Quark flavour physics in the time of European strategy

Marco Ciuchini

- Precision flavour physics
- Flavour physics & European strategy
- Prospects for the UT analysis
  (Prospects for $b\to s$ anomalies)
- Conclusions
The stage

* the Higgs boson discovery closed up the quest for the Standard Model: an extremely successful story which however left us with a well-known list of problems (fermion masses and mixing, strong CP, EW hierarchy, …) and no clear clue for the next step

* the absence of NP discoveries at the LHC has weakened the naturalness argument requiring new particles at close-by energies: future physics programs rely more and more on indirect searches (EWPO, Higgs couplings & potential, …)
Precision flavour physics: a tool of choice for indirect NP searches

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{\mathcal{L}_5}{\Lambda_{\text{NP}}} + \frac{\mathcal{L}_6}{\Lambda_{\text{NP}}^2} + \ldots \]

* rich phenomenology (a variety of FCNCs, mixing, CPV observables in several meson and baryon sectors)

* NP sensitivity is strongly boosted by the suppression of flavor and CP violation present in the SM (weak coupling, small mixing, GIM mechanism in FCNCs & CPV, LF & LFU approximate conservation, ...)

* important successes in the low-precision regime (charm from $K \to \mu\mu$, 3rd gen. from $\varepsilon_K$, heavy $m_\tau$ from $B$ mixing+SL decays)
To achieve sensitivity on subleading NP amplitudes, indirect searches require that the theoretical uncertainty on SM amplitudes matches the experimental error.

In flavour physics dominant SM uncertainties are typically the hadronic ones. Input from a non-perturbative technique able to compute hadronic amplitudes at sub-percent level is needed.

Lattice QCD is expected to achieve sub-percent accuracy on several hadronic parameters. Yet LQCD is not always applicable (non-local operators, amplitudes with 2+ hadrons in the final state, ...)

In specific cases, strategies can be envisaged which rely less on theory inputs, using instead data to control the SM uncertainty (e.g. the UT angles, $b \to c$ inclusive SL decays, ...)

Finally null tests: no theory input needed for those observables having negligible SM contribution (e.g. LFV, CPV in D mixing, ...)

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Ref.</th>
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<th>short-term</th>
<th>mid-term</th>
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<td>$(\Delta m_s/\Delta m_d)_{exp}$</td>
<td>[33]</td>
<td>0.4%</td>
<td>-</td>
<td>-</td>
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<tr>
<td>$\xi$ for $(\Delta m_s/\Delta m_d)_{theor}$</td>
<td>[309]</td>
<td>1.4%</td>
<td>0.3%</td>
<td>0.3%</td>
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<tr>
<td>$B \to \pi$: $</td>
<td>V_{ub}\rangle_{exp}$</td>
<td>[309, 334, 340]</td>
<td>2.3%</td>
<td>1.6%</td>
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<tr>
<td>$B \to \pi$: $</td>
<td>V_{ub}\rangle_{theor}$</td>
<td>[309]</td>
<td>2.9%</td>
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<td>$B \to D$: $</td>
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<td>$B \to D$: $</td>
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<td>[309]</td>
<td>1.4%</td>
<td>0.3%</td>
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<tr>
<td>$B \to D^*$: $</td>
<td>V_{cb}\rangle_{exp}$</td>
<td>[340]</td>
<td>1.2%</td>
<td>-</td>
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<td>$B \to D^*$: $</td>
<td>V_{cb}\rangle_{theor}$</td>
<td>[309]</td>
<td>1.4%</td>
<td>0.4%</td>
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<tr>
<td>$\Lambda_b \to p(\Lambda_c)$: $</td>
<td>V_{ub}/V_{cb}\rangle_{exp}$</td>
<td>[334]</td>
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<td>V_{ub}/V_{cb}\rangle_{theor}$</td>
<td>[309]</td>
<td>4.9%</td>
<td>1.2%</td>
</tr>
</tbody>
</table>

Flavour physics is not just a tool: SM has its own flavour puzzle

$$\mathcal{L}_{SM} = \mathcal{L}_{EWSB} + \mathcal{L}_{\text{kin}} + \mathcal{L}_{\text{gauge}} + \mathcal{L}_{Y}$$

The Yukawa Lagrangian describes quark flavour physics in terms of 10 physical parameters:

- 6 masses,
- 3 mixing angles + 1 CPV phase

The Cabibbo-Kobayashi-Maskawa matrix

The pattern of masses, mixing, and CPV may already be a NP signal we have not been able to interpret within a full-fledged theory so far
European strategy for particle physics: flavour physics in the briefing book

EDMs: neutron, e, ...

FV in lepton decays (\(\mu\) and \(\tau\))

K ultra-rare decays and CPV

Heavy flavour physics
- selected FCNCs
  e.g. \(\text{BR}(B_d \rightarrow \mu\mu)/\text{BR}(B_s \rightarrow \mu\mu)\)
- LFV, LFUV, ...
  e.g. \(R_{D/D^*}, R_{K/K^*} + B_d \rightarrow K^*\mu\mu\)
- CPV in charm mixing and decays

Dark sector, e.g. \(D^* \rightarrow D \gamma_{\text{dark}}\)

Unitarity Triangle Analysis


### Unitarity Triangle Analysis

**Original goal:**
- Determine the UT apex and the CKM matrix parameters

**Overconstrained fit:**
- Predict observables & hadronic parameters or constrain NP

#### Plots

<table>
<thead>
<tr>
<th>Plot 1</th>
<th>Plot 2</th>
<th>Plot 3</th>
<th>Plot 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>(</td>
<td>V_{ub}/V_{cb}</td>
<td>)</td>
<td>(\varepsilon_K)</td>
</tr>
<tr>
<td>(\Delta m_d)</td>
<td>(\Delta m_s/\Delta m_d)</td>
<td>((1 - \bar{\rho})^2 + \bar{\eta}^2)</td>
<td>(2\beta + \gamma)</td>
</tr>
</tbody>
</table>
UTA beyond the SM

genetic NP contributions to mixing amplitudes

\( K \) mixing amplitude (1 real param): \( \text{Im} A_K = C_\varepsilon \text{Im} A_K^{SM} \)

