Impact of lattice QCD on CKM phenomenology

Monika Blanke

Karlsruher Institut für Technologie

Lattice 2016

Southampton – July 28, 2016

Lattice meets flavour

Flavour in the Standard Model (SM)

Flavour and CP violation in SM described by CKM matrix

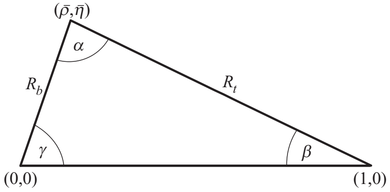
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{\mathsf{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Unitarity implies $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

➢ **Unitarity triangle**

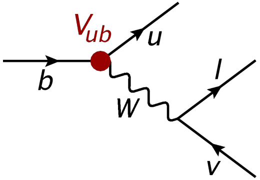
$$R_b = \left| \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right|$$

$$R_t = \left| \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} \right|$$



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 ε_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 $|V_{cb}|$: FNAL/MILC (2014)

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

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

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

Gambino, Healey, Turczyk (2016)

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

➢ **cross-check needed!**

$|V_{cb}|$ from $B \to D\ell\nu$

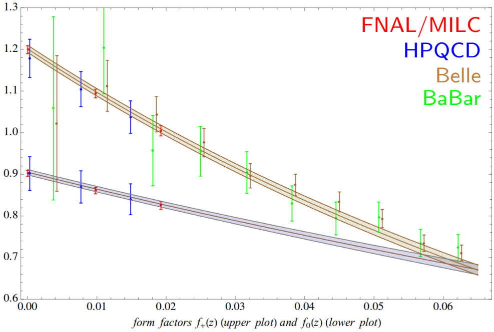
Bigi, Gambino (2016)
see also De Tar (2015)

- 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 $B \to D\ell\nu$:

$$|V_{cb}| = 40.49(97) \cdot 10^{-3}$$

form factors in the $N = 2+1+1$ fit:



$|V_{ub}|$ from $B \to \pi \ell \nu$

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

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

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

- compare to inclusive determination PDG (2016)

$$\boxed{|V_{ub}| = (4.41 \pm 0.15^{+0.15}_{-0.19}) \cdot 10^{-3}}$$

$|V_{ub}/V_{cb}|$ from baryon decays

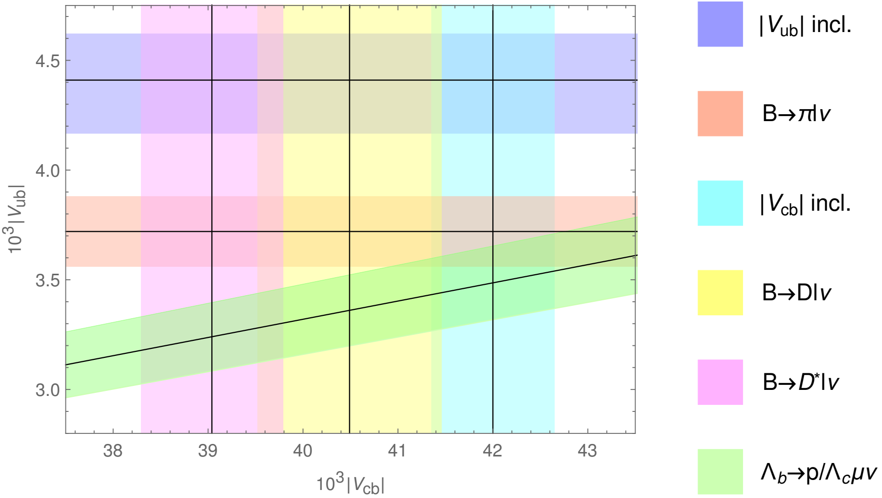
- $\Lambda_b \to p\ell\nu$ and $\Lambda_b \to \Lambda_c\ell\nu$ form factors calculated with $N = 2+1$ dynamical domain-wall fermion flavours

  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 $|V_{ub}|$



New physics in tree level decays?

Chen, Nam (2008)
Crivellin (2009)
Buras, Gemmler, Isidori (2010)
MB, Buras, Gemmler, Heidsieck (2011)

Can discrepancies be explained by new physics?

