Impact of lattice QCD on CKM phenomenology

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Lattice meets flavour

Impact of lattice QCD on CKM phenomenology
Flavour in the Standard Model (SM)

Flavour and CP violation in SM described by CKM matrix

\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix}
= V_{\text{CKM}}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
= \begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
\]

Unitarity implies

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

➤ Unitarity triangle

\[
R_b = \left| \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right|
\]

\[
R_t = \left| \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} \right|
\]
Precision determination of CKM elements

Tree level decays: flavour changing charged current interactions

- direct sensitivity to relevant CKM element
- small impact of new physics contributions

model-independent determination of CKM matrix as a standard candle of the SM
$|V_{cb}|$ from $B \to D^* \ell \nu$

- $|V_{cb}|$ is crucial input for SM prediction of precision observables like $\varepsilon_K$, $K \to \pi \nu \bar{\nu}$, $B_s \to \mu^+ \mu^-$ etc.

- $N_f = 2 + 1$ calculation of $B \to D^*$ form factor at zero recoil gives current most precise determination of $|V_{cb}|$:

  $|V_{cb}| = 39.04(75) \cdot 10^{-3}$

  **FNAL/MILC (2014)**

- $B \to D^*$ form factor only from one unquenched lattice calculation

- compare with determination from inclusive $B \to X_c \ell \nu$

  $|V_{cb}| = 42.00(65) \cdot 10^{-3}$

  **Gambino, Healey, Turczyk (2016)**

> cross-check needed!
lattice QCD calculation of $B \to D$ form factor at small recoil

large recoil (more precise experimental data) using dispersion relations, unitarity, HQET

fit to experimental and lattice results for $B \to D\ell\nu$:

$|V_{cb}| = 40.49(97) \cdot 10^{-3}$
$|V_{ub}|$ from $B \rightarrow \pi \ell \nu$

- recent $N = 2 + 1$ lattice QCD calculation of the $B \rightarrow \pi$ form factors + model-independent $z$-expansion to full $q^2$ range: FNAL/MILC (2015)  
  see also HPQCD (2006)

  $$|V_{ub}| = 3.72(16) \cdot 10^{-3}$$

- note the lower PDG value $|V_{ub}| = 3.28(29) \cdot 10^{-3}$

- compare to inclusive determination PDG (2016)

  $$|V_{ub}| = (4.41 \pm 0.15^{+0.15}_{-0.19}) \cdot 10^{-3}$$
$|V_{ub}/V_{cb}|$ from baryon decays

- $\Lambda_b \to p\ell\nu$ and $\Lambda_b \to \Lambda_c\ell\nu$ form factors calculated with $N = 2 + 1$ dynamical domain-wall fermion flavours

  Detmold, Lehner, Meinel (2015)

- measurement of $|V_{ub}/V_{cb}|$ from ratio of $\Lambda_b \to p\mu\nu$ and $\Lambda_b \to \Lambda_c\mu\nu$ decay rates reduces systematic uncertainties

  LHCb (2015)

$|V_{ub}/V_{cb}| = 0.083 \pm 0.04 \pm 0.04$
The status of $|V_{cb}|$ and $|V_{ub}|$

![Graph showing the status of $|V_{ub}|$ and $|V_{cb}|$](image)

- $|V_{ub}|$ incl.
- $B \rightarrow \pi l \nu$
- $|V_{cb}|$ incl.
- $B \rightarrow D l \nu$
- $B \rightarrow D^* l \nu$
- $\Lambda_b \rightarrow p/\Lambda_c \mu \nu$
Can discrepancies be explained by new physics?

- effect of right-handed currents
  \[ |V_{cb}|^{D\ell\nu} = |V_{cb}|(1 + \delta) \]
  \[ |V_{cb}|^{D^*\ell\nu} = |V_{cb}|(1 - \delta) \]
  \[ |V_{cb}|^{\text{incl}} = |V_{cb}| + \mathcal{O}(\delta^2) \]
  \[ |V_{ub}|^{\pi\ell\nu} = |V_{ub}|(1 - \varepsilon) \]
  \[ |V_{ub}|^{B \rightarrow \tau\nu} = |V_{ub}|(1 + \varepsilon) \]
  \[ |V_{ub}|^{\text{incl}} = |V_{ub}| + \mathcal{O}(\varepsilon^2) \]

- excluded as origin of the tension

- general $SU(2)$-invariant dimension 6 operators can resolve tension, but incompatible with $Z \rightarrow b\bar{b}$

- under-estimated theory uncertainties? experimental issue?
A vast variety of new physics models

Many new physics models on the market...