\( B_d \) and \( B_s \) mixing amplitudes (2+2 real parameters):
- two parametrizations -

\[
A_q e^{2i\phi_q} = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}} = \left[ 1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP} - \phi_q^{SM})} \right] A_q^{SM} e^{2i\phi_q^{SM}}
\]

\[ q = d, s, \quad \phi_d^{SM} = \beta, \quad \phi_s^{SM} = -\beta_s \]
New Physics parameters

\[ C_{B_d} = 1.05 \pm 0.11 \]
\[ \phi_{B_d} = (-2.0 \pm 1.8)^\circ \]

\[ C_{\epsilon_K} = 1.12 \pm 0.12 \]

\[ C_{B_s} = 1.11 \pm 0.09 \]
\[ \phi_{B_s} = (0.42 \pm 0.89)^\circ \]

\[ \Delta m_d^{\text{exp}} = C_{B_d} \Delta m_d^{\text{SM}} \]
\[ \sin 2\beta^{\text{exp}} = \sin(2\beta^{\text{SM}} + 2\phi_{B_d}) \]
\[ \alpha^{\text{exp}} = \alpha^{\text{SM}} - \phi_{B_d} \]

\[ \Delta m_s^{\text{exp}} = C_{B_s} \Delta m_s^{\text{SM}} \]
\[ \phi_{s}^{\text{exp}} = (\beta_{s}^{\text{SM}} - \phi_{B_s}) \]
\[ \epsilon_{K}^{\text{exp}} = C_{\epsilon_K} \epsilon_{K}^{\text{SM}} \]
Lower bound on the NP scale $\Lambda$ from $\Delta F=2$ transitions (TeV @95% prob.)

\[ C_i(\Lambda) = \frac{L \cdot FC}{\Lambda^2} \]

\[ H_{eff}^{\Delta B=2} = \sum_{i=1}^{5} C_i(\mu)Q_i(\mu) + \sum_{i=1}^{3} \tilde{C}_i(\mu)\tilde{Q}_i(\mu) \]

$C_i \sim 1, L \sim 1$
$FC \sim SM, L \sim \alpha_w^2$

<table>
<thead>
<tr>
<th></th>
<th>$K$</th>
<th>$D$</th>
<th>$B_d$</th>
<th>$B_s$</th>
</tr>
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<tbody>
<tr>
<td>$4x10^5$</td>
<td>$4x10^4$</td>
<td>$3x10^3$</td>
<td>$1x10^3$</td>
<td></td>
</tr>
<tr>
<td>$3$</td>
<td>$0.4$</td>
<td>$0.7$</td>
<td>$0.8$</td>
<td></td>
</tr>
</tbody>
</table>

NP scale $\Lambda$ (TeV)

- $C_1$
- $C_2$
- $C_3$
- $C_4$
- $C_5$

SM-like $LC = 1$
$L = \alpha_w^2$
<table>
<thead>
<tr>
<th></th>
<th>$\delta \varepsilon_K$</th>
<th>$\delta \beta$ ($\delta \beta_s$)</th>
<th>$\delta \alpha$</th>
<th>$B_{d/s}$ mass difference uncertainties</th>
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<tbody>
<tr>
<td>Current</td>
<td>$0.12%$</td>
<td>$2%$</td>
<td>$3%$</td>
<td>$1%$</td>
</tr>
<tr>
<td>Phase 1</td>
<td>$0.12%$</td>
<td>$0.8%$</td>
<td>$0.6%$</td>
<td>$0.5%$</td>
</tr>
<tr>
<td>Phase 2</td>
<td>$0.12%$</td>
<td>$0.6%$</td>
<td>$0.5%$</td>
<td>$0.5%$</td>
</tr>
</tbody>
</table>

* $\delta \varepsilon_K \sim 2\%$, limited by long-distance contributions
* $\delta \beta$ ($\delta \beta_s$) $\sim$ few % (few tens %), limited by the subleading decay amplitude. Can be reduced by $\sim 10$ exploiting SU(3)$_f$-related control channels. Eventually limited by SU(3)$_f$ breaking
* $\delta \alpha \sim 1\%$, limited by unknown isospin-breaking corrections
* exclusive semilep. decay uncertainties scale with lattice FFs, inclusive ones need an increasing number of OPE/SF terms
* $B_{d/s}$ mass difference uncertainties scale with lattice ME's, at sub-percent level QED effects need to be included
New opportunities

High precision provides new opportunities

For example:

* $\beta$ from $2\beta+\gamma$ and $\gamma$
  less precise than $\beta$ from $B \rightarrow J/\psi K$,  
  but free from subdominant penguin  
  amplitude and NP in $\Delta F=1$ decays

* $|V_{ts}|/|V_{td}|$ from $BR(B_s \rightarrow \mu\mu) / BR(B_d \rightarrow \mu\mu)$  
  less effective than $\Delta m_s / \Delta m_d$, but  
  affected by NP in $\Delta F=1$ transitions  
  instead of $\Delta F=2$
New Physics parameters: CPV in D-Dbar mixing

SM amplitudes are approximately real

CPV is generated by NP

$|q/p| \neq 1 \leftrightarrow \arg(q/p) \neq 0$
$\Delta B=1$: the $B$ "anomalies"
Global fits to $b \to s$ FCNCs

$Q_7 = \frac{e}{16\pi^2} m_b \bar{s} \sigma_{\mu\nu} F^{\mu\nu} b_R$

$Q_9,\ell = \frac{\alpha e}{4\pi} s_L \gamma_\mu b_L \bar{\ell} \gamma^\mu \ell$

$Q_{10,\ell} = \frac{\alpha e}{4\pi} s_L \gamma_\mu b_L \bar{\ell} \gamma^\mu \gamma^5 \ell$

Hiller&Kruger; Descotes-Genon et al.; Jaeger et al.; Capdevila et al.; Altmannshofer et al.; Hurth et al.;

... MC et al., arXiv:1704.05447

$(\text{V})$ - PMD

$IC = 199$

$(\text{III})$ - PMD

$IC = 172$

All $b \to s$ anomalies, including LFU violation, are accounted for by a large correction of $-(25-30)\%$ to $C_{9,\mu}$
$B \to K^*\mu\mu$ drives the interpretation of the $b\to s$ anomalies in terms of NP in $C_{9,\mu}$

**Short term**: important to confirm the anomaly in $B \to K^*\mu\mu$ with different systematics and theoretical uncertainties

Inclusive $B \to X_s\ell\ell$ @Belle II

**Mid term**: bounds on $C_{9/10,\mu}$ from $B \to K^*\mu\mu$ and $B_s \to \mu\mu$ can be improved by a factor $\sim 2$, probing up to a scale $\Lambda_{NP} \sim 100$ TeV
Summary

In a time when indirect searches become increasingly important, flavour physics remains a tool of choice.