- effect of right-handed currents

$$|V_{cb}|^{D\ell\nu} = |V_{cb}|(1+\delta) \qquad |V_{ub}|^{\pi\ell\nu} = |V_{ub}|(1-\varepsilon)$$
$$|V_{cb}|^{D^*\ell\nu} = |V_{cb}|(1-\delta) \qquad |V_{ub}|^{B\to\tau\nu} = |V_{ub}|(1+\varepsilon)$$
$$|V_{cb}|^{\text{incl}} = |V_{cb}| + \mathcal{O}(\delta^2) \qquad |V_{ub}|^{\text{incl}} = |V_{ub}| + \mathcal{O}(\varepsilon^2)$$

➢ excluded as origin of the tension

- general $SU(2)$-invariant dimension 6 operators can resolve tension, but incompatible with $Z \to b\bar{b}$ Crivellin, Pokorski (2014)

➢ **under-estimated theory uncertainties? experimental issue?**

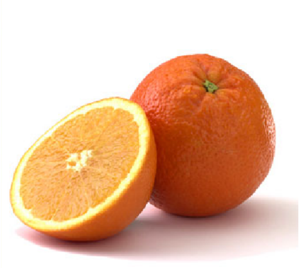
A vast variety of new physics models

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. . .

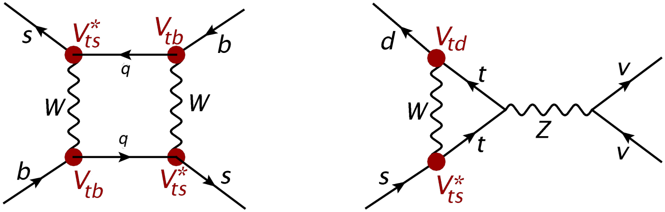
But maybe LHC will leave us with. . .

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

FNAL/MILC (2016)
compare to FLAG (2016) values

$$\begin{aligned} f_{B_d}^2 \hat{B}_{B_d} &= 0.0518(43)(10)\,\text{GeV} \\ f_{B_s}^2 \hat{B}_{B_s} &= 0.0754(46)(15)\,\text{MeV} \\ \xi &= \frac{f_{B_s}\sqrt{\hat{B}_{B_s}}}{f_{B_d}\sqrt{\hat{B}_{B_d}}} = 1.206(18)(6) \end{aligned}$$

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

➢ **If confirmed, what could be the origin of this tension?**

Constrained Minimal Flavour Violation

Buras et al. (2000)

see also D'Ambrosio et al. (2002); MB, Buras, Guadagnoli, Tarantino (2006)

Comstrained 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

$$\boxed{S(v) \geq S_0(x_t) = 2.322}$$

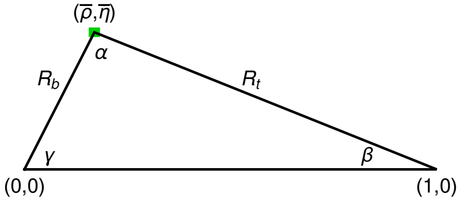
MB, Buras (2006)

The universal unitarity triangle

Universal unitarity triangle holding within all CMFV models

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

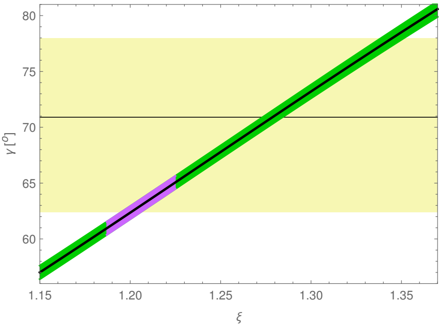
➢ few % precision, main uncertainties in $S_{\psi K_S}^{\text{exp}}$ and ξ



$$\bar{\rho}_{\text{UUT}} = 0.170 \pm 0.013 \qquad \bar{\eta}_{\text{UUT}} = 0.333 \pm 0.011$$

MB, Buras (2016)

Implications from the UUT: the angle γ



MB, Buras (2016)

construction of UUT yields

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

compare to: LHCb (2016)

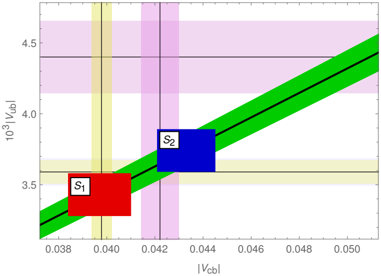
$$\gamma_{\text{tree}} = (70.9^{+7.1}_{-8.5})^\circ$$

➢ **Problem for CMFV?**

More precise γ measurements by LHCb and Belle II will tell!

