HEAVY FLAVOUR 2023 Quo Vadis?

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Particle Physics Phenomenology after the Higgs Discovery

HEAVY FLAVOUR 2023

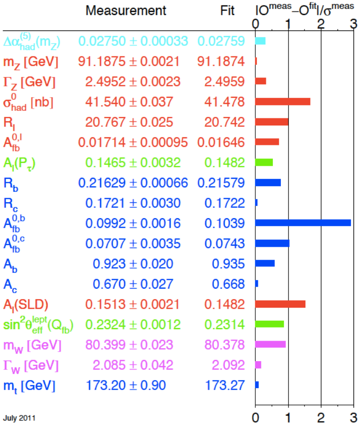
QUO VADIS?

Contents

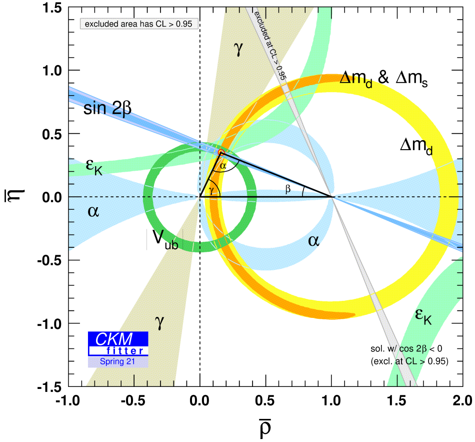
Where do we stand?

Standard Model passed all tests up to $\mathcal{O}(100\ \text{GeV})$:

- LEP: test of the gauge Structure
- Flavour factories: test of the Flavour Sector



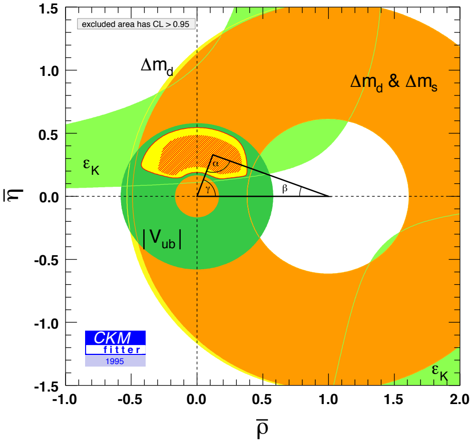
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01646
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1482
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1039
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0743
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1482
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.378
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.27



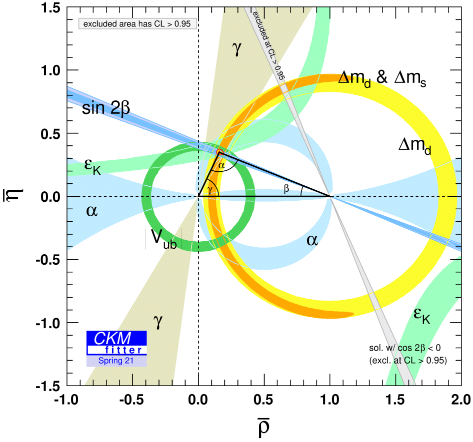
There has been tremendous progress in Flavour Physics

- Experimental facilities for precision measurements in strange, charm and bottom
- Theoretical methods have been refined to the precision level:
  - Lattice
  - Effective Field Theories
  - QCD sum rules
  - (Models)
- Close cooperation between experiment and theory!

Progress documented by the development of our knowledge on the CKM matrix:



1995 (pre-B factory era)



today

Triumph of the Standard model (?)

- LHC discovered a Higgs:
  - It has non-universal (i.e. mass dependent) couplings!
  - Is it THE Higgs? It looks pretty SM like!
  - ... or is ewk. symmetry breaking more complicated?
  - 95 GeV anomaly: the first hint at something new?
- Nevertheless, the Higgs discovery completes the SM, Despite of naturalness
- The SM could be valid up to extremely high scales
- No significant(!) hint at “new physics” yet

Particle Physics at the crossroads

LHC finds New Particles

- Find our what it is!
- How does this become compatible with the precision data?
- Why do we have MFV?
- ... and where does it come from?

LHC finds no New Particles

- Era of indirect searches
- Quark and Lepton Flavor Physics
- Indirect searches at highest energies
- “Precision Colllider Physics” at LHC

We will know soon, but the window for direct detection seems to close ..

- (Ubiquitous) effective field theory picture

$$\mathcal{L} = \mathcal{L}^{SM}_{\mathrm{dim\,4}} + \mathcal{L}_{\mathrm{dim\,5}} + \mathcal{L}_{\mathrm{dim\,6}} + \cdots$$

- $\mathcal{L}_{\mathrm{dim\,n}}$ are suppressed by large mass scales

$$\mathcal{L}_{\mathrm{dim\,n}} = \frac{1}{\Lambda^{n-4}} \sum_i C_n^{(i)} O_n^{(i)}$$

$O_n^{(i)}$: Operators of dimension n, $SU(3)_C \times SU(2)_W \times U(1)_Y$ gauge invariant
$C_n^{(i)}$: dimensionless couplings

- What can we know about this mass scale?

From neutrino physics:

- Majorana masses for the ν's are generated by a unique dim-5 operator:

$$\mathcal{L}_{\rm dim\,5} = \frac{1}{\Lambda_{\rm LNV}} \sum_{ij} C_5^{ij} (\bar{L}_j H^c)^c (H^{c,\dagger} L_i)$$

- Generates a mixing matrix for the leptons (PMNS Matrix), analogous to the CKM Matrix
- This term is Lepton Number Violating, related to the scale $\Lambda_{\rm LNV}$
- Small Neutrino masses: $\Lambda_{\rm LNV} \sim 10^{14}$ GeV , almost as big as the GUT scale?
- Hopefully $\Lambda_{\rm QFV}$ and $\Lambda_{\rm LFV}$ is not that high!

From Quark Flavour Physics:

- For Quarks there is no contribution to $\mathcal{L}_{\mathrm{dim}\,5}$
- Look at $\Delta F = 2$ flavour transitions:

$$\begin{aligned}
O_1^{(6)} &= (\bar{s}_L \gamma_\mu d)(\bar{s}_L \gamma^\mu d) && \text{(Kaon Mixing)} \\
O_2^{(6)} &= (\bar{b}_L \gamma_\mu d)(\bar{b}_L \gamma^\mu d) && (B_d \text{ Mixing}) \\
O_3^{(6)} &= (\bar{b}_L \gamma_\mu 2)(\bar{b}_L \gamma^\mu s) && (B_s \text{ Mixing}) \\
O_4^{(6)} &= (\bar{c}_L \gamma_\mu u)(\bar{c}_L \gamma^\mu u) && (D \text{ Mixing})
\end{aligned}$$

- With generic couplings $\mathcal{O}(1)$:
  - $\Lambda \sim 1000$ TeV from Kaon mixing ($C_i = 1$)
  - $\Lambda \sim 1000$ TeV from D mixing
  - $\Lambda \sim 400$ TeV from B_d mixing
  - $\Lambda \sim 70$ TeV from B_s mixing

How to get TeV Scale new physics?