...but which is the correct one?
A vast variety of new physics models

LHC will (hopefully) give us some idea!

But is it a grapefruit or an orange?

Check its flavour!
What if . . .

But maybe LHC will leave us with . . .

Is there still something hiding?
What if. . .

But maybe LHC will leave us with. . .

Is there still something hiding?

➢ Could we detect it in flavour violating decays?
Flavour changing neutral currents in the SM

Loop suppressed transitions: flavour changing neutral currents (FCNCs)

- strong suppression in the SM
- high sensitivity to new physics contributions

plethora of interesting observables ➤ here: few highlights only!
$B_{d,s} - \bar{B}_{d,s}$ mixing
Recent news from the lattice

- recent lattice determination of hadronic $B_{d,s} - \bar{B}_{d,s}$ mixing parameters with unprecedented precision

  $f_{B_d}^2 \hat{B}_{B_d} = 0.0518(43)(10) \text{ GeV}$

  $f_{B_s}^2 \hat{B}_{B_s} = 0.0754(46)(15) \text{ MeV}$

  $\xi = \frac{f_{B_s} \sqrt{\hat{B}_{B_s}}}{f_{B_d} \sqrt{\hat{B}_{B_d}}} = 1.206(18)(6)$

- discrepancies between exp. values of $\Delta M_d$, $\Delta M_s$, and $\Delta M_d/\Delta M_s$ and SM predictions at 1.8$\sigma$, 1.1$\sigma$, and 2.0$\sigma$

➤ If confirmed, what could be the origin of this tension?
Constrained Minimal Flavour Violation (CMFV)

- flavour symmetry $U(3)_q \times U(3)_u \times U(3)_d$ only broken by Yukawa couplings $Y_u, Y_d$
- no new sources of CP-violation
- only SM effective operators

Consequences:

- BSM contributions suppressed by smallness of CKM elements
- CMFV contributions to $\Delta F = 2$ observables can be parameterised by a single real and flavour-universal function $S'(v)$ with the lower bound $S'(v) \geq S_0(x_t) = 2.322$

**MB, Buras (2006)**
The universal unitarity triangle

Universal unitarity triangle holding within all CMFV models

- $|V_{us}|$ from tree-level decays
- Angle $\beta$ determined from time-dependent CP-asymmetry $S_{\psi K_S}$
- Side $R_t$ determined from $\Delta M_d/\Delta M_s$

▷ few % precision, main uncertainties in $S_{\psi K_S}^{\exp}$ and $\xi$

\[ \bar{\rho}_{UUT} = 0.170 \pm 0.013 \quad \bar{\eta}_{UUT} = 0.333 \pm 0.011 \]

MB, Buras (2016)
Implications from the UUT: the angle $\gamma$

MB, Buras (2016)

Construction of UUT yields

$$\gamma_{\text{UUT}} = (63.0 \pm 2.1)^\circ$$

Compare to:

LHCb (2016)

$$\gamma_{\text{tree}} = (70.9^{+7.1}_{-8.5})^\circ$$

Problem for CMFV?

More precise $\gamma$ measurements by LHCb and Belle II will tell!
Implications from the UUT: the ratio $|V_{ub}/V_{cb}|$

$|V_{ub}/V_{cb}|_{UUT} = 0.0864 \pm 0.0025$

clearly disfavours $|V_{ub}|_{incl}$

Strategies to fully determine CKM matrix:

$S_1$: $\Delta M_s$ is used to determine $|V_{cb}|$ as function of $S(v)$

$S_2$: $\varepsilon_K$ is used to determine $|V_{cb}|$ as function of $S(v)$
Comparing results of $S_1$ and $S_2$:

- inconsistent results for $|V_{cb}|$
- tension smallest for SM case $\Delta S(v) = 0$
Breaking the flavour universality

flavour-universal CMFV contribution

\[ S(v) = S_0(x_t) + \Delta S(v) \quad \text{with} \quad \Delta S(v) > 0 \]

cannot explain the tension in \( \Delta F = 2 \) data

Possible ways out:

- relax lower bound on \( \Delta S(v) \)
  - possible but difficult to achieve in concrete models
  - inconsistencies with tree-level values of \( |V_{cb}| \) and \( \gamma \)

- introduce flavour non-universal contributions

\[ S_0(x_t) \rightarrow S_i = |S_i|e^{i\varphi_i} \quad i = K, d, s \]

- in general possible to fit \( \Delta F = 2 \) data
- correlations with rare decays needed to test given model
Models with $U(2)^3$ flavour symmetry

Barbieri et al. (2012); Buras, Girrbach (2012); MB, Buras (2016)

minimally broken $U(2)^3$ flavour symmetry:

$$S_K = r_K S_0(x_t) \quad \text{with} \quad r_K > 1$$
$$S_d = S_s = r_B S_0(x_t) e^{i\varphi_{\text{new}}}$$

Consequences:

- $\varepsilon_K$ can only be enhanced w. r. t. the SM
- $\gamma = (63.0 \pm 2.1)^\circ$ also holds in $U(2)^3$ models
- $S_{\psi K_S}$ affected by $\varphi_{\text{new}}$, but correlated with $\phi_s$

$U(2)^3$ models in better shape than CMFV, but might get in trouble with more precise determinations of $\gamma$, $|V_{ub}/V_{cb}|$, and $\phi_s$
Direct CP violation in kaon decays
\( \varepsilon'/\varepsilon \) in the SM

simple phenomenological expression: \(^{\text{Buras, Gorbahn, Jäger, Jamin (2015)}}\) 

\[
\text{Re}(\varepsilon'/\varepsilon) = \frac{\text{Im}(V_{ts}^* V_{td})}{1.4 \cdot 10^{-4}} \cdot 10^{-4} \cdot \left( -3.6 + 21.4 B_{6}^{(1/2)} + 1.2 - 10.4 B_{8}^{(3/2)} \right)
\]

\( A_{0}: \text{QCD penguins} \quad A_{2}: \text{EW penguins} \)

- large cancellation between \( A_{0} \) and \( A_{2} \) amplitudes
- hadronic matrix elements from the lattice \(^{\text{RBC-UKQCD (2015)}}\)

\[
B_{6}^{(1/2)} = 0.57 \pm 0.19 \
B_{8}^{(3/2)} = 0.76 \pm 0.05
\]

consistent with large \( N_{c} \) bound \( B_{6}^{(1/2)} < B_{8}^{(3/2)} < 1 \) \(^{\text{Buras, Gérard (2015)}}\)

NLO: \( (1.9 \pm 4.5) \cdot 10^{-4} \) \(^{\text{BGJJ’15}}\) 

NNLO: coming soon! \(^{\text{Gorbahn et al.}}\)

\( 2.9\sigma \) tension with the data! (a bit less with lattice value for Re\( A_{0} \))
The $K$-Unitarity Triangle

Lehner, Lunghi, Soni (2015)


Unitarity Triangle from kaon decay observables

KUT 2015
The $K$-Unitarity Triangle

Lehner, Lunghi, Soni (2015)


Unitarity Triangle from kaon decay observables

KUT 2025?
New physics can induce large deviations from SM in $\varepsilon'/\varepsilon$

Recent studies:

- in the Littlest Higgs model with T-parity \textbf{MB, Buras, Recksiegel (2015)}
- in simplified models with tree level flavour changing $Z$ or $Z'$ couplings \textbf{Buras, Buttazzo, Knegjens (2015)}
- in 331 models \textbf{Buras, de Fazio (2015), (2016)}
- in supersymmetry \textbf{Tanimoto, Yamamoto (2016)} \textbf{Kitahara, Nierste, Tremper (2016)}
- ...
$\varepsilon'/\varepsilon$ in simplified FCNC models

*example*: two simplified models (flavour changing $Z$ or $Z'$ couplings)

