Flavour physics: status and prospects

Marzia Bordone

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Outline:

1. The problem of flavour
2. Open problems in hadronic physics
3. A glance into BSM physics

Motivation

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there are open problems:

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- Hierarchy problem
- dark matter/dark energy
- flavour hierarchies
- neutrino masses
- gravity

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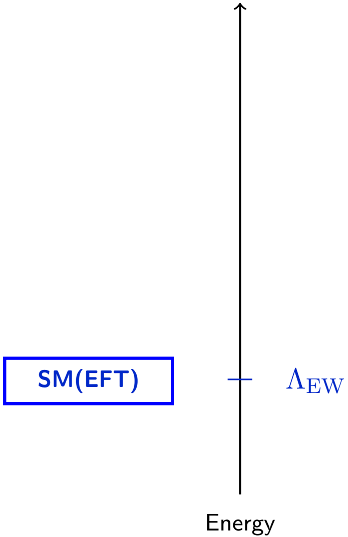

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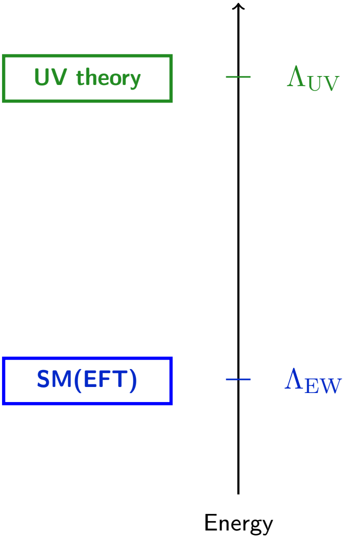

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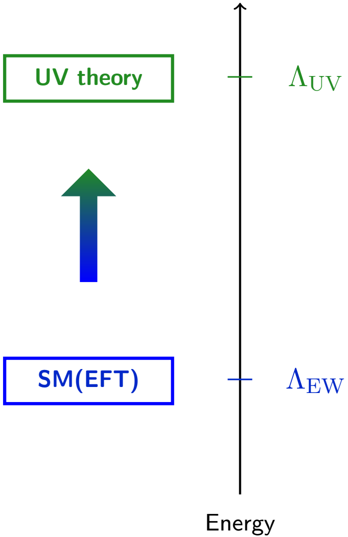

The (two) flavour problems

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

   $\Rightarrow$ 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?

   $\Rightarrow$ 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

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

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Exact $U(2)^n$ limit

The SM flavour problem

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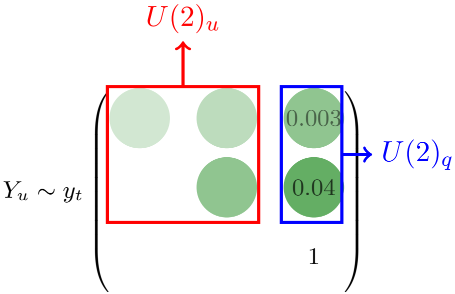

An approximate $U(2)^n$ is acting on the light families!

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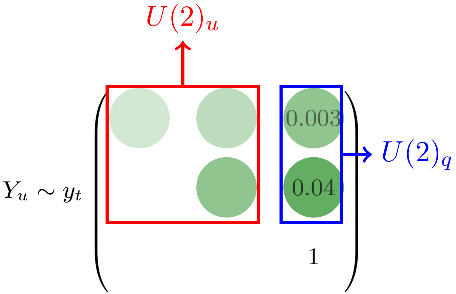

An approximate $U(2)^n$ is acting on the light families!

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

$U(3)^5$ 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

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

Large Flavour symmetry

Three replica of the same fermion fields

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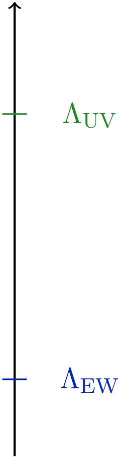
Flavour degeneracy is broken

The breaking is peculiar

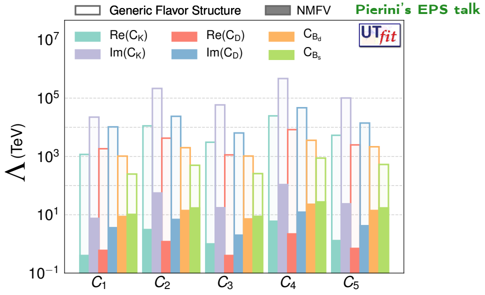
- In the SM: accidental $U(3)^5 \to$ approx $U(2)^n$
- **What happens when we switch on NP?**

The NP flavour problem

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

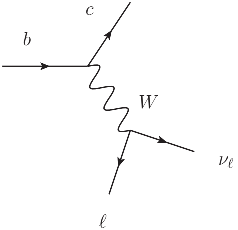


- What is the energy scale of NP?
- Why haven't observed any violation of accidental symmetries yet?

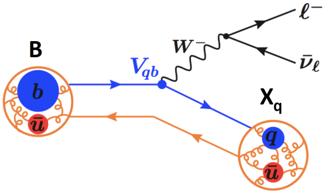


no breaking of the $U(2)^n$ flavour symmetry at low energies

Partonic vs Hadronic



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



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

Fundamental challenge to match partonic and hadronic descriptions

What's the problem for BSM?