Concept of "Minimal Flavour Violation" (MFV)

- In the SM:
  The only source of Flavour (and CP) violation is the non-alignement of the mass matrices.
- This generates the (hierarchical) CKM structure
- This also generates a supression of FCNC processes

MFV: Assume that this is true also for new physics models
(Ali, Buras)

- Implemented by a spurion analysis
  D'Ambrosio at al., Zupan et al., Feldmann et al.
- Generates a supression of the dim-6 couplings in $\mathcal{L}_{\text{eff}}$.

$\boxed{\text{MFV is NOT a Theory of Flavour}}$

??? Many Open Questions ???

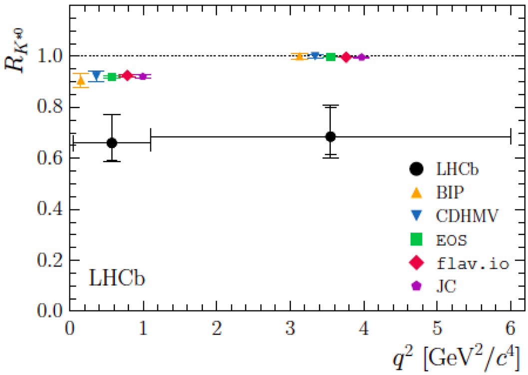
- Our Understanding of Flavour is unsatisfactory:
  - 22 (out of 27) free Parameters of the SM originate from the Yukawa Sector (including Lepton Mixing)
  - Why is the CKM Matrix hierarchical?
  - Why is CKM so different from the PMNS?
  - Why are the quark masses (except the top mass) so small compared with the electroweak VEV?
  - Why do we have three families?
- Underlying principle for the flavor structure? like the gauge principle for the fundamental forces?
  - ... a broken (how?) flavour symmetry
  - ... extra dimensions
  - ... new gauge interactions

Status of the “Anomalies”

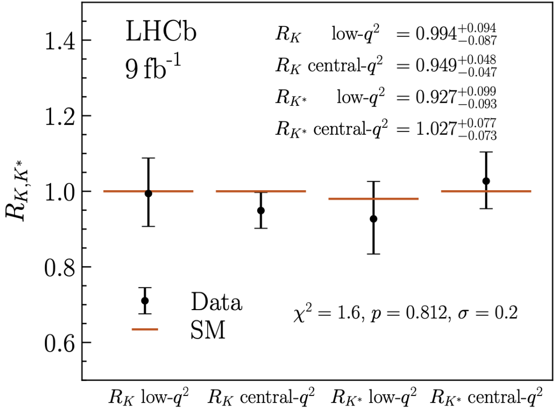
Dec. 20th, 2022: Black Tuesday for Lepton-Universality-Violation

before Dec.20th, 2022 ...

... and after



[arXiv:2212.09152] [arXiv:2212.09153]



We should not be disappointed, there are still more anomalies (and there will always be ...)

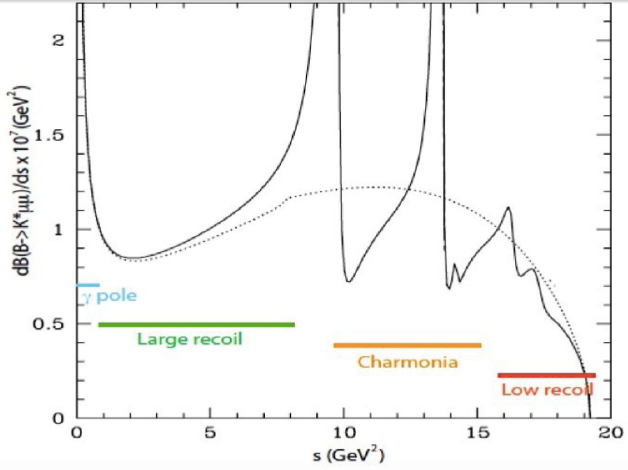
- $b \to s\ell\ell$ Anomalies:
  - P_5': Angular distribution in $B \to K^*\ell\ell$
  - Rates for $B \to K\mu\mu$ and $B_s \to \phi\mu\mu$
- $R(D)$ and $R(D^*)$: Rates for $B \to D^{(*)}\ell\bar{\nu}$
- V_{xb}^{incl} vs. V_{xb}^{excl}: $b \to q\ell\bar{\nu}$ transitions
- Δa_{CP}: CPV in Charm Decays
- ϵ'/ϵ Kaon CP V
- ...

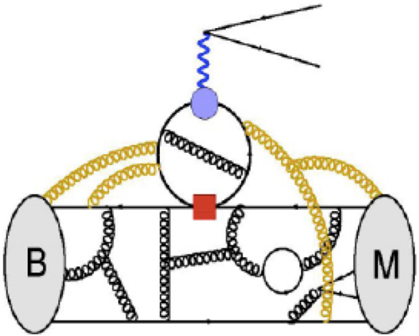
Step 1: Scrutinize the Standard Model
Step 2: Invent a New Physics Model

$b \to s\ell\ell$ Anomalies: Angular distribution in $B \to K^*\ell\ell$

- $B \to K^*\ell\ell \to K\pi\ell\ell$ contains a lot of information
- Angular distributions in the final state
- Set up clever ratios to reduce form-factor uncertainties

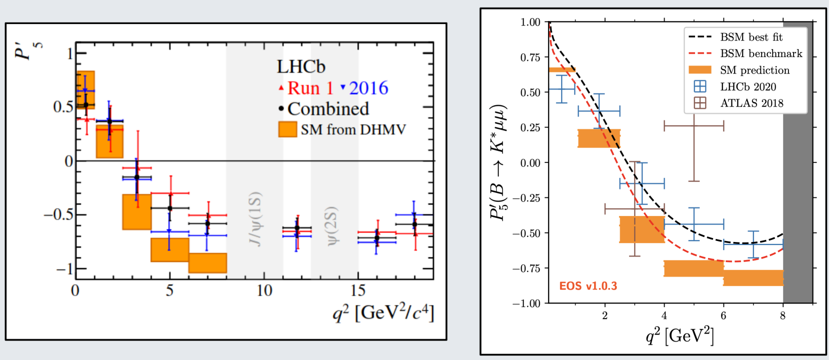
However ...