The SM picture looks very consistent, but so far we have typically excluded NP corrections at the 10% level.

...AND we are now entering the "percent era"!

Anomalies are present in recent $\Delta B=1$ data: despite the caveats, it is remarkable that there is a simple EFT interpretation for all of them.

Theoretical progresses (QED corrections, isospin breaking, bilocal operators, ...) in lattice QCD results are needed to convert exp. precision in NP sensitivity.

As precision further increases, observables with weak/null theory input may take the scene.
Thank you and stay safe!
Backup
Flavour physics in the SM: rich phenomenology (FCNC suppression, mixing, CP violation, ...) but little understanding of the “why” and the “how”

\[ \mathcal{L}_{SM} = \mathcal{L}_{EWSB} + \mathcal{L}_{kin} + \mathcal{L}_{gauge} + \mathcal{L}_Y \]

The Yukawa Lagrangian describes quark flavour physics in terms of 10 physical parameters:

- 6 masses,
- 3 mixing angles + 1 CPV phase

The Cabibbo-Kobayashi-Maskawa matrix

\[ V_{CKM} \]

Beyond the SM: a powerful indirect probe of the New Physics scale \( \Lambda \)

\[ \mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{\mathcal{L}_5}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \ldots \]

has accidental (approximate) symmetries

may violate accidental symmetries
Going BSM with flavour physics: why?

Searches through virtual effects of new particles in loops: a game of suppression and correlation

* SM FCNCs and CPV occur at the loop level
* SM quark FV and CPV are governed by the weak interactions and suppressed by small mixing angles
* SM quark CPV comes from a single source (neglecting $\theta_{QCD}$)
* LF and LFU (approximately) conserved in quark decays

New Physics does not necessarily share the SM pattern of FV and CPV: huge NP effects are possible (and excluded)

Past (SM) successes anticipating new heavy flavours:
- 1970: charm from $K^0 \rightarrow \mu^+\mu^-$ (GIM)
- 1973: 3rd generation from $\epsilon_K$ (Kobayashi & Maskawa)
- mid 80s+: heavy top from semileptonic $B$ decays & $\Delta m_B$
Going BSM with flavour physics: why now?

* next-generation flavour experiments will be able to improve the experimental precision/sensitivity by almost one order of magnitude

* enough NP-insensitive observables to pin down the SM contribution with the required accuracy

* several NP-sensitive observables not limited by systematics or theoretical uncertainties

Overall, the NP sensitivity extends to (i) the TeV region for SM-like flavour violation and to (ii) 10-100 TeV or even more in less constrained cases
Unitarity Triangle

- CKM unitarity implies triangular relations:
  \((V^*V)_{bd} = 0 = V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^*\)

\[
R_b = \left| \frac{V_{ud}V_{ub}}{V_{cd}V_{cb}} \right| \quad R_t = \left| \frac{V_{td}V_{tb}}{V_{cd}V_{cb}} \right|
\]

\[
\alpha = \arg \left( -\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*} \right) \quad \beta = \arg \left( -\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right) \quad \gamma = \arg \left( -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right)
\]

Setting the scale of the UT:
- \(\lambda = \sin \theta_c = 0.22574 \pm 0.00089\)
  from \(K_{l3}, K_{l2}/\pi_{l2}, 0^+ \rightarrow 0^+ \beta\) decays
- \(|V_{cb}|\) from semileptonic \(b \rightarrow c\) decays
The CKM matrix in the SM

\[
\begin{pmatrix}
0.97431(12) & 0.22514(55) & 0.00365(10)e^{-i66.8(2.0)^\circ} \\
-0.22500(54)e^{i0.0351(10)^\circ} & 0.97344(12)e^{-i0.00188(5)^\circ} & 0.04241(65) \\
0.00869(14)e^{-i22.2(0.6)^\circ} & -0.04124(56)e^{i1.056(32)^\circ} & 0.999112(24)
\end{pmatrix}
\]

Standard parametrization (PDG): \(s_{12}, s_{13}, s_{23}, \delta\)

\[
\begin{align*}
s_{12} &= 0.2250 \pm 0.0010 \\
s_{13} &= (3.68 \pm 0.10) \times 10^{-3} \\
s_{23} &= (4.200 \pm 0.059) \times 10^{-2} \\
\delta &= (66.8 \pm 2.0)^{\circ}
\end{align*}
\]

Wolfenstein parametrization: \(\lambda, A, \rho, \eta\)

\[
\begin{align*}
\lambda &= 0.2250 \pm 0.0010 \\
\rho &= 0.152 \pm 0.014 \\
A &= 0.826 \pm 0.012 \\
\eta &= 0.357 \pm 0.010
\end{align*}
\]
SM UT analysis

Summer 2018

SM determination of the Unitarity Triangle

\[ V_{ub}^{*}V_{ud} + V_{cb}^{*}V_{cd} + V_{tb}^{*}V_{td} = 0 \]

\[ R_u e^{i\gamma} + R_t e^{-i\beta} = 1 \]

\[ R_u = 0.380 \pm 0.011 \]

\[ R_t = 0.920 \pm 0.014 \]

\[ \gamma = (66.8 \pm 2.0)^\circ \]

\[ \beta = (22.25 \pm 0.65)^\circ \]

\[ \alpha = (90.9 \pm 2.0)^\circ \]

apex coordinates

\[ \bar{\rho} = 0.148 \pm 0.013 \]

\[ \bar{\eta} = 0.348 \pm 0.010 \]
## SM predictions: $B_d$ & $K$

<table>
<thead>
<tr>
<th>Measurement</th>
<th>%</th>
<th>Prediction</th>
<th>Pull($\sigma$)</th>
</tr>
</thead>
<tbody>
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<td>$\sin 2\beta$</td>
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<td>0.738±0.033</td>
<td>+1.2</td>
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<tr>
<td>$\gamma$ [°]</td>
<td>9</td>
<td>66.9±3.0</td>
<td>&lt; 1</td>
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<tr>
<td>$\alpha$ [°]</td>
<td>6</td>
<td>88.1±3.4</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>$</td>
<td>V_{cb}</td>
<td>\cdot10^3$</td>
<td>3</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>\cdot10^3$</td>
<td>6</td>
</tr>
<tr>
<td>$\varepsilon_K\cdot10^3$</td>
<td>0.5</td>
<td>1.97±0.18</td>
<td>-1.1</td>
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<tr>
<td>BR($B \to \tau V$)$\cdot10^{-4}$</td>
<td>20</td>
<td>0.81±0.07</td>
<td>-1.4</td>
</tr>
</tbody>
</table>
Long-standing problem for semileptonic B decays: inclusive vs exclusive