B-physics

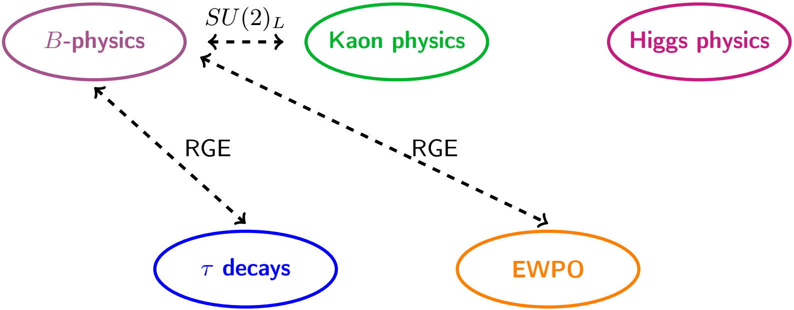
Kaon physics

Higgs physics

τ decays

EWPO

What's the problem for BSM?



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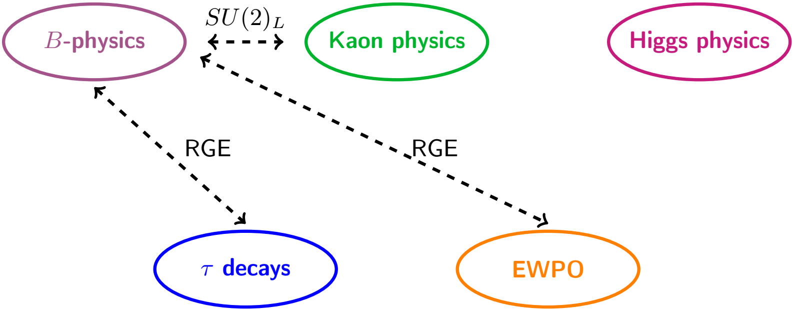


How to satisfy all the constraints at the same time?

Open problems in hadronic physics

What are the open themes in hadronic physics?

1. $B \to D^*$ form factors

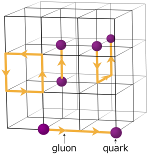
2. Inclusive vs. Exclusive determination of V_{cb}

3. Charm-loop effects in $B \to K^* \ell^+ \ell^-$

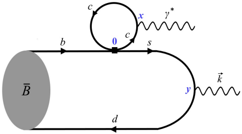
How can we tame the non-perturbative monsters

$$\langle H_c | J_\mu | H_b \rangle = \sum_i S_\mu^i \mathcal{F}_i$$

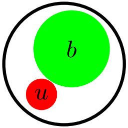
- Lattice QCD



- QCD SR, LCSR



- HQET (exploit $m_{b,c} \to \infty$ limit) + Data driven fits



- Dispersive analysis

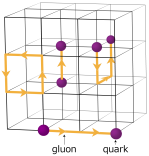
⇒ see talks by L. Vittorio, T. Kaneko, M.Prim, B. Colquhoun, J. Harrison

How can we tame the non-perturbative monsters

$$\langle H_c | J_\mu | H_b \rangle = \sum_i S^i_\mu \mathcal{F}_i$$ ← form factor

scale Λ_{QCD}

independent Lorentz structures



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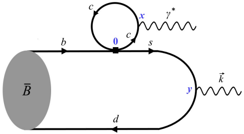

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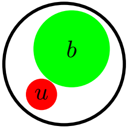

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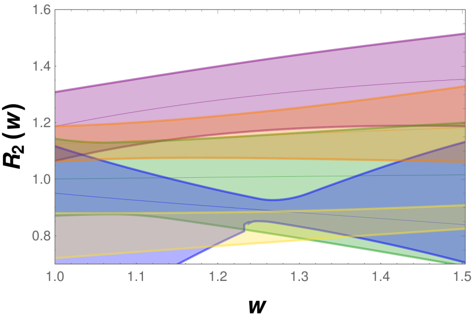
Lattice calculations at $q^2 \neq q^2_{\mathrm{max}}$

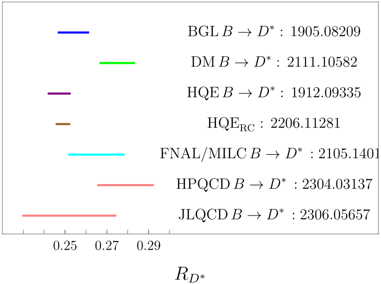


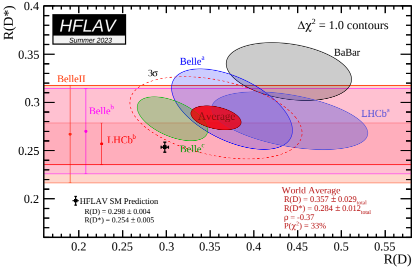
- FNAL/MILC '21
- HQE@$1/m_c^2$
- Exp data (BGL)
- JLQCD '23
- HPQCD '23

- Tensions between different lattice determinations, experimental data and non-lattice theory determination
- No consensus yet, ongoing checks
- New Belle analysis available

$\Rightarrow$ See talk by M. Prim

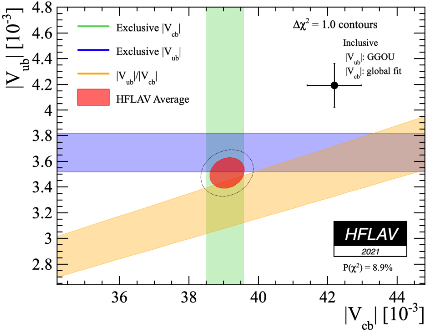
Pheno status





- Without LQCD prediction, the current combined tension is $\sim 3.3\,\sigma$
- Concerning R_D the situation is much stable because different LQCD collaborations agree with each other and experimental data

Inclusive vs. Exclusive determination of V_{cb}



Major impact for

- Test of unitarity for the CKM
- $\epsilon_K \sim |V_{cb}|^4$
- $\mathcal{B}(B_s \to \mu\mu) \sim |V_{cb}|^2$
- $\mathcal{B}(B \to K\nu\bar{\nu}) \sim |V_{cb}|^2$

