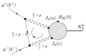
[Barone et al. JHEP (2023)], [Barone et al. arXiv:2504.03358], [De Santis et al. arXiv:2504.06063], [De Santis et al. arXiv:2504.06064]

illustration arXiv:2404.02297



$\epsilon_K, \epsilon'/\epsilon, \Delta M_K$

[Bai et al. PRD 2024]



long-distance effects in rare leptonic decays

e.g. $K \to \ell\ell$

[Chao et al. PRD 2024]

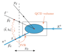
illustration LHCb

rare hyperon decay

[Erben et al. arXiv:2504.07727]

Examples for new and exploratory directions in lattice QCD for flavour

	γ	quarks	μ	e	τ	ν
$3_q \to 2_q$	$b \to s\,\gamma$	$B_s \leftrightarrow \bar{B}_s$	$b \to s\,\mu\mu$ $b \to c\,\mu\nu$	$R_{bs}(e/\mu)$ $R_{bc}(e/\mu)$	$b \to s\,\tau\tau$ $b \to c\,\tau\nu$	$b \to s\,\nu\nu$
$3_q \to 1_q$	$b \to d\,\gamma$	$B_d \leftrightarrow \bar{B}_d$	$b \to d\,\mu\mu$ $b \to u\,\mu\nu$	$R_{bd}(e/\mu)$ $R_{bu}(e/\mu)$	$b \to d\,\tau\tau$ $b \to u\,\tau\nu$	$b \to d\,\nu\nu$
$2_q \to {2_q \atop 1_q}$	$c \to u\,\gamma$	$D \leftrightarrow \bar{D}$	$c \to u\,\mu\mu$ $c \to s\,\mu\nu$ $c \to d\,\mu\nu$	$R_{cu}(e/\mu)$ $R_{cs}(e/\mu)$ $R_{cd}(e/\mu)$		$c \to u\,\nu\nu$



QCD+QED for semileptonic decays

[Christ et al. arXiv:2402.08915]

long-distance contributions to rare kaon decay

[Boyle et al. PRD 2023]

long-distance contributions to charm mixing

[Di Carlo, Erben, Hansen arXiv:2504.16189]

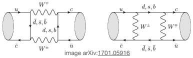
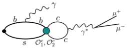


image arXiv:1701.05916



short/long-distance contributions to radiative decays

e.g. $B_s \to \mu\mu\gamma, D_s \to \ell\nu_\ell\gamma$

[Frezzotti et al. PRD 2024], [Frezzotti et al. PRD 2024]

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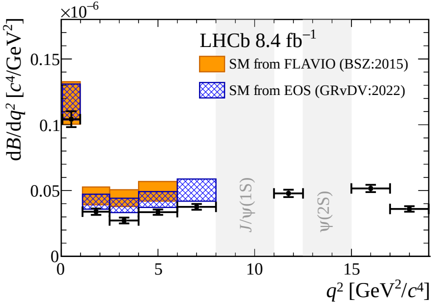
An example: $\mathcal{B}(B \to K^* \ell^+ \ell^-)$



- Consistent pattern of deviations
- What are the prospects at HL-LHC and FCC-ee?

$\Rightarrow$ For HL-LHC, one can rescale the experimental yields based on luminosity

$\Rightarrow$ For FCC-ee, one has to infer what the reconstruction efficiency is for the specific decay mode

For **HL-LHC**, we rescale using the current $B \to K^*\mu\mu$ and the ratio $B \to K^*\mu\mu / B \to K^*ee$

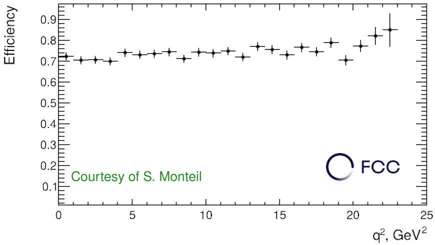
$\Rightarrow$ For $\ell = \mu$ the relative uncertanty is below the $\%$

$\Rightarrow$ For $\ell = e$ the relative uncertanty is still above the $\%$

FCC-ee

$$\frac{d\mathcal{N}}{dq^2}[q^2_{\rm min}, q^2_{\rm max}] = N_Z \cdot \mathcal{B}(Z \to b\bar{b}) \cdot 2 f_B \cdot \frac{d\mathcal{B}(B \to K^*\ell^+\ell^-)}{dq^2}[q^2_{\rm min}, q^2_{\rm max}] \cdot \epsilon_{\rm reco}$$

- Efficiency is inferred $\epsilon_{\rm reco} \sim 0.8$ from $B \to K^*\tau\tau$ studies
- Confirmed by preliminary studies