- Photon pole: Dominance of O_7
- Charmonia: $B \to J/\Psi K^* \to (\ell\ell) K^*$
- Large Recoil: $c\bar{c}$ loop contribution below threshold
- Low Recoil: Duality fo the $c\bar{c}$ loop
- The $c\bar{c}$ loop brings a non-local / non-form-factor like contribution into the game!

Anomalies in the angular distributions: (Plots from Gubernari et al., 2305.06301)

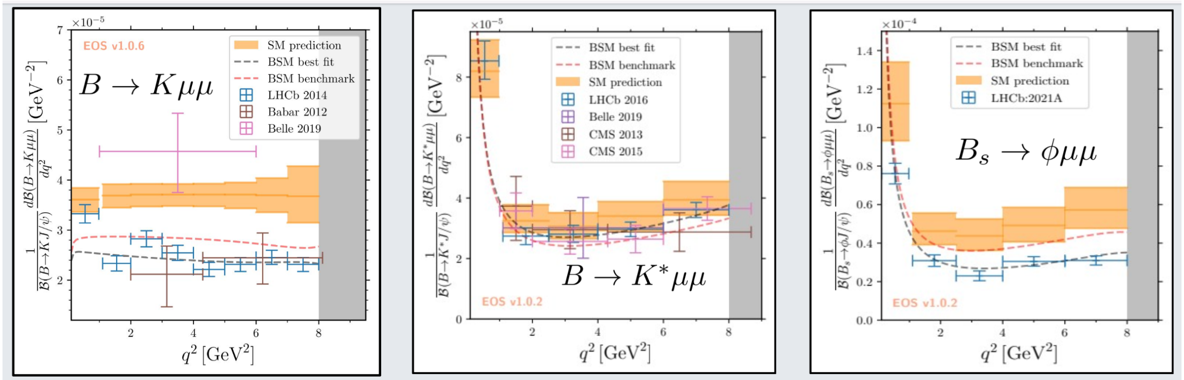


However, how well can we compute this?

- Form factor calculations: Lattice is producing precise prediction, however, still a few problems
- Charm Loop contribution: Various new parametrizations, but new physics input is needed.

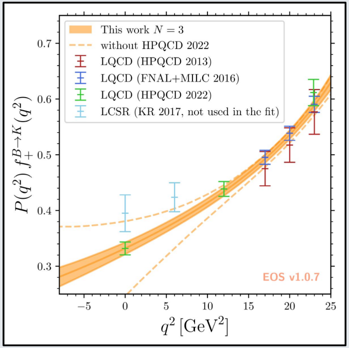
Needs additional scrutiny within the Standard Model!

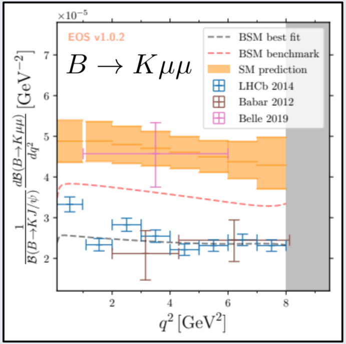
$b \to s\ell\ell$ anomalies: Rates in $B \to K\mu\mu$ and $B_s \to \phi\mu\mu$

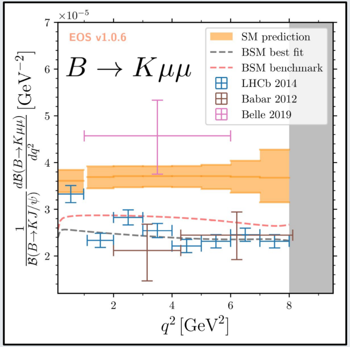


Rates at low q^2 seem to be lower than the SM prediction! (Plots from Gubernari et al., 2305.06301)

Form Factors from HPQCD 2022







QCD SR (Khodjamirian, Rusov 2017)

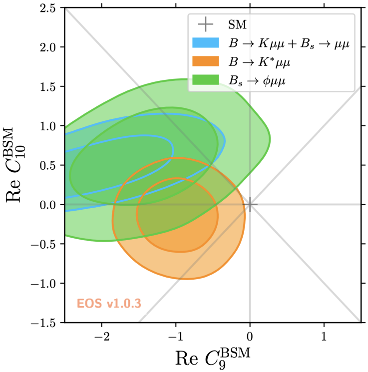
Lattice (HPQCD 2022)

(Plots from Gubernari et al., 2305.06301) C

EFT Fits to the WET Hamiltonian

Fit of the data to the Wilson coeff. of $H_{\rm eff}$

$$H_{\rm eff} = \cdots + C_9\,(\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\ell) + C_{10}\,(\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$

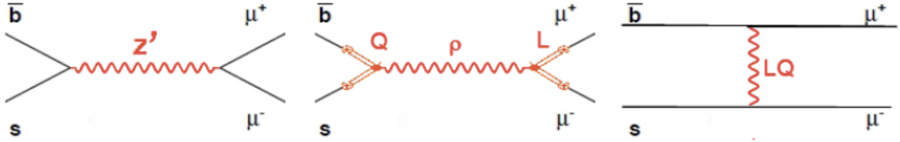


(from Gubernari et al. 2206.03797)

Some Comments ...

- WET Fits have to be re-done, assuming Lepton Universality

In terms of simplified models:

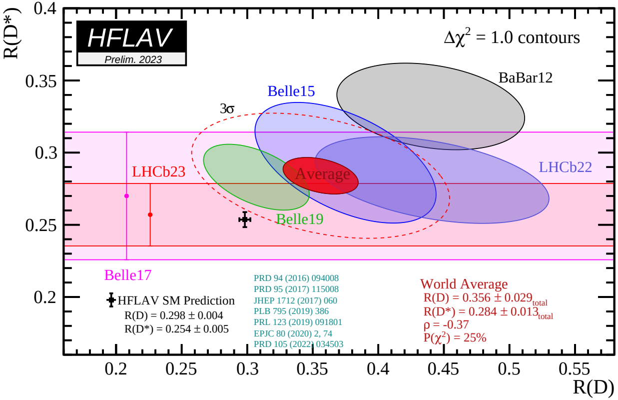


- Conserved LU (LUC) makes Leptoquark scenarios less attractive.
- Other scenarios (in particular the ones with LUC) are back in the game
- ... but this will depend on the fate of $R(D)$ and $R(D^*)$

Problems in Semileptonics

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

$$R(D) = \frac{\Gamma(B \to D\tau\bar{\nu})}{\Gamma(B \to D\ell\bar{\nu})} \quad R(D^*) = \frac{\Gamma(B \to D^*\tau\bar{\nu})}{\Gamma(B \to D^*\ell\bar{\nu})}$$