Inclusive vs. Exclusive determination of V_{cb}

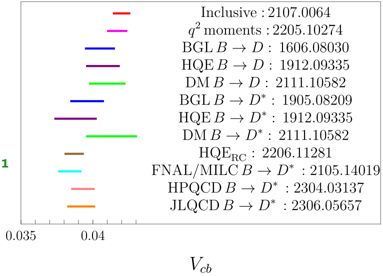
The inclusive determination is solid

- The traditional determination using data for the hadronic mass moments and lepton energy moments yields stable results up to $\mathcal{O}(\alpha_s^3)$ corrections in the width

  [2011.13654]

  MB, Capdevila, Gambino, '21

- New determination using q^2 moments yields very compatible results [2205.10274]



- Only caveat: QED corrections for charged current decays are enhanced by the Coulomb factor (for neutral B mesons)

  MB, Bigi, Gambino, Haisch, Piccione '23

  $\Rightarrow$ The impact has to be checked for each measurement

The exclusive determination depends on the dataset and hadronic form factor used

- Work in progress on the theory side
- New experimental data are available and have to be still scrutinised

$\Rightarrow$ see talks by K.Vos, D. Moreno

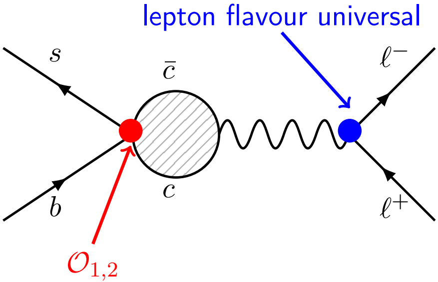
Charm-loop effects in $b \to s\ell^+\ell^-$

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

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

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

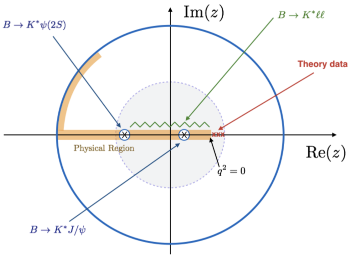
$$\mathcal{O}_7 = (\bar{s}\sigma^{\mu\nu} P_R b)\, F_{\mu\nu}$$



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

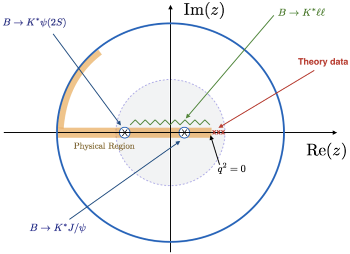
How do we parametrise these long-distance effects?

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



- Conformal transformation $q^2 \mapsto z(q^2)$, with $|z| < 1$
- $C_9^{\mathrm{LD}} \propto \alpha_n z^n$ [1707.07305]
- Dispersive analysis allow to determine the truncation order of the series [2011.09813,2206.03797]
- Effects are **small**

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



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Is this all?

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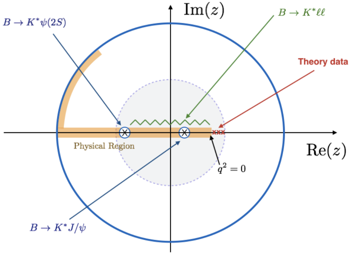

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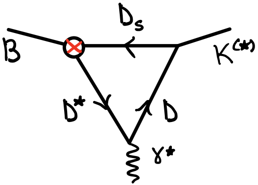


[2212.10516]

- Are these contributions included?
- Are they large that they can reconcile the tension in $B \to K^*\mu\mu$?

Charm loop effects in $B \to K^{(*)}\mu^+\mu^-$

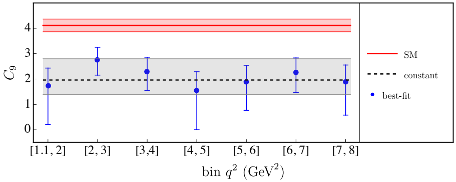
MB, Isidori, Maechler, Tinari, *to appear*

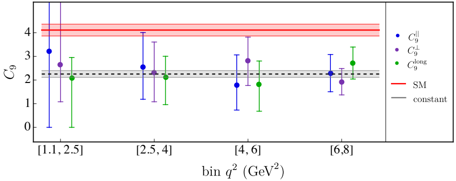
- Can we extract some hints of the shape of $C_9^{\rm LD}(q^2)$ from data?

  $\Rightarrow$ NP yields a **constant** effect in the whole kinematic region

- Is the current sensitivity enough to claim anything?

$$C_9^{\rm eff} = C_9 + \sum_V \eta_V^\lambda e^{i\delta_V^\lambda} \frac{q^2}{(m_V^2)} \frac{m_V \Gamma_V}{m_V^2 - q^2 - i m_V \Gamma_V}$$



