Emerging anomalies in the $\Delta B = 2$ sector

Monika Blanke

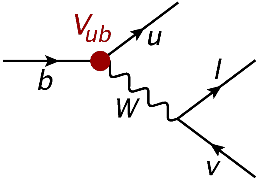
Karlsruher Institut für Technologie

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

Heavy-Quark Physics and Fundamental Symmetries
Seattle – August 22, 2019

Precision determination of CKM elements

Tree level decays: flavour changing charged current interactions



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

model-independent CKM determination

➢ should be used when looking for BSM contributions to FCNCs!

The reference Unitarity Triangle

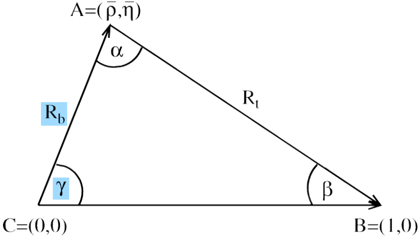
Grossman, Nir, Worah (1997)

- unitary CKM matrix uniquely determined by three mixing angles and one complex phase

$$|V_{us}| \equiv \lambda \qquad |V_{cb}| \qquad |V_{ub}| \qquad \gamma$$

measured in tree level decays ➢ insensitive to BSM contributions

- compare model-indpendent **reference unitarity triangle** (UT) with model-dependent FCNCs to discover BSM physics

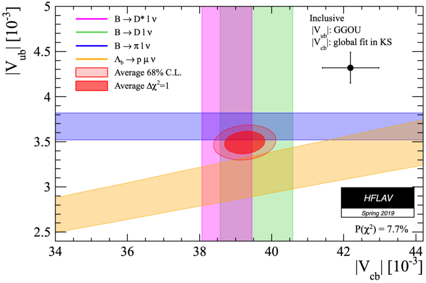


$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$$R_b = \left(1 - \frac{\lambda^2}{2}\right)\frac{1}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right|$$

The side R_b

R_b determined by ratio $|V_{ub}|/|V_{cb}|$



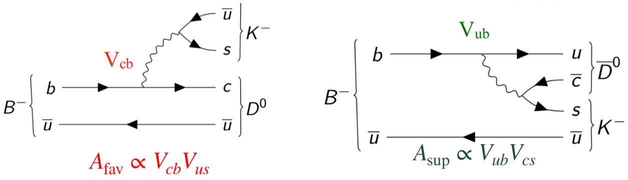
- long-standing tension in inclusive vs. exclusive determinations of $|V_{ub}|$
  ➢ significant uncertainty
- problem still unsolved also in $|V_{cb}|$ determinations
  ➢ important input for FCNCs

Strategy used (by me, for now)

- avoid $|V_{ub}|$ as input parameter for the time being
  ➢ need to rely on loop-induced $\sin 2\beta$ (consistent with $|V_{ub}|_{\text{excl}}$)
- use $|V_{cb}|_{\text{incl}}$ (least debated) and watch out for impact of lower $|V_{cb}|_{\text{excl}}$

The angle γ from tree-level decays: $B \to DK$

CP asymmetry in $B \to DK$ measures $\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$



- only UT angle that can be determined from tree level decays
- impressive precision achieved by LHCb: $\gamma = \left(74.0^{+5.0}_{-5.8}\right)^\circ$ LHCb (2018)
- BaBar and Belle results with significant uncertainties
- experimental prospects (LHCb & Belle II): precision $< 1^\circ$ expected!
- practically free from theory uncertainties Brod, Zupan (2013)

Indirect determination of γ

Constraint on γ from the UT analysis MB, Buras (2016), (2018)

- γ determined indirectly from length $R_t \propto \sqrt{\Delta M_d/\Delta M_s}$
- recent results for ratio ξ of relevant hadronic matrix elements:

lattice QCD

- Fermilab Lattice/MILC Bazavov et al. (2016)

  $\xi = 1.206 \pm 0.019 \succ \gamma = (63.0 \pm 2.1)^\circ$

- RBC/UKQCD Boyle et al. (2018)

  $\xi = 1.1853 \pm 0.0054^{+0.0116}_{-0.0156} \succ \gamma = (60.7 \pm 1.5)^\circ$

- HPQCD Dowdall et al (2019)

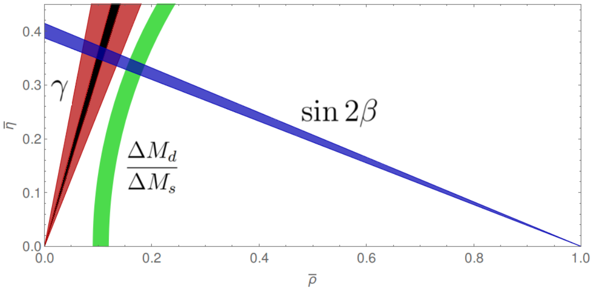
  $\xi = 1.212 \pm 0.012 \succ \gamma = (64.4 \pm 1.4)^\circ$

QCD sum rules King, Lenz, Rauh (2019)

- $\xi = 1.2014^{+0.0065}_{-0.0072} \succ \gamma = (62.5 \pm 0.9)^\circ$

Implications for the Unitarity Triangle

MB, Buras (2018)



- tension currently at the 2σ level
- may become significant with improved experimental precision in γ
- NP in $\sin 2\beta$ measurement would increase the tension