- Theory predictions are quite precise:
- Heavy Quark Symmetry fixes the longitudinal form factor f_0
- in Addition, its contribution is supressed by m_τ^2 / m_b^2

However:

- Inclusive rate $B \to X_c\tau\bar{\nu}$ can be calculated within OPE (Ligeti, Tackmann (2014); ThM, Rusov, Shahriaran (2017))

$$\mathrm{Br}(B \to X_c\tau\bar{\nu}) = (2.42 \pm 0.06)\%$$

- There is a measurement of the inclusive rate by LEP (B hadron admixture)

$$\mathrm{Br}(B \to X_c\tau\bar{\nu}) = (2.41 \pm 0.23)\%$$

- Theoretical predictions for the exclusive channels (Kamenik, Fajfer)

$$\mathrm{Br}_{\mathrm{th.}}(B \to D\tau\bar{\nu}) + \mathrm{Br}_{\mathrm{th.}}(B \to D^*\tau\bar{\nu}) = (2.01 \pm 0.07)\%$$

- On the other hand: (BaBar 2012, Compatible with LHCb 2015)

$$\mathrm{Br}_{\mathrm{expt.}}(B \to D\tau\bar{\nu}) + \mathrm{Br}_{\mathrm{expt.}}(B \to D^*\tau\bar{\nu}) = (2.78 \pm 0.25)\%$$

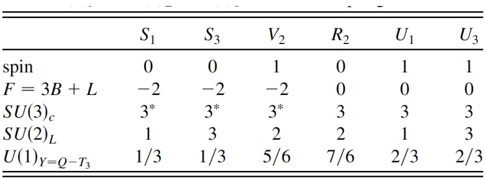
- ... and (Belle 2015)

$$\mathrm{Br}_{\mathrm{expt.}}(B \to D\tau\bar{\nu}) + \mathrm{Br}_{\mathrm{expt.}}(B \to D^*\tau\bar{\nu}) = (2.39 \pm 0.32)\%$$

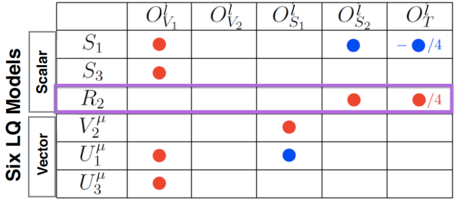
- Leptoquark Interpretations: (for example Tanaka, Watanabe, Sakaki 2015)

  Operator Basis:

$$\mathcal{O}^l_{V_1} = (\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_{lL}), \quad \mathcal{O}^l_{V_2} = (\bar{c}_R \gamma^\mu b_R)(\bar{\tau}_L \gamma_\mu \nu_{lL}),$$
$$\mathcal{O}^l_{S_1} = (\bar{c}_L b_R)(\bar{\tau}_R \nu_{lL}), \quad \mathcal{O}^l_{S_2} = (\bar{c}_R b_L)(\bar{\tau}_R \nu_{lL}),$$
$$\mathcal{O}^l_T = (\bar{c}_R \sigma^{\mu\nu} b_L)(\bar{\tau}_R \sigma_{\mu\nu} \nu_{lL}). \tag{7}$$



	S_1	S_3	V_2	R_2	U_1	U_3
spin	0	0	1	0	1	1
$F = 3B + L$	-2	-2	-2	0	0	0
$SU(3)_c$	3^*	3^*	3^*	3	3	3
$SU(2)_L$	1	3	2	2	1	3
$U(1)_{Y=Q-T_3}$	$1/3$	$1/3$	$5/6$	$7/6$	$2/3$	$2/3$

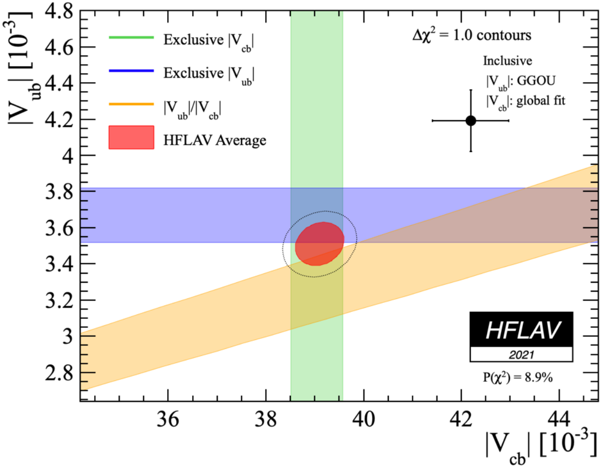


	$O^l_{V_1}$	$O^l_{V_2}$	$O^l_{S_1}$	$O^l_{S_2}$	O^l_T
S_1	🔴			🔵	−🔵/4
S_3	🔴				
R_2				🔴	🔴/4
V_2^μ			🔴		
U_1^μ	🔴		🔵		
U_3^μ	🔴				

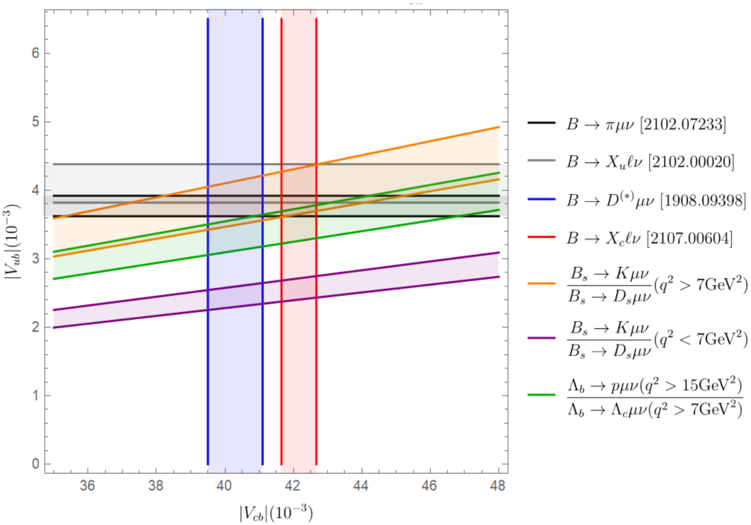
- ... al this was designed to explain explains R_K and $R(D^{(*)})$
- it needs a fresh look.

$$V_{xb}^{\mathrm{incl}} \text{ versus } V_{xb}^{\mathrm{excl}}$$

... The problem remains:



... However



Keri Vos, TRR 257 annual meeting

- Form Factors for Exclusive decays: Lattice QCD is the method of choice!
- Inclusive decays make use of Heavy Quark Expansions:
  - Local OPE for inclusive V_{cb}: HQE parameters μ_π, μ_G, ρ_D, ρ_{LS}, ...
  - Light-Cone OPE for inclusive V_{ub}: Shape functions (leading and sub-leading)

My personal view on the current situation:
Use inclusive V_{cb} and exclusive V_{ub} (from $B \to \pi\ell\bar{\nu}$)

$V_{ub}^{\rm incl}$ versus $V_{ub}^{\rm excl}$

- Inclusive V_{ub} depends on non-perturbative functions:
  $\to$ Precision is less than in $b \to c$

$$\begin{aligned} |V_{ub}| &= (4.49 \pm 0.16^{+0.16}_{-0.18}) \times 10^{-3} \quad \text{(PDG)} \\ |V_{ub}| &= (4.03^{+0.20}_{-0.22}) \times 10^{-3} \quad \text{(BaBar)} \end{aligned}$$

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

$$|V_{ub}| = (3.72 \pm 0.19) \times 10^{-3} \quad \text{(PDG)}$$

- Persistent tension in V_{ub},
  however, slightly receeding due to new data
- New Input from $\Lambda_b \to p \ell \bar{\nu}$ (LHCb)

Progress in inclusive semileptonic decays: V_{cb}

- Structure of the expansion (@ tree):

$$\begin{aligned} d\Gamma &= d\Gamma_0 + \left(\frac{\Lambda_{\rm QCD}}{m_b}\right)^2 d\Gamma_2 + \left(\frac{\Lambda_{\rm QCD}}{m_b}\right)^3 d\Gamma_3 + \left(\frac{\Lambda_{\rm QCD}}{m_b}\right)^4 d\Gamma_4 \\ &\quad + d\Gamma_5 \left(a_0 \left(\frac{\Lambda_{\rm QCD}}{m_b}\right)^5 + a_2 \left(\frac{\Lambda_{\rm QCD}}{m_b}\right)^3 \left(\frac{\Lambda_{\rm QCD}}{m_c}\right)^2 \right) \\ &\quad + \ldots + d\Gamma_7 \left(\frac{\Lambda_{\rm QCD}}{m_b}\right)^3 \left(\frac{\Lambda_{\rm QCD}}{m_c}\right)^4 \end{aligned}$$

- $d\Gamma_3 \propto \ln(m_c^2/m_b^2)$
- Power counting $m_c^2 \sim \Lambda_{\rm QCD} m_b$

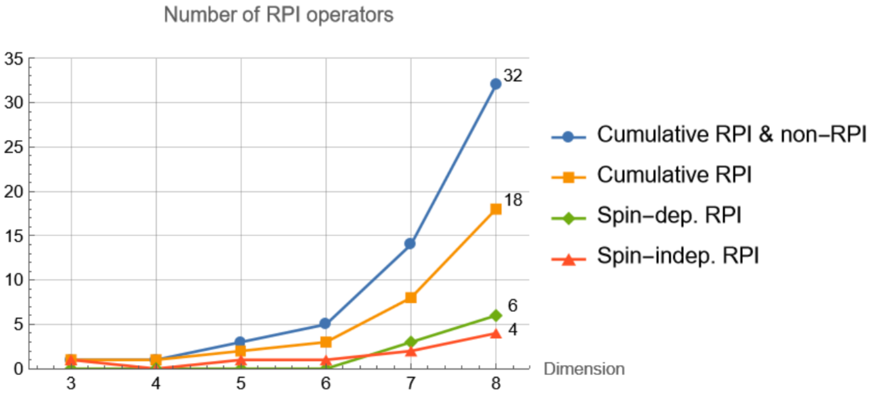
Present state of the $b \to c$ semileptonic Calculations

- Tree level terms up to and including $1/m_b^5$ known
  Bigi, Zwicky, Uraltsev, Turczyk, Vos, Milutin, ThM, ...
- $\mathcal{O}(\alpha_s)$ and full $\mathcal{O}(\alpha_s^2)$ for the partonic rate and spectra are known
  Melnikov, Czarnecki, Pak
- $\mathcal{O}(\alpha_s^3)$ to the partonic rate known (Fael, Schonwald, Steinhauser: 2011.13654)
- $\mathcal{O}(\alpha_s)$ for $1/m_b^2$ is known for rates and spectra
  Becher, Boos, Lunghi, Gambino, Pivovarov, Rosenthal, Alberti
- $\mathcal{O}(\alpha_s)$ for $1/m_b^3$ is known for rates and spectra Pivovarov, Moreno, ThM
- In the pipeline:
  - Estimation of Duality Violation

We are moving towards a TH-uncertainty of 1% in $V_{cb,incl}$!

Recent Development: Reducing the Number of HQE Parameters

New Idea based on an old observation: Reparametrization Invariance Problem: Number of HQE parameters in higher orders! (ThM, Vos: 1802.09409, Fael, ThM, Vos: 1812.07472)



HQE parameters (for the total rate) to $O(1/m^4)$

$$
\begin{aligned}
2m_H\mu_3 &= \langle H(p)|\bar{Q}_v Q_v|H(p)\rangle = \langle \bar{Q}_v Q_v\rangle \qquad \mu_3 = 1 + \frac{\mu_\pi^2 - \mu_G^2}{2m_Q^2} \\
2m_H\mu_G &= \langle \bar{Q}_v (iD^\mu)(iD^\nu)(-i\sigma_{\mu\nu}) Q_v\rangle \\
2m_H\rho_D &= \langle \bar{Q}_v \left[(iD^\mu) \, , \left[\left((ivD) + \frac{(iD)^2}{2m} \right) \, , (iD_\mu) \right] \right] Q_v\rangle \\
2m_H r_G^4 &= \langle \bar{Q}_v \, [(iD_\mu) \, , (iD_\nu)] \, [(iD^\mu) \, , (iD^\nu)] \, Q_v\rangle \qquad \langle G^2\rangle \\
2m_H r_E^4 &= \langle \bar{Q}_v \, [(ivD) \, , (iD_\mu)] \, [(ivD) \, , (iD^\mu)] \, Q_v\rangle \qquad \langle \vec{E}^2\rangle \\
2m_H s_B^4 &= \langle \bar{Q}_v \, [(iD_\mu) \, , (iD_\alpha)] \, [(iD^\mu) \, , (iD_\beta)] \, (-i\sigma^{\alpha\beta}) Q_v\rangle \qquad \langle (\vec{B} \times \vec{B}) \cdot \vec{\sigma}\rangle \\
2m_H s_E^4 &= \langle \bar{Q}_v \, [(ivD) \, , (iD_\alpha)] \, [(ivD) \, , (iD_\beta)] \, (-i\sigma^{\alpha\beta}) Q_v\rangle \qquad \langle (\vec{E} \times \vec{E}) \cdot \vec{\sigma}\rangle \\
2m_H s_{qB}^4 &= \langle \bar{Q}_v \, [iD_\mu \, , [iD^\mu \, , [iD_\alpha \, , iD_\beta]]] \, (-i\sigma^{\alpha\beta}) Q_v\rangle \qquad \langle \Box\vec{\sigma} \cdot \vec{B}\rangle
\end{aligned}
$$