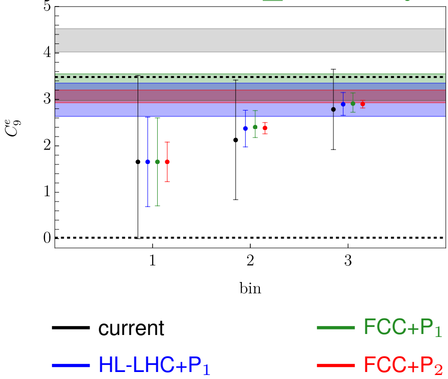


- The theory predictions depend **strongly** on the $B \to K^*$ hadronic matrix elements

- At the current status, the K^* is always considered stable and narrow, but there are attempts to go beyond this approximation [Leskovec et al, '25, Erben et al, '26]

- We need to define benchmark scenarios

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



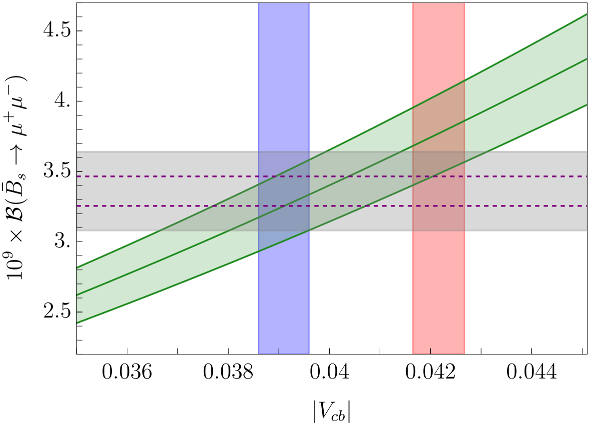
- Projections for $\mathcal{B}(B \to K^* e^+ e^-)$
- High Lumy projections: $\sigma_{\rm stat} = \sigma_{\rm syst}$
- Theory projections:

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

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

The V_{cb} puzzle

Long-standing discrepancy between exclusive and inclusive V_{cb} determination



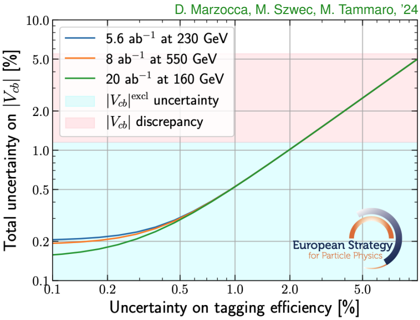
⇒ The puzzle creates a bias in interpreting the experimental data as SM-like or not

⇒ First inclusive LQCD determination of V_{cb} is now available [N.Tantalo, Flavour@FCC Part II]

V_{cb} at the WW threshold

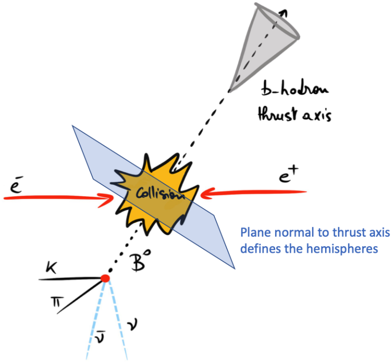
Why interesting?

- Lattice-free determination of CKM elements.
- Particularly relevant for $|V_{cb}|$, independent of inclusive/exclusive semileptonic B decays.
- Uses the clean FCC-ee environment and jet-flavour tagging calibrated at the Z pole.



- The key ingredient is the error on the tagging efficiency
- Reaching the sub-percent precision is doable

Di-neutrino modes at FCC-ee

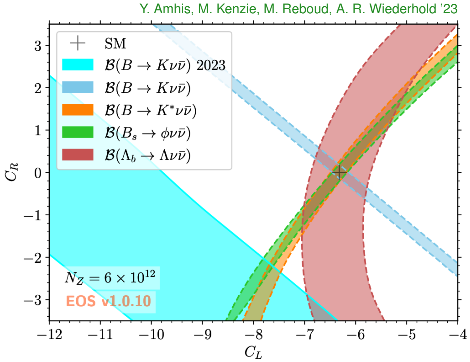


- Events are reconstructed using the thrust axis

$$T = \frac{\sum_i |p_i \cdot \hat{n}|}{\sum_i |p_i|}$$

- Particles associated with the signal events are required to have $\cos\theta > 0$
- Signal candidates are required to have two opposite-sign tracks
- Events are required to have at least one primary vertex and an intermediate resonance on the mass window of the K^*