Implications from the UUT: the ratio $|V_{ub}/V_{cb}|$

MB, Buras (2016)



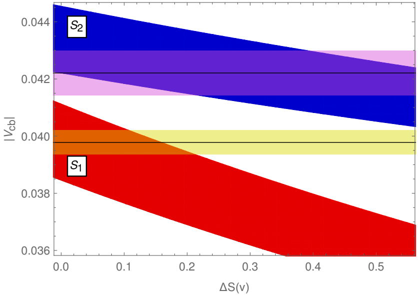
$$|V_{ub}/V_{cb}|_{\text{UUT}} = 0.0864 \pm 0.0025$$

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

➢ **Strategies to fully determine CKM matrix:**
$\boldsymbol{S_1}$: ΔM_s is used to determine $|V_{cb}|$ as function of $S(v)$
$\boldsymbol{S_2}$: ε_K is used to determine $|V_{cb}|$ as function of $S(v)$

$|V_{cb}|$ from ΔM_s and ε_K

MB, Buras (2016)



$$|V_{cb}|_{S_1} = (39.7 \pm 1.3) \cdot 10^{-3} \left[\frac{2.322}{S(v)}\right]^{1/2}$$

$$|V_{cb}|_{S_2} = (43.3 \pm 1.1) \cdot 10^{-3} \left[\frac{2.322}{S(v)}\right]^{1/4}$$

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

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

cannot explain the tension in $\Delta F = 2$ data

Possible ways out:

- relax lower bound on $\Delta S(v)$ MB, Buras (2006)
  - ➢ possible but difficult to achieve in concrete models
  - ➢ inconsistencies with tree-level values of $|V_{cb}|$ and γ
- introduce flavour non-universal contributions

$$S_0(x_t) \to S_i = |S_i| e^{i\varphi_i} \qquad i = K, d, s$$

  - ➢ 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:

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

Consequences:

- ε_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 φ_{new}, but correlated with ϕ_s

➢ $U(2)^3$ models in better shape than CMFV, but might get in trouble with more precise determinations of γ, $|V_{ub}/V_{cb}|$, and ϕ_s

Direct CP violation in kaon decays

ε'/ε in the SM

simple phenomenological expression: Buras, Gorbahn, Jäger, Jamin (2015)
see also Kitahara, Nierste, Tremper (2016)

$$\mathrm{Re}(\varepsilon'/\varepsilon) = \frac{\mathrm{Im}(V_{ts}^* V_{td})}{1.4 \cdot 10^{-4}} \cdot 10^{-4} \cdot \Big(\underbrace{-3.6 + 21.4 B_6^{(1/2)}}_{A_0\text{: QCD penguins}} + \underbrace{1.2 - 10.4 B_8^{(3/2)}}_{A_2\text{: EW penguins}} \Big)$$

- large cancellation between A_0 and A_2 amplitudes
- hadronic matrix elements from the lattice RBC-UKQCD (2015)

$$B_6^{(1/2)} = 0.57 \pm 0.19 \qquad B_8^{(3/2)} = 0.76 \pm 0.05$$

consistent with large N_c bound $B_6^{(1/2)} < B_8^{(3/2)} < 1$

Buras, Gérard (2015)

NLO: $(1.9 \pm 4.5) \cdot 10^{-4}$ BGJJ'15 $\qquad (0.96 \pm 4.96) \cdot 10^{-4}$ KNT'16

NNLO: coming soon! Gorbahn et al.

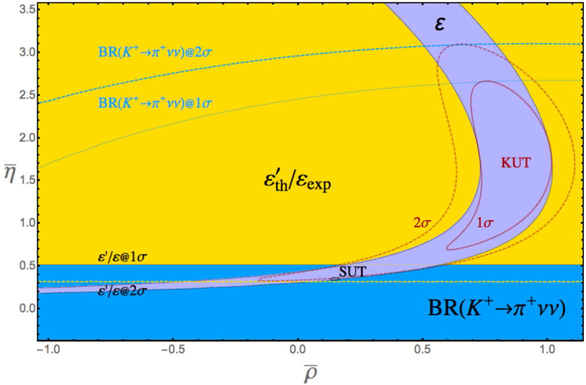
➢ **2.9σ tension with the data!** (a bit less with lattice value for ReA_0)

The K-Unitarity Triangle

Lehner, Lunghi, Soni (2015)

earlier studies: Buras, Lautenbacher, Ostermaier (1994); Buchalla, Buras (1994)