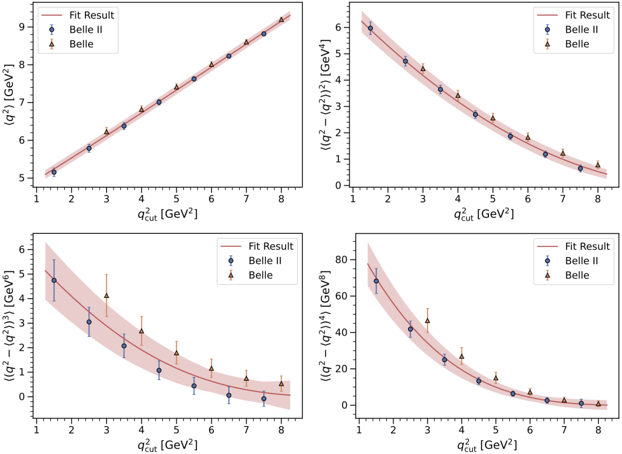
Alternative V_{cb} Determination

The leptonic invariant mass is RPI: and so are

$$\frac{1}{\Gamma_0}\int d\hat{q}^2 (\hat{q}^2)^n \frac{d\Gamma}{d\hat{q}^2} \quad \text{and} \quad \frac{1}{\Gamma_0}\int_{\hat{q}^2_{\mathrm{cut}}} d\hat{q}^2 (\hat{q}^2)^n \frac{d\Gamma}{d\hat{q}^2}$$

$$\begin{aligned}
\mathcal{Q}_1 = {} & \frac{3}{10}\mu_3 - \frac{7}{5}\frac{\mu_G^2}{m_b^2} + \frac{\tilde{\rho}_D^3}{m_b^3}(19 + 8\log\rho) - \frac{r_E^4}{m_b^4}\left(\frac{1292}{45} + \frac{40}{3}\log\rho\right) - \frac{s_B^4}{m_b^4}(8 + 2\log\rho) \\
& + \frac{13}{120}\frac{s_{qB}^4}{m_b^4} + \frac{s_E^4}{m_b^4}\left(\frac{63}{5} + 4\log\rho\right) + \frac{r_G^4}{m_b^4}\left(\frac{827}{45} + \frac{22}{3}\log\rho\right), \qquad (4.10) \\
\mathcal{Q}_2 = {} & \frac{2}{15}\mu_3 - \frac{16}{15}\frac{\mu_G^2}{m_b^2} + \frac{\tilde{\rho}_D^3}{m_b^3}\left(\frac{358}{15} + 8\log\rho\right) - \frac{r_E^4}{m_b^4}\left(\frac{2888}{45} + \frac{64}{3}\log\rho\right) - \frac{s_B^4}{m_b^4}\left(\frac{259}{15} + 4\log\rho\right) \\
& + \frac{s_{qB}^4}{m_b^4}\left(\frac{251}{180} + \frac{1}{3}\log\rho\right) + \frac{s_E^4}{m_b^4}\left(\frac{908}{45} + \frac{16}{3}\log\rho\right) + \frac{r_G^4}{m_b^4}\left(\frac{1373}{45} + \frac{28}{3}\log\rho\right), \qquad (4.11)
\end{aligned}$$

Data on q^2 Moments II



(Bernlochner et al. 2205.10274)

$\Longrightarrow$ New V_{cb} Determination

$$R^*(q^2_{\mathrm{cut}}) \qquad \langle (q^2)^n \rangle_{\mathrm{cut}}$$

$$\downarrow$$

$$\mu_3, \mu_G^2, \tilde{\rho}_D^3, r_E^4, r_G^4, s_E^4, s_B^4, s_{qB}^4, m_b, m_c$$

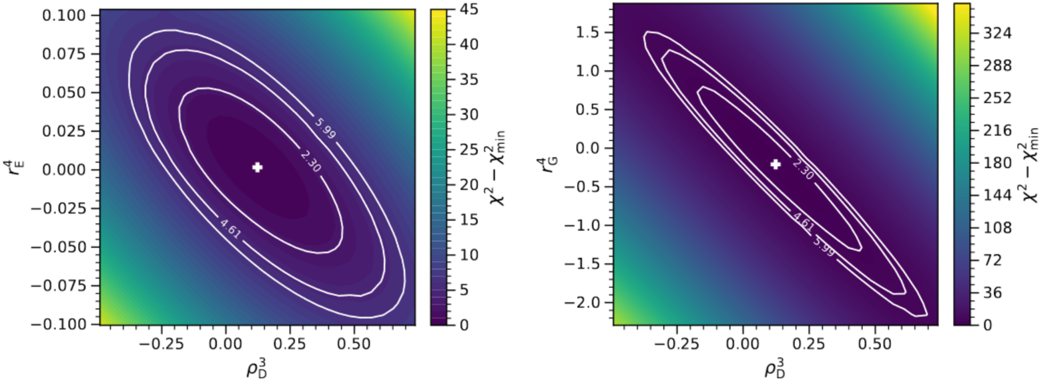
$$\downarrow$$

$$\mathrm{Br}(\bar{B} \to X_c \ell \bar{\nu}) \propto \frac{|V_{cb}|^2}{\tau_B} \Bigg[\Gamma_{\mu_3} \mu_3 + \Gamma_{\mu_G} \frac{\mu_G^2}{m_b^2} + \Gamma_{\tilde{\rho}_D} \frac{\tilde{\rho}_D^3}{m_b^3}$$
$$+ \Gamma_{r_E} \frac{r_E^4}{m_b^4} + \Gamma_{r_G} \frac{r_G^4}{m_b^4} + \Gamma_{s_B} \frac{s_B^4}{m_b^4} + \Gamma_{s_E} \frac{s_E^4}{m_b^4} + \Gamma_{s_{qB}} \frac{s_{qB}^4}{m_b^4} \Bigg]$$

$$\downarrow$$

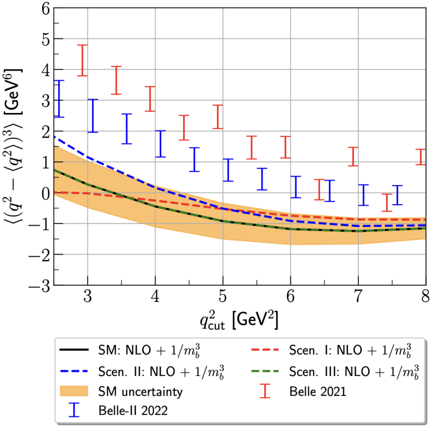
$$V_{cb} = (41.69 \pm 0.63) \cdot 10^{-3}$$