Reconsidering the CLN parametrization of the FFs for $|V_{cb}|$: exclusive → inclusive

Grinstein, Kobach, arXiv:1703.08170
Bigi et al., arXiv:1707.09509

Improved measurements of $|V_{cb}|$ & $|V_{ub}|$ are crucial for a determination of the CKM parameters independent of New Physics

Gambino et al., arXiv:1905.08209
Long-standing problem for semileptonic B decays: inclusive vs exclusive

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<th>Prediction</th>
<th>Pull ($\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_s [\text{ps}^{-1}]$</td>
<td>17.757±0.021</td>
<td>0.1</td>
<td>17.25±0.85</td>
</tr>
<tr>
<td>$\beta_s [^\circ]$</td>
<td>0.60±0.89</td>
<td>150</td>
<td>1.06±0.03</td>
</tr>
<tr>
<td>$A_{SL} \cdot 10^4$</td>
<td>-6±28</td>
<td>450</td>
<td>-0.13±0.01</td>
</tr>
</tbody>
</table>
model-independent determination of the CKM parameters

assumptions:
* three generations
* negligible NP in tree decays

\[ \bar{\rho} = 0.147 \pm 0.030 \]
\[ \bar{\eta} = 0.377 \pm 0.028 \]

in the SM was:
\[ \bar{\rho} = 0.148 \pm 0.013 \]
\[ \bar{\eta} = 0.348 \pm 0.010 \]
The mixing amplitudes $A_q e^{2i\phi_q} = \langle \tilde{M}_q | H_{\text{eff}}^{\Delta F=2} | M_q \rangle$

$H_{\text{eff}}^{\Delta B=2} = \sum_{i=1}^{5} C_i(\mu) Q_i(\mu) + \sum_{i=1}^{3} \tilde{C}_i(\mu) \tilde{Q}_i(\mu)$

$Q_1 = \bar{q}_L^\alpha \gamma^\mu b_L^\alpha \bar{q}_L^\beta \gamma^\mu b_L^\beta$ (SM/MFV)

$Q_2 = \bar{q}_R^\alpha b_L^\beta \bar{q}_R^\alpha b_L^\beta$

$Q_3 = \bar{q}_R^\alpha b_L^\beta \bar{q}_R^\alpha b_L^\beta$

$Q_4 = \bar{q}_R^\alpha b_L^\beta \bar{q}_L^\beta b_R^\beta$

$Q_5 = \bar{q}_R^\alpha b_L^\beta \bar{q}_R^\alpha b_L^\beta$

$\tilde{Q}_1 = \bar{q}_R^\alpha \gamma^\mu b_R^\alpha \bar{q}_R^\beta \gamma^\mu b_R^\beta$

$\tilde{Q}_2 = \bar{q}_L^\alpha b_R^\beta \bar{q}_L^\beta b_R^\beta$

$\tilde{Q}_3 = \bar{q}_L^\alpha b_R^\beta \bar{q}_L^\beta b_R^\beta$

Loop factor $L$:

- tree/strong interact. NP, $L \sim 1$
- perturbative NP, $L \sim \alpha_s^2, \alpha_W^2$

Flavor couplings $FC$:

- (i) generic $|FC| \sim 1$
- (ii) SM-like $|FC| \sim F_{SM}$

$C_i(\Lambda)$ can be extracted from the data (one by one)

$\Lambda = \sqrt{\frac{L \cdot FC}{C_i(\Lambda)}}$
Implications for the NP amplitudes

The ratio of NP/SM amplitudes is (if not aligned):

\[ < \sim 10\% \text{ @68\% prob. (15\% @95\%) in } B_d \text{ mixing} \]
\[ < \sim 2\% \text{ @68\% prob. (5\% @95\%) in } B_s \text{ mixing} \]
Theoretical issues

QUITE A FEW!

In the sub-percent era, many solid approximations used so far to compute hadronic amplitudes can’t be relied on anymore (e.g. isospin symmetry, no QED corrections, no subleading amplitudes, no higher-dimensional operators, etc.)

Good news: the tree-level determination of $\gamma$ from $B \to DK$ (GLW, ADS, GGSZ) safely extrapolates to the high precision. D mixing is manageable and EW corrections are still negligible

Brod, Zupan, arXiv:1308.5663
Loop-level constraints: th. prospects

→ $\Delta m_d$ and $\Delta m_s$: decay constants and B parameters @1%
call for QED corrections

→ $\epsilon_K$: QED corrections, long-distance contributions,
dimension-8 operators need to be controlled

→ $\alpha$: isospin breaking

→ $\beta$: subleading amplitude

\[ A(B^0 \to J/\psi K) = V_{cb}^* V_{cs} T + V_{ub}^* V_{us} P \]

bound using SU(3)-related $b \to d$ decays

$B_s \to J/\psi K_S$ and

$B \to J/\psi \pi^0$ where the 2\textsuperscript{nd} term is not Cabibbo suppressed