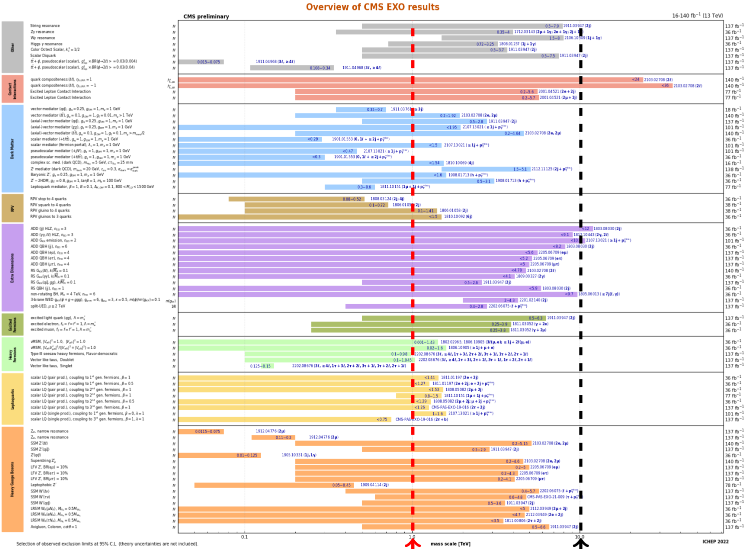


No evidence for q^2 dependence

$\Rightarrow$ see talk by A. Mauri

A glance into BSM physics

Status of high energy bounds



3rd generation

universal new physics

Flavour Non-Universal New Physics

Dvali, Shifman, '00
Panico, Pomarol, '16
MB, Cornella, Fuentes-Martin, Isidori '17
Allwicher, Isidori, Thomsen '20
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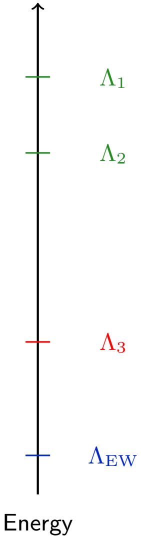

Basic idea:

- 1st and 2nd have small masses and small couplings to NP because they are generated by dynamics at a heavier scale
- 3rd generation is linked to dynamics at lower scales and has stronger couplings

Flavour deconstruction:
fermion families interact with different gauge groups and flavour hierarchies emerge as accidental symmetries

Flavour Non-Universal New Physics

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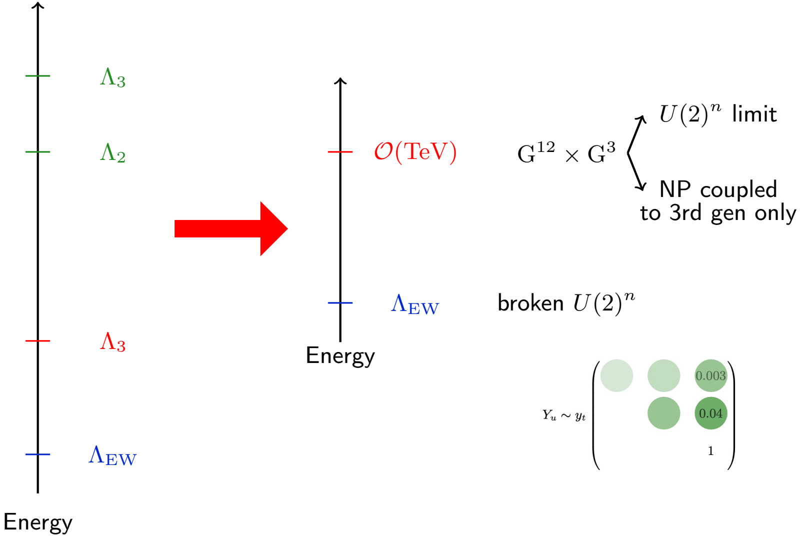


What do we expect in the SMEFT?

$$\mathcal{L}_{\rm EFT} \supset \boxed{\frac{C_{bc\tau\tau}}{\Lambda^2}} (\bar{b}^i_L \gamma_\nu c^j_L)(\bar{\nu}_\tau \gamma^\mu \tau_L)$$

From $U(2)^n \Rightarrow C_{bc\tau\tau} \sim V_{cb}\mathcal{O}(1)$

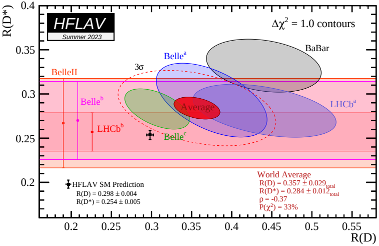
From $R_{D^{(*)}} \Rightarrow \Lambda \sim \mathcal{O}(\text{TeV})$

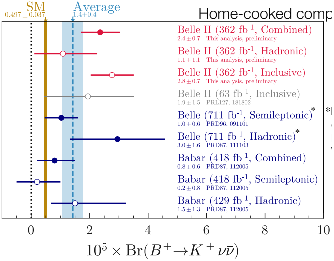
Using $SU(2)_L$ invariance, we have

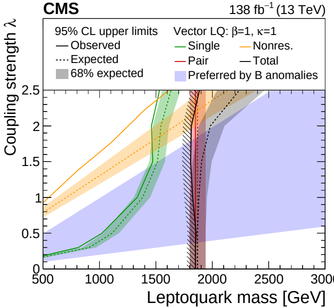
$$\mathcal{L}_{\rm EFT} \supset \boxed{\frac{C_{bs\tau\tau}}{\Lambda^2}} (\bar{b}^i_L \gamma_\nu s^j_L)(\bar{\nu}_\tau \gamma^\mu \tau_L)$$

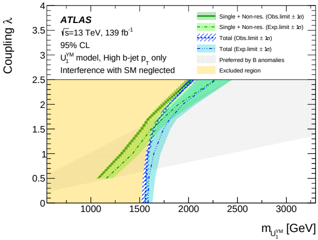
From $U(2)^n \Rightarrow C_{bs\tau\tau} \sim V_{cb}\mathcal{O}(1)$

Belle II measurement of $B \to K\nu\bar{\nu}$ in agreement with $U(2)^n$









The present hints align well together, but it is too soon to claim victory...