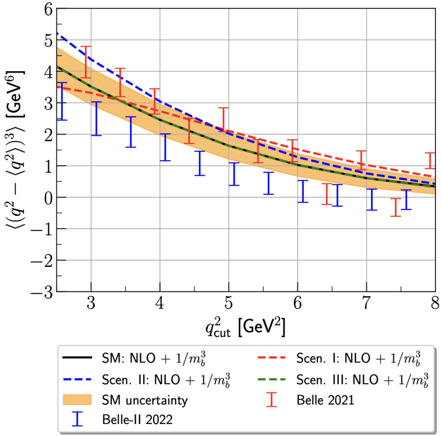
- Agrees with previous determinations
- It includes a data driven determination of the $1/m^4$ HQE Parameters
- $1/m^4$ turns our to be small → good fot the HQE



Interesting side remark for Alex: The value of ρ_D:

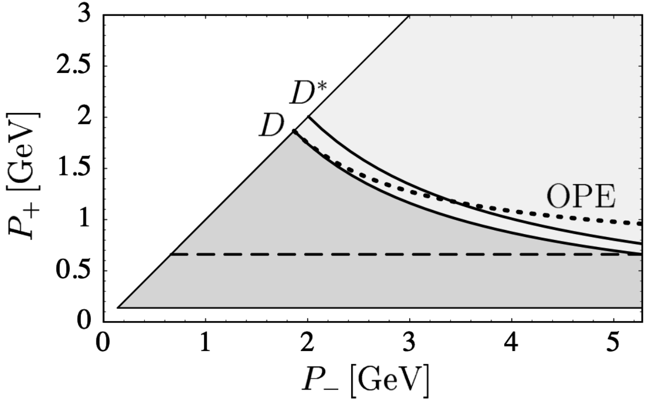
- Gambino et al.: $\rho_D = (0.185 \pm 0.031) GeV^3$ (kinetic scheme)
- Bernlochner et al. $\rho_D = (0.03 \pm 0.02) GeV^3$ (kinetic scheme)





Inclusive V_{ub}

- Problem: Cuts needed to suppress charmed decays
- Forces us into corners of phase space, where the usual OPE breaks down



Approaches to inclusive V_{ub}

- Obtaining the Shape functions:
  - From Comparison with $B \to X_s\gamma$
  - From the knowledge of (a few) moments
  - From modeling
- QCD based:
  - BLNP (Bosch, Lange, Neubert, Paz)
  - GGOU (Gambino, Giordano, Ossola, Uraltsev)
  - SIMBA (Tackmann, Tackmann, Lacker, Liegti, Stewart ...)
- QCD inspired:
  - Dressed Gluon Exponentiation (Andersen, Gardi)
  - Analytic Coupling (Aglietti, Ricciardi et al.)
- Attempts to avoid the shape functions (Bauer Ligeti, Luke ...)

Update for BLNP is non the way (Lange, ThM, Olschewsky, Paz, Vos)

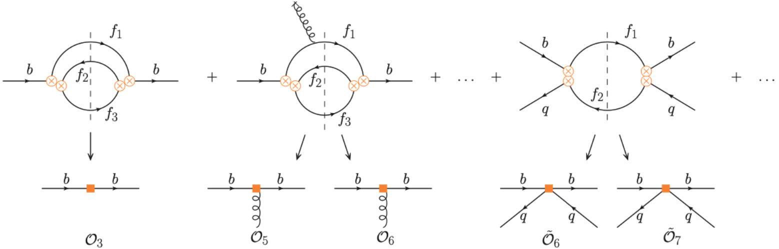
Other issues

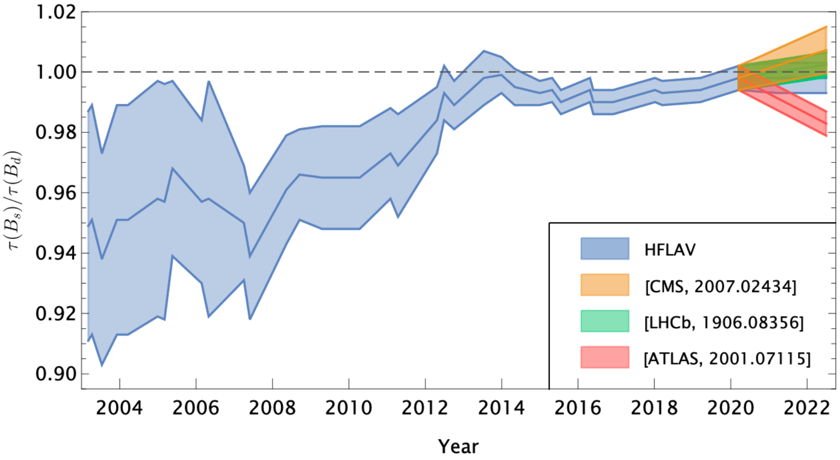
Bottom Lifetimes and Mixing

- Lifetimes and mixing parameters can be calculated in the HQE

$$\Gamma(B_q) = \Gamma_3 + \Gamma_5 \frac{\langle \mathcal{O}_5 \rangle}{m_b^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle}{m_b^3} + \ldots + 16\pi^2 \left(\tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_b^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_b^4} + \ldots \right),$$

- Matrix Elements of $\mathcal{O}_i$ = HQE parameters
- Systematic calculation of SD contributions



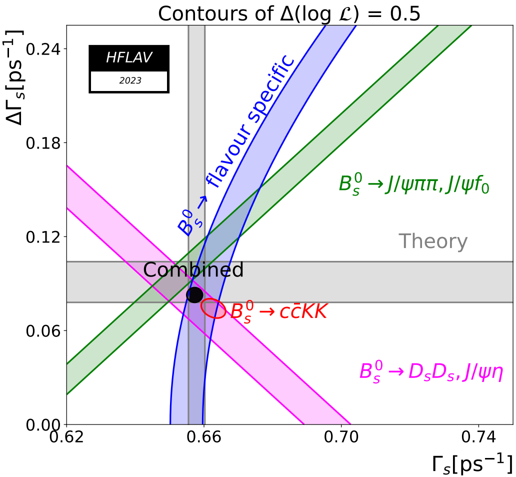


(Lenz, Piscopo, Rusov 220802643)