Prospects for di-neutrino modes



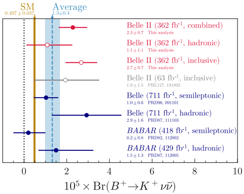
$$\mathcal{O}_{L,R} = (\bar{s}\gamma_\mu P_{L,R} b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)$$

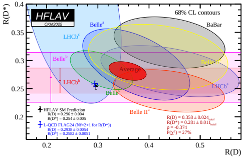
- Theory uncertainties reduced by a factor of 10
- For $B \to K$ means going below 1%
- Relative experimental uncertainties from 0.53%-9.86%
- For $B \to K^*\nu\nu$ it means a reduction of ~ 10 wrt Belle II

BSM for flavour at FCC-ee

- Even though the core of the flavour program is definitely centred around the precision frontier, wondering about BSM potential is interesting
- Which BSM? Hard question...
  - ⇒ Existing flavour tensions provide concrete benchmark scenarios
  - ⇒ An interesting class of scenarios is the ones where new physics is coupled mainly to the third generation

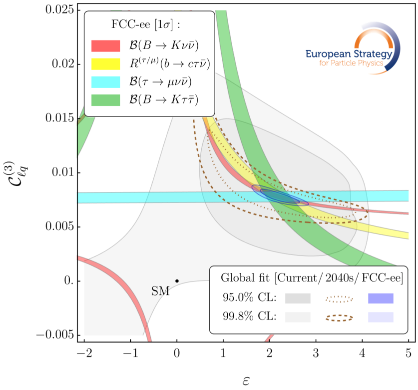
Flavour Puzzle





Projections for new physics in the 3rd family

- Assuming the current central values
- Improved theory predictions and experimental measurements



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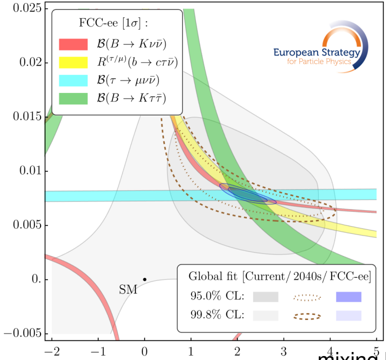
$(\bar{q}_L^3 \gamma_\mu \tau^a q_L^3)(\bar{\ell}_L^3 \gamma^\mu \tau^a \ell_L^3) \longrightarrow C_{\ell q}^{(3)}$



$\varepsilon \longleftarrow$ mixing between third and light quark families

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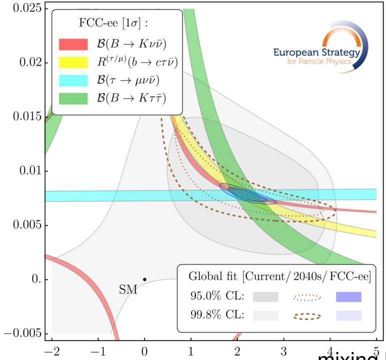


$\varepsilon \longleftarrow$ mixing between third and light quark families

Flavour can be studied at FCC-ee from
low- and high-energy perspective with unprecedented precision

Summary

- FCC-ee offers a unique environment to study flavour physics from all perspectives
- Theoretical precision is a key aspect; a lot of progress has been made and is ongoing
- We are in the process of defining the flavour physics program, and there is much more to come
- Regular updates at the Flavour@FCC Workshop (June 2026 and November 2025) and final write-up by the end of 2027

Appendix

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

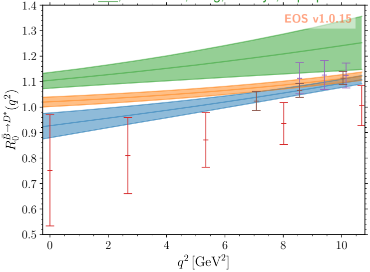
Why?

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

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

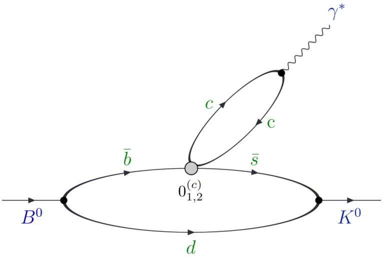
- Currently a 4σ descrepancy
  MB, Huber, Gubernari, Jung, van Dyk, '20
- Initiated further works on power correction
  M.L. Piscopo, A. Rusov, '23

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

News from the lattice



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

$\Rightarrow$ 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

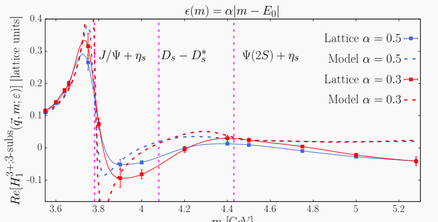
News from the lattice

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