Conclusions

- Flavour physics is a powerful test for new physics living at different energy scales
- At the current status, we haven't observed any clear sign of new physics
- No clear sign of new physics can hint to a peculiar structure for the flavour structure of NP and to flavour deconstruction

  ⇒ Theoretical and Experimental efforts will shed light on puzzles in hadronic predictions, aiming to a deeper understanding of the SM

  ⇒ From the phenomenological point of view, a few hints point to a strong link between new physics and the third generations, with possible new physics reach close to the current searches

Appendix

$B \to D^{(*)}$ form factors

- 7 (SM) + 3 (NP) form factors
- Lattice computation for $q^2 \neq q^2_{\text{max}}$ only for $B \to D$
- Calculation usually give only a few points
- q^2 dependence must be inferred
- Conformal variable z

$$z(q^2, t_0) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$$

- $t_+ = (m_B + m_{D^{(*)}})^2$ pair production threshold
- $t_0 < t_+$ free parameter that can be used to minimise $|z_{\text{max}}|$
- $|z| \ll 1$, in the $B \to D$ case $|z| < 0.06$

The HQE parametrisation 1

- Expansion of QCD Lagrangian in $1/m_{b,c} + \alpha_s$ corrections

  [Caprini, Lellouch, Neubert, '97]

- In the limit $m_{b,c} \to \infty$: all $B \to D^{(*)}$ form factors are given by a **single** Isgur-Wise function

$$F_i \sim \xi$$

- at higher orders the form factors are still related $\Rightarrow$ **reduction** of free parameters

$$F_i \sim \left(1 + \frac{\alpha_s}{\pi}\right)\xi + \frac{\Lambda_{\mathsf{QCD}}}{2m_b}\xi^i_{\mathsf{SL}} + \frac{\Lambda_{\mathsf{QCD}}}{2m_c}\xi^i_{\mathsf{SL}}$$

  - at this order 1 leading and 3 subleading functions enter
  - ξ^i are not predicted by HQE, they have to be determined using some other information

The HQE parametrisation 2

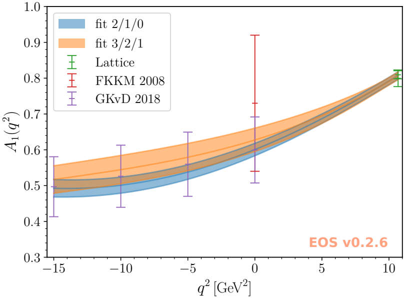
- Important point in the HQE expansion: $q^2 = q^2_{\text{max}}$
- At this point Luke's Theorem applies: the subleading corrections vanish for some form factors
- The leading Isgur-Wise function is normalised: $\xi(q^2 = q^2_{\text{max}}) = 1$
- **Problem**: contradiction with lattice data!
- $1/m_c^2$ corrections **have to be systematically included** **[Jung, Straub, '18, MB, M.Jung, D.van Dyk, '19]**
  - well motivated also since $\alpha_s/\pi \sim 1/m_b \sim 1/m_c^2$

The HQE results

[MB, Jung, van Dyk, EPJC 80 (2020), MB, Gubernari, Jung, van Dyk, EPJC 80 (2020)]

Data points:

- theory inputs only (Lattice QCD, QCD Sum Rules, Light-cone Sum Rules, Dispersive Bounds)

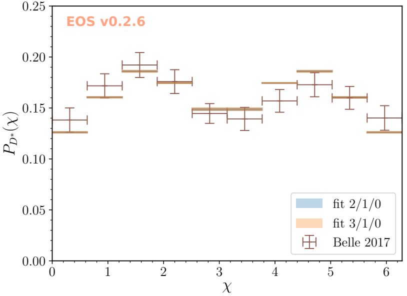


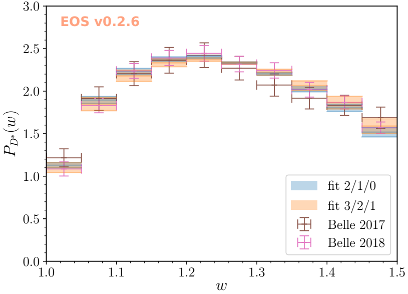
- Expansion in z up to order

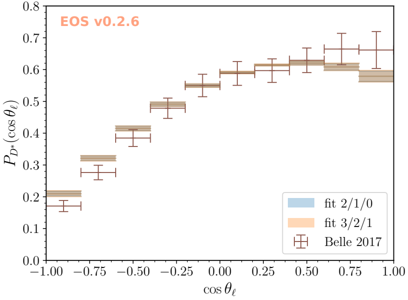
$$k/l/m$$

leading (k), subleading (l), subsubleading (m)

Comparison with kinematical distributions



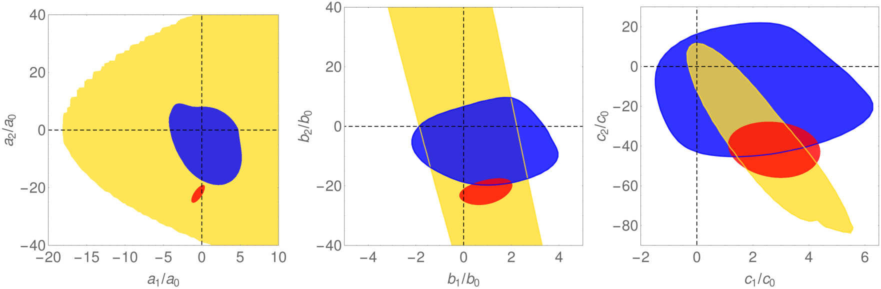




good agreement with kinematical distributions

Fit stability

- BGL fit to Belle 2017 and 2018 data (yellow)
- HQE fit 2/1/0 (red)
- HQE fit 3/2/1 (blue)



- compatibily of HQE fit with data driven one
- 2/1/0 underestimates massively uncertainties