th. error scales with the ones on control

channels & matches the measurement accuracy

→ $\beta_s$: same as $\beta$, but trickier (larger effect, $\phi$ is not a pure

octet, ...). Still likely controllable
<table>
<thead>
<tr>
<th>Quantity</th>
<th>Published averages</th>
<th>Reference</th>
<th>error (to be published/not in FLAG-2016)</th>
<th>Phase I</th>
<th>Phase II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{K^+}$</td>
<td>155.7(7) MeV</td>
<td>$N_f = 2 + 1$ [66]</td>
<td>0.4%</td>
<td>0.4%</td>
<td>0.4%</td>
</tr>
<tr>
<td>$f_{K^0}/f_{\pi^+}$</td>
<td>1.193(3)</td>
<td>$N_f = 2 + 1 + 1$ [66]</td>
<td>0.25%(0.15%, symmet. [822])</td>
<td>0.15%</td>
<td>0.15%</td>
</tr>
<tr>
<td>$f_{K^0}\to\pi(0)$</td>
<td>0.9706(27)</td>
<td>$N_f = 2 + 1 + 1$ [66]</td>
<td>0.28% (0.20% [1527])</td>
<td>0.12%</td>
<td>0.12%</td>
</tr>
<tr>
<td>$B_K$</td>
<td>0.7625(97)</td>
<td>$N_f = 2 + 1$ [66]</td>
<td>1.3%</td>
<td>0.7%</td>
<td>0.5%</td>
</tr>
<tr>
<td>$\bar{f}_{D_s}$</td>
<td>248.83(1.27)</td>
<td>$N_f = 2 + 1 + 1$ [66]</td>
<td>0.5%(0.16% [822])</td>
<td>0.16%</td>
<td>0.16%</td>
</tr>
<tr>
<td>$\bar{f}<em>{D_s}/\bar{f}</em>{D_s^+}$</td>
<td>1.1716(32)</td>
<td>$N_f = 2 + 1 + 1$ [66]</td>
<td>0.27%(0.14% [822])</td>
<td>0.14%</td>
<td>0.14%</td>
</tr>
<tr>
<td>$\bar{f}_{B_s}$</td>
<td>228.4(3.7)</td>
<td>$N_f = 2 + 1$ [66]</td>
<td>1.6%(0.56% [822])</td>
<td>0.5%</td>
<td>0.5%</td>
</tr>
<tr>
<td>$\bar{f}<em>{B_s}/\bar{f}</em>{B_s}^+$</td>
<td>1.205(7)</td>
<td>$N_f = 2 + 1 + 1$ [66]</td>
<td>0.6%(0.4% [822])</td>
<td>0.4%</td>
<td>0.4%</td>
</tr>
<tr>
<td>$B_{B_s}/B_{B_d}$</td>
<td>1.32(5)/1.35(6)</td>
<td>$N_f = 2/N_f = 2 + 1$ [66]</td>
<td>$\sim 4%$</td>
<td>0.8%</td>
<td>0.5%</td>
</tr>
<tr>
<td>$\xi$</td>
<td>1.206(17)</td>
<td>$N_f = 2 + 1$ [66]</td>
<td>1.4%</td>
<td>0.4%</td>
<td>0.4%</td>
</tr>
<tr>
<td>$\bar{m}_c(\bar{m}_c)$</td>
<td>1.275(8) GeV</td>
<td>$N_f = 2 + 1$ [66]</td>
<td>0.6%</td>
<td>0.4%</td>
<td>0.4%</td>
</tr>
</tbody>
</table>

| B → π for $|V_{ub}|$ | $N_f = 2 + 1$ [66] | 2.9% | 1%(1.4%) | 1% |
| B → D for $|V_{cb}|$ | $N_f = 2 + 1$ [66] | 1.4% | 0.3%(1%) | 0.3% |
| (first param. BCL z-exp.) | $N_f = 2 + 1$ [66] | 1.5% | 0.5%(1.1%) | 0.5% |
| B → D* for $|V_{cb}|$ | $N_f = 2 + 1$ [66] | 1.4% | 0.4%(0.7%) | 0.4% |
| $h_{A_1}^{B\to D^*}(\omega = 1)$ | 1.5% | 0.4%(0.7%) | 0.4% |
| $P_{1}^{B\to D^*}(\omega = 1)$ | 1.5% | 0.4%(0.7%) | 0.4% |
| $A_b \to p(A_c)$ | 4.9% | 1.2%(1.6%) | 1.2% |

| B → K | $N_f = 2 + 1$ [66] | 2% | 0.7%(1.2%) | 0.7% |
| B_s → K | $N_f = 2 + 1$ [66] | 4% | 1.3%(1.7%) | 1.3% |

| λ | 0.12% | 9% | 3% | 1.5% | 4.5% | 3% | 2.5% | 3% |
| ρ | 0.12% | 2% | 0.8% | 0.6% | 0.9% | 0.9% | 0.7% | 0.8% |
| η | 0.12% | 1% | 0.6% | 0.5% | 0.6% | 0.8% | 0.4% | 0.5% |
Large significance driven by the BaBar results, trend of recent measurements is unclear

Anomaly in $B \rightarrow \tau \nu$ washed out in time (perhaps)

Large new physics in tree-level charged currents? Really??!!

$\Lambda_{NP} \sim 2-3$ TeV
* **SM uncertainties**

**$R_D$:** LQCD calculations of both FF's for $q^2 \leq q^2_{\text{max}}$

$$\langle D(k)|\bar{c}\gamma^\mu b|B(p)\rangle = f_+(q^2) \left[ (p + k)^\mu - \frac{m_B^2 - m_D^2}{q^2} q^\mu \right] + f_0(q^2) \frac{m_B^2 - m_D^2}{q^2} q^\mu$$

**$R_{D^*}$:** LQCD results only at $q^2_{\text{max}}$, scalar form factors not available. FFs from data + HQET

MILC '14/'15, HPQCD '15/'17
Bernlochner et al. '17, Bordone et al. '19
For LCSR results, see Gubernari et al., '18

* **New physics parametrization**

$$\mathcal{L}_{\text{eff}} = -2\sqrt{2} G_F V_{cb} \left[ (1 + C_{V_L}) \bar{c}_L \gamma^\mu b_L \bar{\ell}_L \gamma_\mu \nu_L + C_{V_R} \bar{c}_R \gamma^\mu b_R \bar{\ell}_L \gamma_\mu \nu_L \\
+ C_{S_R} \bar{c}_L b_R \bar{\ell}_R \nu_L + C_{S_L} \bar{c}_R b_L \bar{\ell}_R \nu_L + C_T \bar{c}_R \sigma^{\mu\nu} b_L \bar{\ell}_R \sigma_{\mu\nu} \nu_L \right] + H.c.$$  

- $C$'s vanish in the SM
- Data explained by $C_{V_L} \sim 15\%$, but there are other viable solutions involving more than one coefficient
The anomalous anomalies

Large violation of lepton flavour universality?! Sure??!!

