Cornering New Physics at Belle II

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Particle Physics Phenomenology after the Higgs Discovery

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The Standard Model (SM) Flavour Puzzle

SM flavour in a nutshell

- Quark flavour violation described by CKM matrix

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

- No flavour violating decays in the SM lepton sector
- Lepton flavour universality only violated by the (small) lepton masses

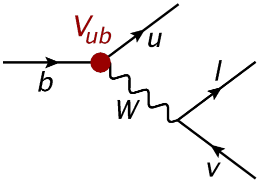
$$m_e \ll m_\mu \ll m_\tau$$

➢ **Where do the flavour hierachies come from?**

➢ **Why does this simple picture work so well?**

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 determination of CKM matrix as a **standard candle** of the SM

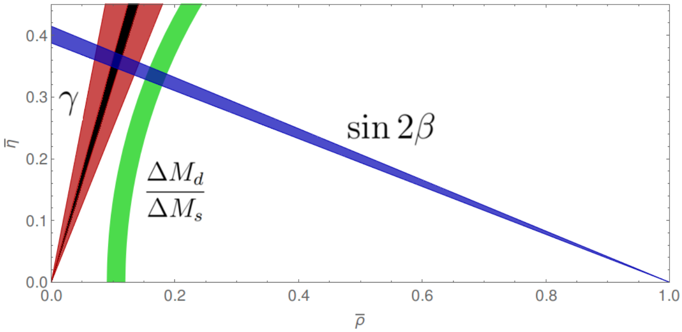
Status of Tree Level CKM Determinations

CKM matrix determined from four parameters

- $|V_{us}|$: most precisely known $|V_{us}| = 0.2248 \pm 0.0008$ FLAG
- $|V_{ub}|$: tension between inclusive and exclusive determinations
  $|V_{ub}|_{\text{excl}} \simeq 3.6 \cdot 10^{-3}$ – in good agreement with global CKM fits
  $|V_{ub}|_{\text{incl}} \simeq 4.5 \cdot 10^{-3}$ – in better agreement with $\text{BR}(B^+ \to \tau^+ \nu)$
- $|V_{cb}|$: inclusive/exclusive tension resolved?
  $|V_{cb}|_{\text{incl}} = (42.0 \pm 0.6) \cdot 10^{-3}$, in perfect agreement with
  $|V_{cb}|_{\text{excl}} = (41.5 \pm 1.3) \cdot 10^{-3}$ Bigi, Gambino, Schacht (2017)
  ➢ precise knowledge crucial for kaon physics, e. g. ε_K, $K \to \pi\nu\bar{\nu}\ldots$
- γ/ϕ_3: increasing precision by LHCb: $\gamma = \left(74.0^{+5.0}_{-5.8}\right)^\circ$
  essentially free from theory uncertainties Brod, Zupan (2013)
  future Belle II and LHCb accuracy $\pm 1^\circ$

Implications for the Unitarity Triangle

- ideally determined solely through tree-level measurements
  ➢ $R_b \sim |V_{ub}|/|V_{cb}|$ not well known due to persisting $|V_{ub}|$ problem
- some tension in R_t determined from γ vs. $\Delta M_d/\Delta M_s$

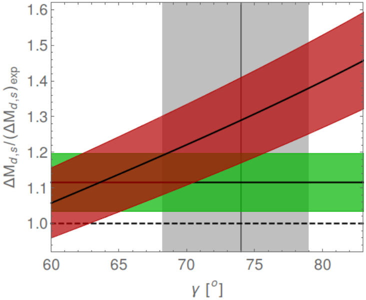


MB, Buras (2018)

$\Delta M_{s,d}$ – anomalous boxes?

A Closer Look at ΔM_d and ΔM_s

MB, Buras (2018)



- $(\Delta M_d)_{\text{SM}} > (\Delta M_d)_{\text{exp}}$ due to large γ and $|V_{cb}|$ $(+\mathcal{O}(30\%)!)$
- smaller enhancement in ΔM_s (independent of γ)
- smaller $|V_{cb}|$ cannot cure $\Delta M_d/\Delta M_s$ & introduces tension in ϵ_K

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

➢ **emerging anomaly in $\Delta F = 2$?**

New Physics Pattern in $\Delta F = 2$

NP in meson mixing described by three functions ($i = K, d, s$)

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

- $\mathrm{Im}(\Delta S_K) \simeq 0$ (but $\mathrm{Re}(\Delta S_K) \neq 0$ from ε'/ε anomaly?)
- pattern of NP effects in $B_{d,s}$ mixing

$$|\Delta S_d| > |\Delta S_s| > 0 \qquad \delta_d \simeq \delta_s \simeq \pi$$

- $\delta_{s,d} \simeq \pi$ typically requires maximal CP violation in corresponding $\Delta F = 1$ transitions (and/or new operators) MB (2009)