$3/2/1$ is our nominal fit

Phenomenological results

- V_{cb} extraction

$$V_{cb}^{\text{average}} = (41.1 \pm 0.5) \times 10^{-3}$$

compatibility of 1.8σ between inclusive and exclusive

- Universality ratios

$$R_{D^*} = 0.2472 \pm 0.0050 \qquad R_{D_s^*} = 0.2472 \pm 0.0050$$

towards the combined 4σ discrepancy

- We observe no $SU(3)_F$ breaking

- Good compatibility with LHCb $\bar{B}_s \to D_s^{(*)}$ analysis in 2001.03225

Inclusive vs Exclusive determination of V_{cb}

Inclusive determination of V_{cb}:

$$V_{cb}^{\text{incl}} = (42.00 \pm 0.65) \times 10^{-3}$$

**[P. Gambino, C. Schwanda, 1307.4551
A. Alberti, P. Gambino, K. J. Healey, S. Nandi, 1411.6560
P. Gambino, K. J. Healey, S. Turczyk, 1606.06174]**

Exclusive determination of V_{cb}: depends on the data set used and the assumptions for the hadronic parameters

- $B \to D\ell\bar{\nu}$: $V_{cb}^{\text{excl}}|_{BD} = (40.49 \pm 0.97) \times 10^{-3}$

  [P.Gambino, D.Bigi, 1606.08030, + $\cdots$]

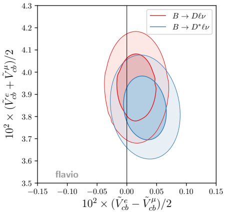
- $B \to D^*\ell\bar{\nu}$: not a general consensus yet, but systematically lower $V_{cb}^{\text{excl}}|_{BD}$

  **[P.Gambino, M.Jung, S.Schacht, '19
  F.Bernlochner, Z. Ligeti, M. Papucci, D. Robinson,'17 + $\cdots$]**

- $B_s \to D_s^{(*)}\ell\bar{\nu}$: new extraction by LHCb $\Rightarrow$ still large uncertainties **[2001.03225]**

No evidence so far that this tension is due to NP

[M. Jung, D. Straub, 1801.01112]



HQET in a nutshell

- In HQET it is convenient to work with **velocities** instead of momenta
- Instead of q^2 we use the dimensionless variable $w = v_B \cdot v_{D^*}$
- When the $B(b)$ decays such that the $D^*(c)$ is at rest in the $B(b)$ frame

$$v_B = v_{D^*} \qquad \Rightarrow \qquad w = 1$$

- The brown muck doesn't realise that anything changed
- At zero recoil, the leading IW function is **normalized**

$$\xi(w = 1) = 1$$

V_{cb} and NP

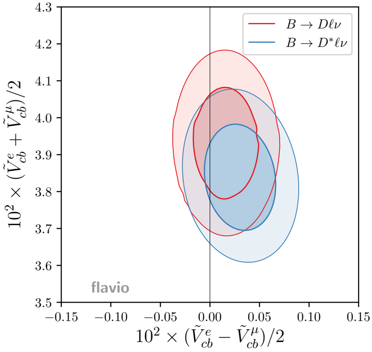
[Jung, Straub 2018]

- If we allow LFUV between μ and electrons

$$\tilde{V}^{\ell}_{cb} = V_{cb}(1 + C^{\ell}_{V_L})$$

- Fitting data from Babar and Belle

$$\frac{\tilde{V}^{e}_{cb}}{\tilde{V}^{\mu}_{cb}} = 1.011 \pm 0.012$$



$$\frac{1}{2}(\tilde{V}^{e}_{cb} + \tilde{V}^{\mu}_{cb}) = (3.87 \pm 0.09)\%$$

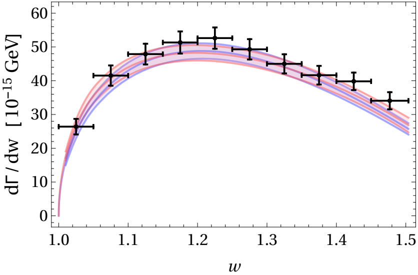
$$\frac{1}{2}(\tilde{V}^{e}_{cb} - \tilde{V}^{\mu}_{cb}) = (0.022 \pm 0.023)\%$$

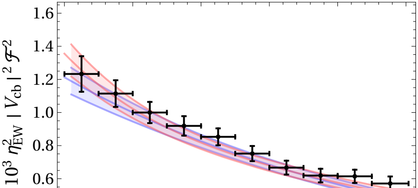
BGL vs CLN

- Both BGL and CLN parametrisation of form factors rely on using unitarity arguments.

[Boyd, Grinstein, Lebed, '95
Caprini, Neubert, Lellouch, '98]

- CLN relies on HQET.
- Unfolded distributions from Belle allowed to repeat an independent fit.





BGL vs CLN parametrisations

CLN

[Caprini, Lellouch, Neubert, '97]

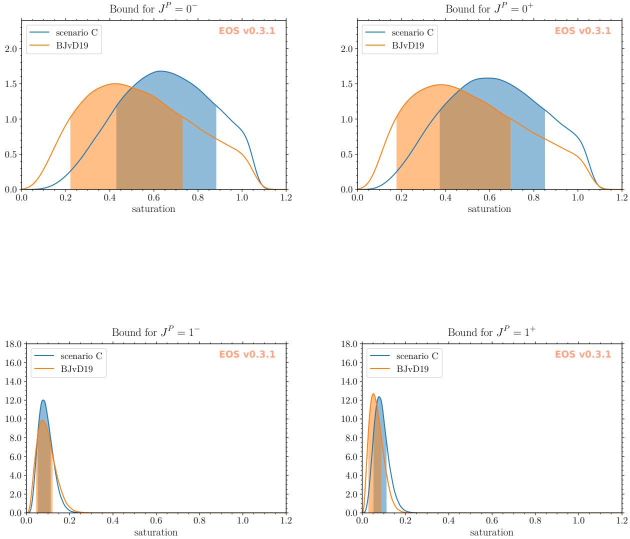
- Expansion of FFs using HQET
- $1/m_{b,c}$ corrections included
- Expansion of leading IW function up to 2nd order in $(w-1)$