\[ \Lambda_{NP} \sim 40 \text{ TeV} \]
The anomalous anomalies

\[ \frac{d^{(4)}\Gamma}{dq^2 \, d(\cos \theta_t) \, d(\cos \theta_K) \, d\phi} = \frac{9}{32\pi} \left( I_1^2 \sin^2 \theta_k + I_1^5 \cos^2 \theta_k + (I_2^2 \sin^2 \theta_k + I_2^5 \cos^2 \theta_k) \cos 2\theta_t + I_3 \sin^2 \theta_k \sin^2 \theta_t \cos 2\phi + I_4 \sin 2\theta_k \sin 2\theta_t \cos \phi 
+ I_5 \sin 2\theta_k \sin \theta_t \cos \phi + (I_6^2 \sin^2 \theta_k + I_6^5 \cos^2 \theta_K) \cos \theta_t 
+ I_7 \sin 2\theta_k \sin \theta_t \sin \phi + I_8 \sin 2\theta_k \sin 2\theta_t \sin \phi 
+ I_9 \sin^2 \theta_k \sin^2 \theta_t \sin 2\phi \right) \]

\[ B \rightarrow K^*\mu\mu \]

angular analysis

Are theory estimates reliable close to the resonant region?

the charm-loop monster

3.7σ
Impact of the 2019 $R_K$ measurement

Single coefficient $R_K$-$R_{K^*}$ correlation weakened by the new measurement
In the SMEFT two four-fermion operators produce LFUV in quark decays assuming NP in the 3rd generation

\[ Q_S = Q_{L,3}^\prime \gamma_\mu Q_{L,3}^\prime L_{L,3}^\prime \gamma^\mu L_{L,3}^\prime, \quad Q_T = Q_{L,3}^\prime \gamma_\mu \sigma^i Q_{L,3}^\prime L_{L,3}^\prime \gamma^\mu \sigma^i L_{L,3}^\prime \]

i) give typically (but not necessarily) rise to large LFV generated passing from weak to mass eigenstates

ii) can account for the anomalies in \( R_K, R_{K^*}, R(D) & R(D^*) \)

large tree-level effect in charged currents from \( Q_T \)
b \to s \text{ FCNC suppressed to loop level through mixing angles}
The leptoquark revenge

Models with a single mediator which generate $Q_S$ and $Q_T$ at tree-level can be classified:

<table>
<thead>
<tr>
<th>Field</th>
<th>Spin</th>
<th>SU(3)$_c$</th>
<th>SU(2)$_L$</th>
<th>$U(1)_Y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B'_\mu$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$W'_\mu$</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>$U'^{\mu}_{1}$</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>$2/3$</td>
</tr>
<tr>
<td>$U'^{\mu}_{3}$</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>$2/3$</td>
</tr>
<tr>
<td>$S_1$</td>
<td>0</td>
<td>$\frac{3}{3}$</td>
<td>1</td>
<td>$1/3$</td>
</tr>
<tr>
<td>$S_3$</td>
<td>0</td>
<td>$\frac{3}{3}$</td>
<td>3</td>
<td>$1/3$</td>
</tr>
</tbody>
</table>

Present data already select one option (vector singlet leptoquark $U_1$) independently of the flavour structure of the model once all bounds are considered.

Actual UV completions are not this simple...
Implications of LFUV for NP flavour breaking

NP needs to respect SM gauge symmetry

\[ Q_i [Q, D, U, L, E] \]

At EW scale: in terms of four-fermion operators

\[ R_{K'}(\star) \]

\[ R(D(\star)) \]

Simplest UV:

\[ Z'/W' \]

\[ LQ's \]

\[ H^\pm \]

*bc lifetime, decays

Alonso et al., 1611.06676

Akeroyd & Chen, 1708.04072

*right-handed currents

Asadi et al., 1804.04135

Grejo et al., 1804.04642

Azatov et al., 1807.10745

Robinson et al., 1807.04753

courtesy of J. Kamenik, TH Institutre 2020
Immediate implications for LHC

Flavour alignment implies lower NP scale:

\[ (\bar{Q}_3 Q_3)(\bar{L}_3 L_3) \rightarrow V_{cb}(\bar{c}b)(\bar{\tau}\nu) \]
\[ \Rightarrow R(D^{(*)}) \text{ anomaly} \]
\[ \Lambda \sqrt{|V_{cb}|} \sim 500 \text{ GeV} \]

\[ (\bar{Q}_3 Q_3)(\bar{L}_2 L_2) \rightarrow V_{tb}V_{ts}(\bar{s}b)(\bar{\mu}\mu) \]
\[ \Rightarrow R_K^{(*)} \text{ anomaly} \]
\[ \Lambda \sqrt{|V_{ts}|} \sim 8 \text{ TeV} \]

Well within LHC reach! Still only marginally!

see e.g. Abdullah et al., 1805.01869
Robinson et al., 1807.04753

courtesy of J. Kamenik, TH Institutre 2020
The other tree-level constraints from semileptonic B decays are in less good shape: the long-standing disagreement between incl. and excl. measurements is still there, but there are promising new developments.

CLN parametrization of the $B \to D^*$ FF’s uses HQ relations which may be responsible for the $|V_{cb}|$ discrepancy.

Still inconclusive, but…

New attempts at computing FF’s on the lattice at small $q^2$

Grinstein, Kobach, arXiv:1703.08170
Bigi, Gambino, Schacht, arXiv:1703.0612

Martinelli et al., in progress
EFT global analysis

Altmannshofer, Straub., arXiv:1411.3161

\[ * \mathcal{B} \to \mathcal{K}^{(*)} \mu \mu \]
\[ * \mathcal{B} \to \mathcal{X}_s \gamma \]
\[ * \mathcal{B}_s \to \phi \mu \mu \]
\[ * \mathcal{R}_K \]
\[ * \mathcal{B} \to \mathcal{K}^* \gamma \]

Hurth et al., arXiv:1603.00865

point to an O(1) correction to the WC of \[ Q_9^\mu = \bar{s}_L \gamma_\alpha b_L \bar{\mu} \gamma^\alpha \mu \]
Angular analysis of $B \to K^* \mu \mu$