Unitarity Triangle from kaon decay observables



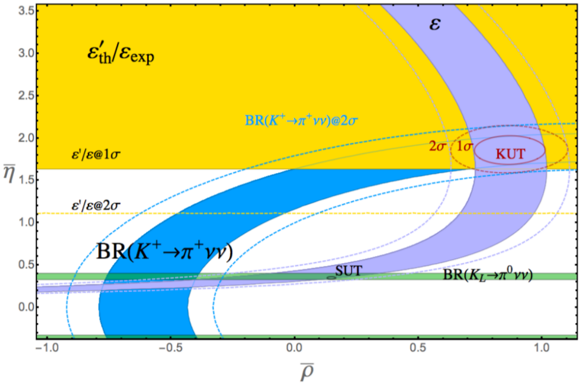
KUT 2015

The K-Unitarity Triangle

Lehner, Lunghi, Soni (2015)

earlier studies: Buras, Lautenbacher, Ostermaier (1994); Buchalla, Buras (1994)

Unitarity Triangle from kaon decay observables



KUT 2025?

ε'/ε beyond the SM

New physics can induce large deviations from SM in ε'/ε

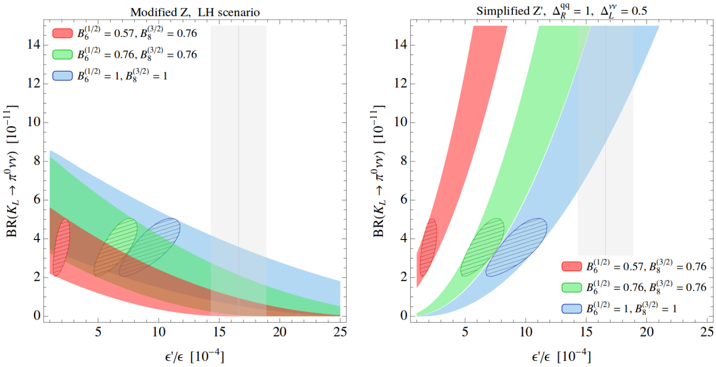
Recent studies:

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

ε'/ε in simplified FCNC models

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

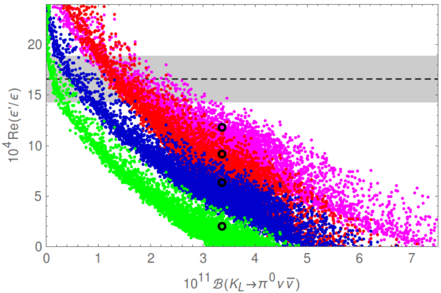
Buras, Buttazzo, Knegjens (2015)

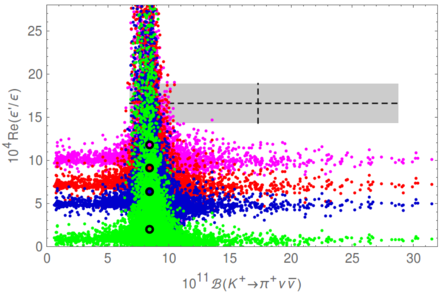


- tension in $|\varepsilon'/\varepsilon|$ can be removed
- simultaneous large effects in $K_L \to \pi^0 \nu\bar{\nu}$

ε'/ε in the Littlest Higgs model with T-parity

MB, Buras, Recksiegel (2015)

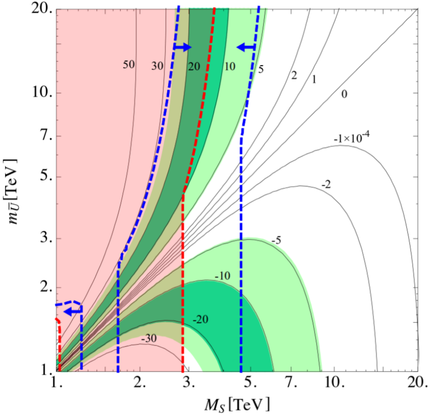




$$(B_6^{(1/2)}, B_8^{(3/2)}) = (1.0, 1.0), (0.76, 0.76), (0.57, 0.76), (1.0, 0.76)$$

➢ also in LHT strong correlation with $K \to \pi\nu\bar\nu$

ε'/ε in the MSSM



KITAHARA, NIERSTE, TREMPER (2016)

contribution to ε_K suppressed by

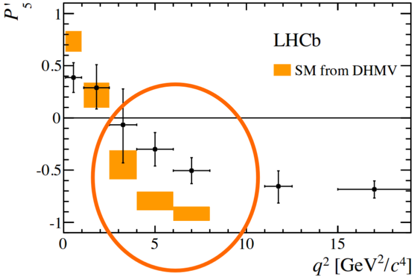
- small LR mixing
- $m_{\tilde{g}} = 1.5 M_S$
  $(M_S = m_{\tilde{Q}} = m_{\tilde{D}})$