BGL

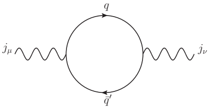
[Boyd, Grinstein, Lebed, '95]

- Based on analyticity of the form factors
- Expansion of FFs using the conformal variable z
- Large number of free parameters

Results: unitary bounds



Unitarity Bounds



$$= i\int d^4x\, e^{iqx}\langle 0|T\left\{j_\mu(x), j_\nu^\dagger(0)\right\}|0\rangle = (g_{\mu\nu} - q_\mu q_\nu)\Pi(q^2)$$

- If $q^2 \ll m_b^2$ we can calculate $\Pi(q^2)$ via perturbative techniques $\Rightarrow \chi(0)$
- Dispersion relations link Im $\left(\Pi(q^2)\right)$ to sum over matrix elements

$$\sum_i |F_i(0)|^2 < \chi(0)$$

**[Boyd, Grinstein,Lebed, '95
Caprini, Lellouch, Neubert, '97]**

- The sum runs over <u>all</u> possible states hadronic decays mediated by a current $\bar{c}\Gamma_\mu b$
  - The unitarity bounds are more effective the most states are included in the sum
  - The unitarity bounds introduce correlations between FFs of different decays
  - $B_s \to D_s^{(*)}$ decays are expected to be of the same order of $B_{u,d} \to D_{u,d}^{(*)}$ decays due to $SU(3)_F$ simmetry

Theory framework

$$\Gamma = \frac{1}{m_B} \mathrm{Im} \int d^4x \langle B(p)| T \left\{ \mathcal{H}^{\dagger}_{\mathrm{eff}}(x) \mathcal{H}_{\mathrm{eff}}(0) \right\} |B(p)\rangle$$

Theory framework

$$\Gamma = \frac{1}{m_B}\mathrm{Im}\int d^4x \langle B(p)| T\left\{\mathcal{H}^\dagger_{\rm eff}(x)\mathcal{H}_{\rm eff}(0)\right\}|B(p)\rangle$$

$$\uparrow$$

$$\sum_{n,i}\frac{1}{m_b^n}\mathcal{C}_{n,i}\mathcal{O}_{n+3,i}$$

Theory framework

$$\Gamma = \frac{1}{m_B} \text{Im} \int d^4x \langle B(p)| T \left\{ \mathcal{H}^\dagger_{\text{eff}}(x) \mathcal{H}_{\text{eff}}(0) \right\} |B(p)\rangle$$

$$\uparrow$$

$$\sum_{n,i} \frac{1}{m_b^n} \mathcal{C}_{n,i} \mathcal{O}_{n+3,i}$$

- The Wilson coefficients are calculated perturbatively
- The matrix elements $\langle B(p)|\mathcal{O}_{n+3,i}|B(p)\rangle$ are non perturbative

  $\Rightarrow$ They need to be determined with non-perturbative methods, e.g. Lattice QCD

  $\Rightarrow$ They can be extracted from data

  $\Rightarrow$ With large n, large number of operators

Theory framework

$$\Gamma = \frac{1}{m_B} \mathrm{Im} \int d^4x \langle B(p) | T \left\{ \mathcal{H}^{\dagger}_{\mathrm{eff}}(x) \mathcal{H}_{\mathrm{eff}}(0) \right\} | B(p) \rangle$$

$\uparrow$

$\sum_{n,i} \frac{1}{m_b^n} \mathcal{C}_{n,i} \mathcal{O}_{n+3,i}$

- The Wilson coefficients are calculated perturbatively
- The matrix elements $\langle B(p) | \mathcal{O}_{n+3,i} | B(p) \rangle$ are non perturbative
  - $\Rightarrow$ They need to be determined with non-perturbative methods, e.g. Lattice QCD
  - $\Rightarrow$ They can be extracted from data
  - $\Rightarrow$ With large n, large number of operators

$\uparrow$

loss of predictivity

Theory framework

$$\Gamma_{sl} = \Gamma_0 f(\rho)\Big[1 + a_1\left(\frac{\alpha_s}{\pi}\right) + a_2\left(\frac{\alpha_s}{\pi}\right)^2 + a_3\left(\frac{\alpha_s}{\pi}\right)^3 - \left(\frac{1}{2} - p_1\left(\frac{\alpha_s}{\pi}\right)\right)\frac{\mu_\pi^2}{m_b^2}$$
$$+ \left(g_0 + g_1\left(\frac{\alpha_s}{\pi}\right)\right)\frac{\mu_G^2(m_b)}{m_b^2} + d_0\frac{\rho_D^3}{m_b^3} - g_0\frac{\rho_{LS}^3}{m_b^3} + \dots\Big]$$

$$\mu_\pi^2(\mu) = \frac{1}{2m_B}\langle B|\bar{b}_v(i\vec{D})^2 b_v|B\rangle_\mu \qquad \mu_G^2(\mu) = \frac{1}{2m_B}\langle B|\bar{b}_v\frac{i}{2}\sigma_{\mu\nu}G^{\mu\nu}b_v|B\rangle_\mu$$