In the helicity amplitude formalism ($m_\ell \sim 0$), we need to compute few helicity amplitudes:

\[ I_1^c = -I_2^c = \frac{F}{2} (|H_V^0|^2 + |H_A^0|^2), \]
\[ I_1^s = 3I_2^s = \frac{3}{8} F (|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2), \]
\[ I_3 = -\frac{F}{2} \text{Re}\left[ H_V^+(H_V^-)^* + H_A^+(H_A^-)^* \right], \]
\[ I_4 = \frac{F}{4} \text{Re}\left[ (H_V^+ + H_V^-)(H_V^0)^* + (H_A^+ + H_A^-)(H_A^0)^* \right], \]
\[ I_5 = \frac{F}{4} \text{Re}\left[ (H_V^- - H_V^+)(H_V^0)^* + (H_A^- - H_A^+)(H_A^0)^* \right], \]

\[ I_6^s = F \text{Re}\left[ H_V^-(H_A^-)^* - H_V^+(H_A^+)^* \right], \]
\[ I_6^c = 0, \]
\[ I_7 = \frac{F}{2} \text{Im}\left[ (H_A^+ + H_A^-)(H_V^0)^* + (H_V^+ + H_V^-)(H_A^0)^* \right], \]
\[ I_8 = \frac{F}{4} \text{Im}\left[ (H_V^- - H_V^+)(H_V^0)^* + (H_A^- - H_A^+)(H_A^0)^* \right], \]
\[ I_9 = \frac{F}{4} \text{Im}\left[ H_V^+(H_V^-)^* + H_A^+(H_A^-)^* \right]. \]
\[ H_V^\lambda = \frac{4iG_F m_B}{\sqrt{2}} \frac{\alpha_e}{4\pi} \lambda_t \left\{ C_9^{\text{eff}} \tilde{V}_{L\lambda} + \frac{m_B^2}{q^2} \left[ \frac{2m_b}{m_B} C_7^{\text{eff}} \tilde{T}_{L\lambda} - 16\pi^2 h_\lambda \right] \right\}, \]

\[ H_A^\lambda = \frac{4iG_F m_B}{\sqrt{2}} \frac{\alpha_e}{4\pi} \lambda_t C_{10} \tilde{V}_{L\lambda}. \]

\( \lambda = 0, \pm \)

**NNLO Wilson coefficients from the \( \Delta B=1, \Delta S=1 \) effective Hamiltonian:**

\[ \mathcal{H}_{\text{eff}}^{\Delta B=1} = \mathcal{H}_{\text{eff}}^{sl+\gamma} + \mathcal{H}_{\text{eff}}^{\text{had}} \]

\[ \mathcal{H}_{\text{eff}}^{sl+\gamma} = -\frac{4G_F}{\sqrt{2}} \lambda_t (C_7 Q_{7\gamma} + C_9 Q_{9V} + C_{10} Q_{10A}) \]

\[ Q_{7\gamma} = \frac{e}{16\pi^2} m_b \bar{s}_L \sigma_{\mu\nu} F^{\mu\nu} b_R, \]

\[ Q_{9V} = \frac{\alpha_e}{4\pi} (\bar{s}_L \gamma_\mu b_L) (\bar{\ell} \gamma^\mu \ell), \]

\[ Q_{10A} = \frac{\alpha_e}{4\pi} (\bar{s}_L \gamma_\mu b_L) (\bar{\ell} \gamma^\mu \gamma^5 \ell). \]

**Hadronic matrix elements of quark currents:**

**FORM FACTORS**
An estimate in 2 steps:

1. at $q^2 \ll 4m_c^2$ the charm loop is dominated by light-cone dynamics.
   
   One can write the ME
   \[
   [\mathcal{H}_{B \rightarrow K^{(*)}}^\mu(p, q)]_{\text{non fact}} = 2C_1(K^{(*)}(p)|\tilde{\mathcal{O}}_{\mu}(q)|B(p + q)),
   \]
   
   where $\tilde{\mathcal{O}}_{\mu}(q) = \int d\omega I_{\mu\rho\alpha\beta}(q, \omega)\bar{s}_L\gamma^\rho \delta[\omega - \frac{(in + D)}{2}]\tilde{G}_{\alpha\beta}b_L$ is a non-local operator representing the first subleading term of an expansion in $\Lambda^2/(4m_c^2 - q^2)$ (single soft gluon approximation), whose ME is computed using light-cone sum rules.

**step 1** estimate of the hadronic contribution at small $q^2 \ll \text{few GeV}^2$

but large uncertainties (100%? more?)

no hard gluons, no phases, no scale and scheme dependence, ...
2. extend the previous result to larger $q^2$ using a dispersion relation, modeling the spectral function (2 physical $\Psi^{(c)} +$ effective poles)

$$\Delta C_{9,i}^{(c\bar{c})}(q^2) = \frac{r_{1,i} \left( 1 - \frac{\vec{q}^2}{q^2} \right) + \Delta C_{9,i}^{(c\bar{c})}(q^2) \frac{\vec{q}^2}{q^2}}{1 + r_{2,i} \frac{\vec{q}^2 - q^2}{m_{J/\psi}^2}}$$

**but** model dependence, no pert. gluons and phases: uncertainty?

Step 1: no new non-perturbative calculation. However an hierarchy among contributions in the helicity basis has been found

\[ h_+ \sim \mathcal{O} \left( \frac{\Lambda}{m_b} \right) h_- \]

\[ \text{Jäger, Camalich, arXiv:1212.2263} \]

Step 2: recent attempts to gain more control over the \( q^2 \) dependence improving the dispersion relation approach

1. empirical model using resonance data over the full dimuon spectrum

\[ \text{Blake, Egede, Owen, Pomery, Petridis, arXiv:1709.03921} \]

2. replace the dispersion relation with a \( z \)-expansion of \( h_\Lambda \), constraining the coefficients using analiticty and

1. resonant \( B \to \Psi^{(n)}K^* \) data (masses and amplitudes)
2. LCSR + QCDF theoretical results at small/negative \( q^2 \)

\[ \text{Bobeth, Chrzaszcz, van Dyk, Virto, arXiv:1707.07305} \]
The hadronic contribution is modeled as the sum of $1^-$ resonances represented by relativistic Breit-Wigner functions

$$\Delta C_{9,\lambda}^{\text{had}}(q^2) = \sum_j \eta_j^\lambda e^{i\theta_j^\lambda} A_j^{\text{res}}(q^2)$$

$$A_j^{\text{res}}(q^2) = \frac{m_{\text{res},j}^{\lambda} \Gamma_{\text{res},j}}{(m_{\text{res},j}^{\lambda} - q^2) - i m_{\text{res},j}^{\lambda} \Gamma_j(q^2)}$$

**Open issues:**

- Why should it work far from the resonances? What about double counting? How large is the model uncertainty?