Buras, Buttazzo, Knegjens (2015)

- tension in $|\varepsilon'/\varepsilon|$ can be removed
- simultaneous large effects in $K_L \rightarrow \pi^0 \nu \bar{\nu}$
\( \varepsilon' / \varepsilon \) in the Littlest Higgs model with T-parity

\[ (B_{6}^{(1/2)}, B_{8}^{(3/2)}) = (1.0, 1.0), (0.76, 0.76), (0.57, 0.76), (1.0, 0.76) \]

➤ also in LHT strong correlation with \( K \to \pi \nu \bar{\nu} \)
$\varepsilon'/\varepsilon$ in the MSSM

Kitahara, Nierste, Tremper (2016)

Contribution to $\varepsilon_K$ suppressed by

- Small LR mixing
- $m_{\tilde{g}} = 1.5M_S$
  \[(M_S = m_{\tilde{Q}} = m_{\tilde{D}})\]

$\varepsilon'/\varepsilon$ can be explained with multi-TeV squarks
$b \rightarrow s$ penguins
Tensions in $b \to s$ transitions

Recent LHCb (and Belle, CMS etc.) data show an intriguing discrepancy in semileptonic $b \to s$ transitions

$$B \to K^* \mu^+ \mu^- \quad B^+ \to K^+ \mu^+ \mu^-$$

Impact of lattice QCD on CKM phenomenology
Radiative and semileptonic $b \rightarrow s$ transitions

$b \rightarrow s\ell^+\ell^-$ and $b \rightarrow s\gamma$ transitions described by effective Hamiltonian

$$H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}^* V_{ts} \frac{e^2}{16\pi^2} \sum_i \left( C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right) + \text{h.c.}$$

where the operators most sensitive to new physics are

$$\mathcal{O}_i^{(r)} = \left( s_L(R) \right) \Gamma \gamma$$

$$\mathcal{O}_{9,10}^{(r)} = \left( s_L(R) \right) \Gamma \ell_{L,R}$$

$$\mathcal{O}_{S,P}^{(r)} = \left( s_L(R) \right) \Gamma \ell_{L,R}$$

SM:
Global fit to Wilson coefficients

Altmannshofer, Straub (2015) and others

$\sim 4\sigma$ evidence for a new contribution to $C_9$
What could it be?

New physics! ... or some underestimated theory contribution?

\[ B \rightarrow K^* \text{ form factor} \]

non-factorisable corrections

- from lattice QCD (high \( q^2 \)) and light-cone sum rules (low \( q^2 \))
- systematic improvements possible

- “charm loops” at low \( q^2 \) and broad \( c \bar{c} \) resonances
- dominant uncertainty, no systematic theory description

Can lattice QCD help resolve this tension?
$B_{s,d} \rightarrow \mu^+ \mu^- - a precision test of the SM

combined LHCb & CMS result

\[ B(B_s \rightarrow \mu^+ \mu^-) = (2.8^{+0.7}_{-0.6}) \cdot 10^{-9} \]
\[ B(B_d \rightarrow \mu^+ \mu^-) = (3.9^{+1.6}_{-1.4}) \cdot 10^{-10} \]

consistent with SM at 2\sigma level

- major improvement in experimental precision expected soon
- very clean in the SM $\Rightarrow$ high NP sensitivity
- main theory uncertainties in $|V_{cb}|$ and $f_{B_{s,d}}$ decay constants

$\Rightarrow$ yet another quest for the lattice
Concluding remarks

Lattice QCD

- has made **substantial contributions** to the understanding of flavour violating processes
- plays a **crucial role** in many more observables than highlighted here*
  * see also talk by Ran Zhou and parallel sessions

My top 5 wishes to the lattice community

1. improved form factors for $|V_{ub}|$ and $|V_{cb}|$ determinations
2. precise results for $B_{d,s}$ mixing parameters and decay constants
3. confirmation of results for $K \rightarrow \pi \pi$ amplitudes entering $\epsilon'/\epsilon$
4. input on non-perturbative contributions entering the $b \rightarrow s$ anomalies
5. long-distance contributions to neutral kaon and $D$ meson mixing