Observable	HQE Scenario A	HQE Scenario B	Exp. value
$\Gamma(B^+)[\mathrm{ps}^{-1}]$	$0.563^{+0.106}_{-0.065}$	$0.576^{+0.107}_{-0.067}$	0.6105 ± 0.0015
$\Gamma(B_d)[\mathrm{ps}^{-1}]$	$0.615^{+0.108}_{-0.069}$	$0.627^{+0.110}_{-0.070}$	0.6583 ± 0.0017
$\Gamma(B_s)[\mathrm{ps}^{-1}]$	$0.597^{+0.109}_{-0.069}$	$0.625^{+0.110}_{-0.071}$	0.6596 ± 0.0026
$\tau(B^+)/\tau(B_d)$	$1.0855^{+0.0232}_{-0.0219}$	$1.0851^{+0.0230}_{-0.0217}$	1.076 ± 0.004
$\tau(B_s)/\tau(B_d)$	$1.0279^{+0.0113}_{-0.0113}$	$1.0032^{+0.0063}_{-0.0063}$	0.998 ± 0.005

(Lenz, Piscopo, Rusov 220802643)

B_s Mixing


Contours of $\Delta(\log \mathcal{L}) = 0.5$
HFLAV
2023
$\Delta\Gamma_s[\mathrm{ps}^{-1}]$
0.24
0.18
0.12
0.06
0.00
0.62
0.66
0.70
0.74
$\Gamma_s[\mathrm{ps}^{-1}]$
$B_s^0 \to$ flavour specific
$B_s^0 \to J/\psi\pi\pi, J/\psi f_0$
Theory
Combined
$B_s^0 \to c\bar{c}KK$
$B_s^0 \to D_sD_s, J/\psi\eta$

Charm

Theoretical issues: Do we have a method to compute anything?

- Is charm heavy enough for an HQE approach?
- Charm is not light enough for a flavour $SU(4)$ with u, d, s, c!
- Lattice can do a lot, but not everything!

HQE for charm

HQE certainly need to be modified: Compare

$$\left.\frac{\tau(B_s)}{\tau(B_d)}\right|^{\text{exp}} = 0.995 \pm 0.006\,, \qquad \left.\frac{\tau(B^+)}{\tau(B_d)}\right|^{\text{exp}} = 1.076 \pm 0.004\,.$$

to

$$\left.\frac{\tau(D^\pm)}{\tau(D^0)}\right|^{\text{exp}} = 2.563 \pm 0.017\,, \qquad \left.\frac{\tau(D_s)}{\tau(D^0)}\right|^{\text{exp}} = 1.219 \pm 0.017\,,$$

This is usually blamed to terms at order $1/m^3$

$$\Gamma(B_q) = \Gamma_3 + \Gamma_5 \frac{\langle \mathcal{O}_5 \rangle}{m_b^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle}{m_b^3} + \ldots + 16\pi^2 \left(\tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_b^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_b^4} + \ldots \right),$$

$$16\pi^2 \frac{\Lambda_{\text{QCD}}^3}{m_b^3} = 0.15 \quad \text{but} \quad 16\pi^2 \frac{\Lambda_{\text{QCD}}^3}{m_c^3} = 5 \ldots 10$$

Observable	HQE prediction	Exp. value
$\Gamma(D^0)[\mathrm{ps}^{-1}]$	$1.59 \pm 0.36^{+0.45}_{-0.36}{}^{+0.01}_{-0.01}$	2.44 ± 0.01
$\Gamma(D^+)[\mathrm{ps}^{-1}]$	$-0.15 \pm 0.76^{+0.58}_{-0.27}{}^{+0.25}_{-0.10}$	0.96 ± 0.01
$\bar{\Gamma}(D_s^+)[\mathrm{ps}^{-1}]$	$1.57 \pm 0.43^{+0.51}_{-0.40}{}^{+0.02}_{-0.01}$	1.88 ± 0.02
$\tau(D^+)/\tau(D^0)$	$2.80 \pm 0.85^{+0.01}_{-0.14}{}^{+0.11}_{-0.26}$	2.54 ± 0.02
$\bar{\tau}(D_s^+)/\tau(D^0)$	$1.01 \pm 0.15^{+0.02}_{-0.03}{}^{+0.01}_{-0.01}$	1.30 ± 0.01
$B_{sl}^{D^0}[\%]$	$5.91 \pm 1.57^{+0.33}_{-0.28}$	6.49 ± 0.11
$B_{sl}^{D^+}[\%]$	$15.0 \pm 4.04^{+0.83}_{-0.72}$	16.07 ± 0.30
$B_{sl}^{D_s^+}[\%]$	$7.76 \pm 2.62^{+0.43}_{-0.38}$	6.30 ± 0.16
$\Gamma_{sl}^{D^+}/\Gamma_{sl}^{D^0}$	$1.001 \pm 0.008 \pm 0.001$	0.985 ± 0.028
$\Gamma_{sl}^{D_s^+}/\Gamma_{sl}^{D^0}$	$1.06 \pm 0.23 \pm 0.01$	0.790 ± 0.026

(King et al. 210913219)

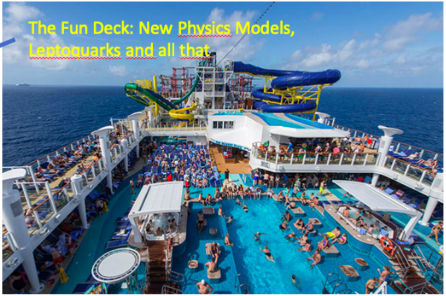
Instead of a Summary

- We will get an enormous amount of data on heavy flavours in the next decade
- ... raising some difficult questions:
  - What can we do with 50 fb^{-1} of LHCb date at the end of run 4?
  - What can we do with 70 ab^{-1} of Belle II data?
  - Data form charm factories ...
- From the Theory side we need to prepare to look into
  - Very rare processes, i.e. possible violation of sacred symmetries
  - Improve our tools to be able to match the experimental precision
  - Lattice will be indispensable for progress here
  - ... but it cannot access all observables needed
    such as e.g. nonleptonic decays, in particular those with multibody final states

Theory is under way ...


Ship of Flavour Theory


The Fun Deck: New Physics Models, Leptoquarks and all that
Ship of Flavour Theory



The Fun Deck: New Physics Models, Leptoquarks and all that

Ship of Flavour Theory

The Machine Deck: QCD Loops, Hadronic Matrix Elements and all that

We definitively need more people on the machine deck!