- Coefficients of the expansions are known
- Ellipses stands for higher orders

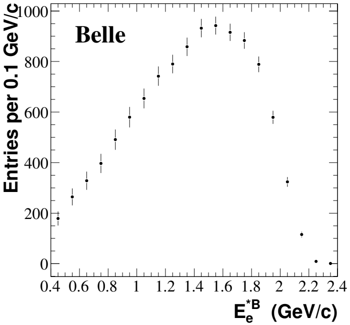
Theory framework

$$\Gamma_{sl} = \Gamma_0 f(\rho)\Big[1 + a_1\left(\frac{\alpha_s}{\pi}\right) + a_2\left(\frac{\alpha_s}{\pi}\right)^2 + a_3\left(\frac{\alpha_s}{\pi}\right)^3 - \left(\frac{1}{2} - p_1\left(\frac{\alpha_s}{\pi}\right)\right)\frac{\mu_\pi^2}{m_b^2}$$
$$+ \left(g_0 + g_1\left(\frac{\alpha_s}{\pi}\right)\right)\frac{\mu_G^2(m_b)}{m_b^2} + d_0\frac{\rho_D^3}{m_b^3} - g_0\frac{\rho_{LS}^3}{m_b^3} + \ldots\Big]$$

$$\mu_\pi^2(\mu) = \frac{1}{2m_B}\langle B|\bar{b}_v(i\vec{D})^2 b_v|B\rangle_\mu \qquad \mu_G^2(\mu) = \frac{1}{2m_B}\langle B|\bar{b}_v\frac{i}{2}\sigma_{\mu\nu}G^{\mu\nu}b_v|B\rangle_\mu$$

- Coefficients of the expansions are known
- Ellipses stands for higher orders

How do we constrain the OPE parameters?



- Lepton energy and hadronic invariant mass distributions can be used to extract non perturbative information
- Moments of the kinematic distributions

$$\langle E_\ell^n \rangle = \frac{\int_{E_\ell > E_{\ell,\mathrm{cut}}} dE_\ell E_\ell^n \frac{d\Gamma}{dE_\ell}}{\Gamma_{E_\ell > E_{\ell,\mathrm{cut}}}}$$

$$R^* = \frac{\int_{E_\ell > E_{\ell,\mathrm{cut}}} dE_\ell \frac{d\Gamma}{dE_\ell}}{\int dE_\ell \frac{d\Gamma}{dE_\ell}}$$

- Similar definition for hadronic mass moments

- The moments give access to the distribution, but not to the normalisation
- They admit an HQE as the rate

$\Rightarrow$ No $\mathcal{O}(\alpha_s^3)$ terms are known yet

Inclusive V_{cb} from q^2 moments

[Bernlochner et al., '22]

An alternative for the inclusive determination

- q^2 moments

$$R^* = \frac{\int_{q^2 > q^2_{\rm cut}} dq^2 \frac{d\Gamma}{dq^2}}{\int_0 dq^2 \frac{d\Gamma}{dq^2}} \qquad \langle (q^2)^n \rangle = \frac{\int_{q^2 > q^2_{\rm cut}} dq^2 (q^2)^n \frac{d\Gamma}{dq^2}}{\int_0 dq^2 \frac{d\Gamma}{dq^2}}$$

- Exploits HQE to reduce numbers of higher dimensional operators [Fael, Mannel, Vos, '18]

- Preliminary result:

$$|V_{cb}| = (41.69 \pm 0.63) \times 10^{-3}$$

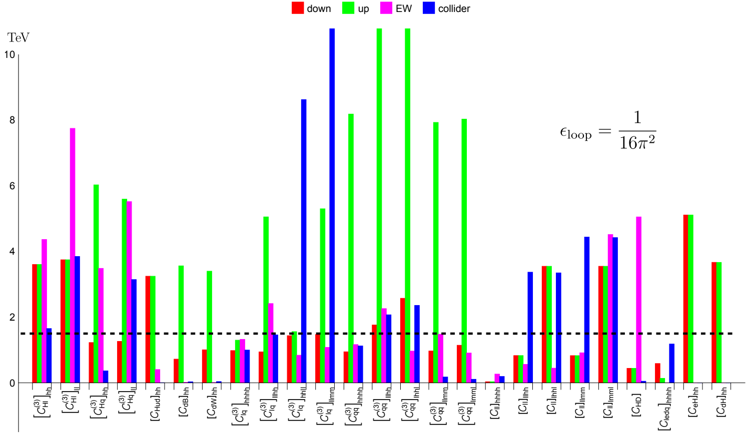
What's the issue with the previous determination?

- The q^2 moments require a measurement of the branching ratio with a cut in q^2 which is not available yet
- By extrapolating from the current available measurements, the branching ratio is lower then what used
- If the same branching ratios is used, the two methods give the **same** result

The results for inclusive V_{cb} are stable

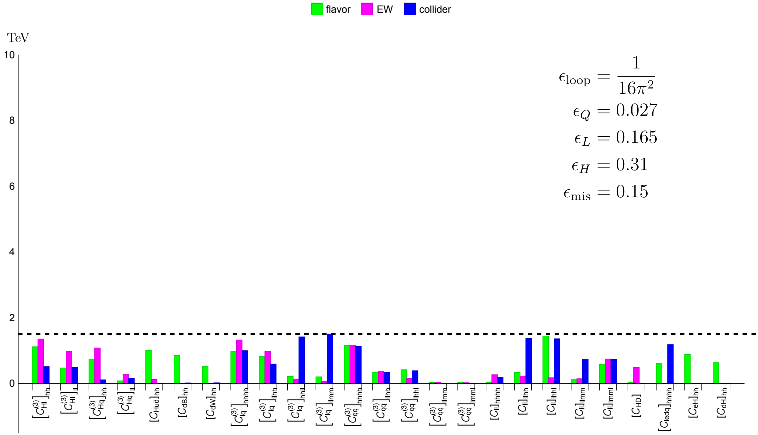
SMEFT with Flavour 1

[Allwicher, Cornella, Isidori, Stefanek, in preparation]



SMEFT with Flavour 2

[Allwicher, Cornella, Isidori, Stefanek, in preparation]



C_9 from $B \to K^{(*)}\mu^+\mu^-$ data