➢ **if confirmed, this anomaly would signal NP in ΔM_d and/or ΔM_s**

A closer look at ΔM_d and ΔM_s

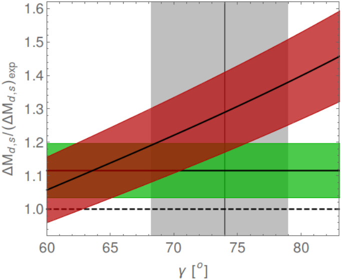
using FNAL/MILC'16 MB, Buras (2018)

- $(\Delta M_d)_{\text{SM}} > (\Delta M_d)_{\text{exp}}$ due to large γ and $|V_{cb}|_{\text{incl}}$ $(+\mathcal{O}(30\%)!)$
- smaller enhancement in ΔM_s (independent of γ)

  see also Di Luzio, Kirk, Lenz (2017)

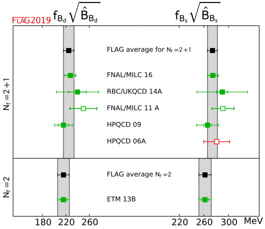
- $|V_{cb}|_{\text{excl}}$ reduces $\Delta M_{d,s}$ individually, but cannot cure $\Delta M_d/\Delta M_s$ and introduces tension in ϵ_K

  see also MB, Buras (2016); Bailey et al (2018)



➢ **emerging anomaly in $b \to d$ transitions?**

Status of $\Delta B = 2$ hadronic matrix elements

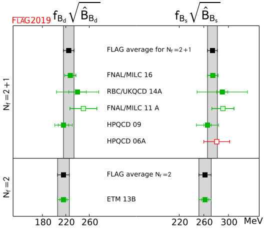


FLAG 2019 averages

- based on 2+1 dynamical flavours
- dominated by Fermilab/MILC (2016)

➢ implying a 2σ tension in ΔM_d

Status of $\Delta B = 2$ hadronic matrix elements



FLAG 2019 averages

- based on 2+1 dynamical flavours
- dominated by Fermilab/MILC (2016)

➢ implying a 2σ tension in ΔM_d

Recent 2+1+1 flavour lattice result

HPQCD (2019)

- different extrapolation to continuum limit (bag parameters vs. matrix elements) ➢ known issue: yields inconsistent results
- obtained matrix elements lower by $\sim 10\%$

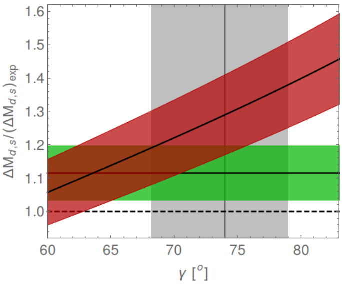
➢ no tension in individual mass differences $\Delta M_{d,s}$

➢ **clarification needed!**
(QCD sum rules don't seem to help here...)

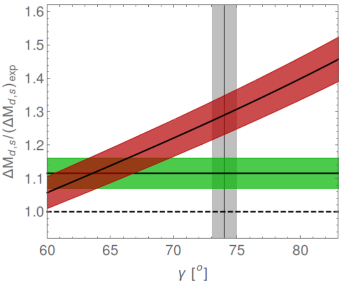
Fast-forward to the future

What if. . .

- LHCb and Belle II confirm large $\gamma_{B\to DK} = (74 \pm 1)^\circ$ and
- FNAL/MILC central values turn out to be correct and their uncertainties shrink to 1/3?



➢➢



Emerging New Physics pattern in $\Delta F = 2$

NP in meson mixing described model-independently by three functions

$$S_i \equiv S_0(x_t) + \Delta S_i \qquad \text{with} \quad \Delta S_i = |\Delta S_i| e^{i\delta_i}$$

➢ six new parameters $|\Delta S_i|$, δ_i $(i = K, d, s)$

Required pattern

- $\mathrm{Im}(\Delta S_K) \simeq 0$ from ε_K (but $\mathrm{Re}(\Delta S_K) \neq 0$ possible)
- relative size of NP effects in $B_{d,s}$ mixing: $|\Delta S_d| > |\Delta S_s| > 0$

➢ **violation of flavour universality in $\Delta F = 2$ transitions**
requires new source of flavour violation beyond MFV and $U(2)^3$
and/or contributions from new operators

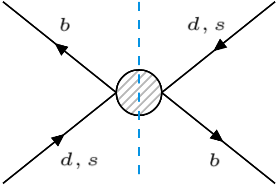
MB, Buras (2018)

Lessons from destructive interference

$\Delta F = 2$ processes have an intrinsic square-like structure

➢ typically constructive interference between SM and NP

MB, Buras (2006)
Di Luzio, Kirk, Lenz (2017)



Routes to destructive interference see also MB, Buras (2006)

- "crossed boxes" – e. g. with Majorana fermions
- new operators – LR structure breaks square pattern
- CP violation – $\delta_{s,d} \simeq \pi$ can be generated from large CP-violating phase $\pm\pi/2$ in $b \to s, d$ transition MB (2009)

➢ expect **large non-standard CP-violating effects** in $b \to d$ (and $b \to s$) rare decays!

Conclusions

- recent **lattice determinations of $B_{d,s}$ meson mixing matrix elements** hint for a tension between tree level CKM determinations (γ from $B \to DK$) and the ratio $\Delta M_d / \Delta M_s$
  - ➢ signals NP in ΔM_d and/or ΔM_s
- predictions of individual mass differences currently unconclusive
  - ➢ Fermilab/MILC results imply a negative NP contribution to ΔM_d not seen using HPQCD numbers
- if anomaly in ΔM_d is eventually confirmed, it will imply the **presence of new sources of flavour and possibly CP violation**