Illustrate nicely the importance of strong phases
c loop from analyticity

Features:
- get rid of DD branch cut modeling by mapping it at the boundary of the expansion region
- exploits the $\psi^{(i)}$ resonance data to constrain the expansion

Open issues:
- strong phases related to the DD$_s$ cut in $p^2$ are taken from LCSR and QCDF calculations. Are they reliable?
- $z$ expansion: no sign of convergence for the typical values $|z| \sim 0.2$-$0.4$
- NB: $z$ expansion of FF at much smaller values

<table>
<thead>
<tr>
<th>$k$</th>
<th>0</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re[$\alpha_k^{(\perp)}$]</td>
<td>$-0.06 \pm 0.21$</td>
<td>$-6.77 \pm 0.27$</td>
<td>$18.96 \pm 0.59$</td>
</tr>
<tr>
<td>Re[$\alpha_k^{(R)}$]</td>
<td>$-0.35 \pm 0.62$</td>
<td>$-3.13 \pm 0.41$</td>
<td>$12.20 \pm 1.34$</td>
</tr>
<tr>
<td>Re[$\alpha_k^{(0)}$]</td>
<td>$0.05 \pm 1.52$</td>
<td>$17.26 \pm 1.64$</td>
<td>$-$</td>
</tr>
<tr>
<td>Im[$\alpha_k^{(\perp)}$]</td>
<td>$-0.21 \pm 2.25$</td>
<td>$1.17 \pm 3.58$</td>
<td>$-0.08 \pm 2.24$</td>
</tr>
<tr>
<td>Im[$\alpha_k^{(R)}$]</td>
<td>$-0.04 \pm 3.67$</td>
<td>$-2.14 \pm 2.46$</td>
<td>$6.03 \pm 2.50$</td>
</tr>
<tr>
<td>Im[$\alpha_k^{(0)}$]</td>
<td>$-0.05 \pm 4.99$</td>
<td>$4.29 \pm 3.14$</td>
<td>$-$</td>
</tr>
</tbody>
</table>
Parametrizing the charm loop

\[ H_V^- = -iN \left\{ (C_{9}^{\text{eff}} + h_1^-) V_L^- + \frac{m_B^2}{q^2} \left[ \frac{2m_b}{m_B} (C_{7}^{\text{eff}} + h_0^-) T_{L^-} - 16\pi^2 h_-^2 q^4 \right] \right\} \]

\[ H_V^0 = -iN \left\{ (C_{9}^{\text{eff}} + h_1^-) \tilde{V}_{L0} + \frac{m_B^2}{q^2} \left[ \frac{2m_b}{m_B} (C_{7}^{\text{eff}} + h_0^-) \tilde{T}_{L0} - 16\pi^2 \left( \tilde{h}_0^0 + \tilde{h}_0^1 q^2 \right) \right] \right\} \]

\[ H_V^+ = -iN \left\{ (C_{9}^{\text{eff}} + h_1^-) V_{L+} + \frac{m_B^2}{q^2} \left[ \frac{2m_b}{m_B} (C_{7}^{\text{eff}} + h_0^-) T_{L+} - 16\pi^2 (h_+^0 + h_+^1 q^2 + h_+^2 q^4) \right] \right\} \]

\[ \Delta C_7^{(cc)} = h_0^- \quad \text{and} \quad \Delta C_9^{(cc)} = h_1^- \quad \text{shift the} \]

\text{corresponding Wilson coefficients (as NP contributions do), while the other parameters have no short-distance counterparts.} \]
**Fitting hadronic parameters**

- Compute all amplitudes using QCD factorization and form factors from LQCD (Bailey et al. '15) and LCSR (Bharucha, Straub & Zwicky '15)

- add hadronic parameters and
  - use LCSR calculation from KMPW at low $q^2$ (0 and 1 GeV$^2$) only (PDD)
  - extrapolate LCSR calculation to larger $q^2$ using KMPW (PMD)

- fit all available experimental data using the HEPfit code

- compare different models using $IC = -2\log L + 4\sigma_{\log L}^2$
(IV) - PDD

$IC = 173$
Deviations from the SM to keep an eye on

- $\epsilon'/\epsilon$
- $\text{BR}(B_s \rightarrow m \bar{m})$
- $R(B \rightarrow D^{*} \bar{m} m)$
- $\Gamma(B^+ \rightarrow K^+ m \bar{m})/\Gamma(B^+ \rightarrow K^+ e e)$
- $q^2$ spectrum of $B \rightarrow K^* m \bar{m}$

Direct CP violation in $K \rightarrow \pi\pi$

Long-established experimental result:
\[
\frac{(\epsilon'/\epsilon)}{\text{exp}} = (16.6 \pm 2.3) \times 10^{-4}
\]

Theory breaking news: all the hadronic matrix elements entering the SM prediction have finally been computed on the lattice

(RBC-UKQCD coll.'s, arXiv:1505.07863)
\[
\frac{(\epsilon'/\epsilon)}{\text{SM}} = (1.4 \pm 6.8) \times 10^{-4}
\]
\[
-2.1\sigma
\]

(Buras et al., arXiv:1507.06345)
\[
= (1.9 \pm 4.5) \times 10^{-4}
\]
\[
-2.9\sigma
\]

- a “new” constraint on $\eta$ in the UT analysis
- one of the most powerful NP probes in flavour physics finally fully at work!!
Deviations from the SM to keep an eye on

- $\varepsilon'/\varepsilon$
- $\text{BR}(B_s \to \mu\mu), \text{BR}(B \to \mu\mu)$

\[
\text{BR}(B_s \to \mu^+\mu^-) = \frac{2.8^{+0.7}_{-0.6}}{} \times 10^{-9}
\]

\[
\text{BR}(B_s \to \mu^+\mu^-)_{SM} = \frac{3.65 \pm 0.23}{0.23} \times 10^{-9} + 1.2\sigma
\]

\[
\text{BR}(B \to \mu^+\mu^-) = \frac{3.9^{+1.6}_{-1.4}}{} \times 10^{-10}
\]

\[
\text{BR}(B \to \mu^+\mu^-)_{SM} = \frac{1.06 \pm 0.09}{0.09} \times 10^{-10} - 2.2\sigma
\]

SM predictions from Bobeth et al., arXiv:1311.0903

**Minimal Flavour Violation test**