➢ **ε'/ε can be explained with multi-TeV squarks**

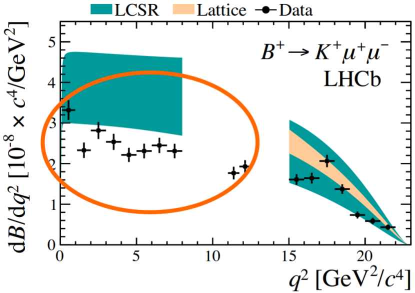
$b \to s$ penguins

Tensions in $b \to s$ transitions

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



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



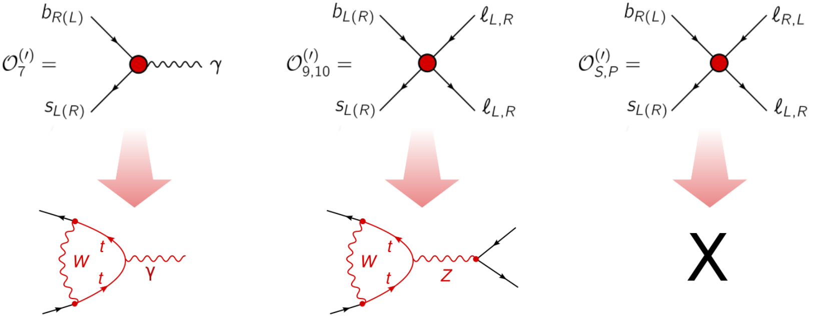
$B^+ \to K^+ \mu^+ \mu^-$

Radiative and semileptonic $b \to s$ transitions

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

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

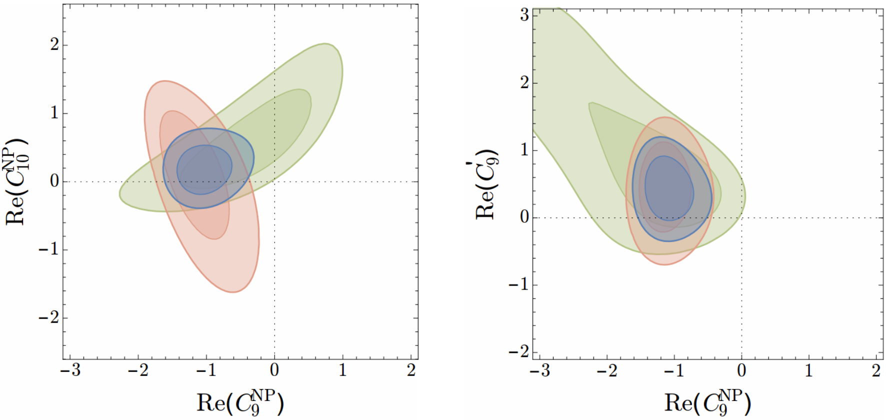
where the operators most sensitive to new physics are



SM:

Global fit to Wilson coefficients

Altmannshofer, Straub (2015) and others

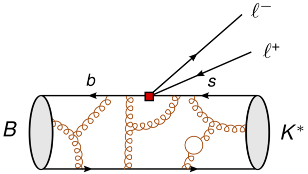


➢ $\sim 4\sigma$ **evidence for a new contribution to** C_9

What could it be?

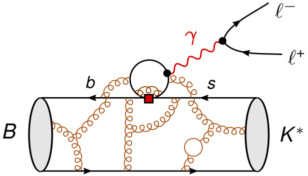
New physics! . . . or some underestimated theory contribution?

$B \to K^*$ form factor



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

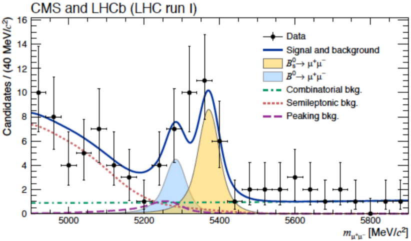
non-factorisable corrections



- "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?**

$B_{s,d} \to \mu^+\mu^-$ – a precision test of the SM



combined LHCb & CMS result

$$\mathcal{B}(B_s \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \cdot 10^{-9}$$
$$\mathcal{B}(B_d \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \cdot 10^{-10}$$

consistent with SM at 2σ level

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

➢ **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 $K \to \pi\pi$ amplitudes entering ε'/ε
4. input on non-perturbative contributions entering the $b \to s$ anomalies
5. long-distance contributions to neutral kaon and D meson mixing