➢ **watch out for NP in rare and CP-violating $b \to d$ decays**, e. g. $B \to \pi\ell^+\ell^-$, $B \to \rho\ell^+\ell^-$, $B_d \to \mu^+\mu^-$, $B \to \pi\nu\bar{\nu}$, $B \to \rho\nu\bar{\nu}$

MB, Buras (2018)

Recent Anomalies in LFU-Violating B Decays

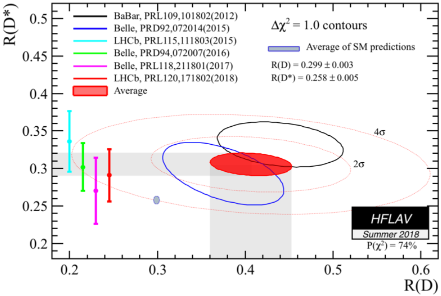
1. 3.8σ anomaly in semi-tauonic B decays, exhibiting lepton flavour universality violation
2. various *consistent* $2-3\sigma$ deviations in $b \to s\mu^+\mu^-$ transitions, leading to a $\sim 5\sigma$ tension in the global fit

$b \to c\tau\nu$ – anomalous trees

The $\mathcal{R}(D^{(*)})$ Anomaly

Test of lepton flavour universality in semi-leptonic B decays

$$\mathcal{R}(D^{(*)}) = \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)} \qquad (\ell = e, \mu)$$



- theoretically clean, as hadronic uncertainties largely cancel in ratio
- measurements by BaBar, Belle, and LHCb (so far $\mathcal{R}(D^*)$ only)
- 3.8σ tension between HFLAV fit and SM value
- (qualitatively) supported by measurement of $\mathcal{R}(J/\psi)$ (LHCb)

related observables: $\mathcal{R}(\Lambda_c)$, $F_L(D^*)$, $P_\tau(D^{(*)})$, $\mathrm{BR}(B_c \to \tau\nu)\ldots$

Effective Hamiltonian

New Physics above B meson scale described model-independently by

$$\mathcal{H}_{\text{eff}}^{\text{NP}} = 2\sqrt{2} G_F V_{cb} \Big[(1 + C_V^L) O_V^L + C_S^R O_S^R + C_S^L O_S^L + C_T O_T \Big]$$

with the vector, scalar and tensor operators

$$O_V^L = (\bar{c}\gamma^\mu P_L b)\,(\bar{\tau}\gamma_\mu P_L \nu_\tau) \qquad O_S^R = (\bar{c} P_R b)\,(\bar{\tau} P_L \nu_\tau)$$

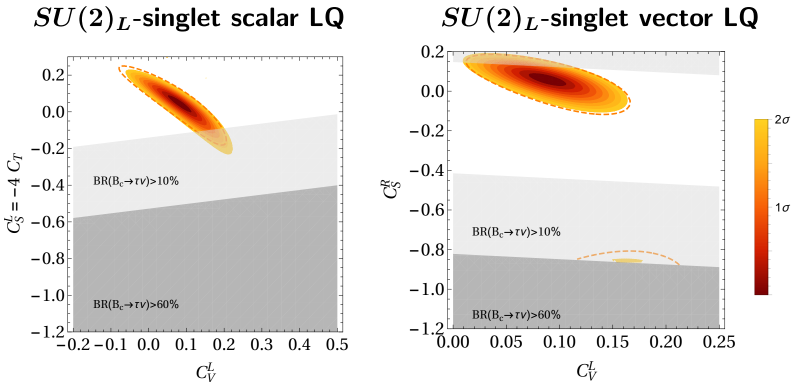
$$O_T = (\bar{c}\sigma^{\mu\nu} P_L b)\,(\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau) \qquad O_S^L = (\bar{c} P_L b)\,(\bar{\tau} P_L \nu_\tau)$$

Popular BSM scenarios:

- charged Higgs contributions ➢ $C_S^{L,R} \neq 0$
- new charged vector boson W' ➢ $C_V^L \neq 0$
- (scalar or vector) leptoquark ➢ $C_j \neq 0$ (depending on model)

Fit Results: Single Particle Scenarios (I)

MB, Crivellin, de Boer, Kitahara, Moscati, Nierste, Nišandžić (2018)

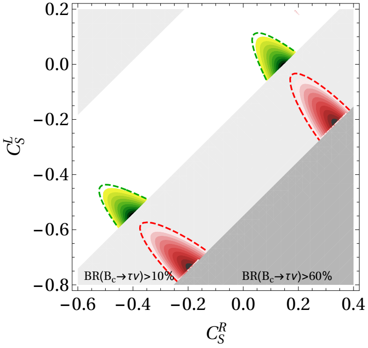


- good fit for both $(C_V^L, C_S^L = -4C_T)$ and (C_V^L, C_S^R)
- small impact of $\mathrm{BR}(B_c \to \tau\nu)$ constraint

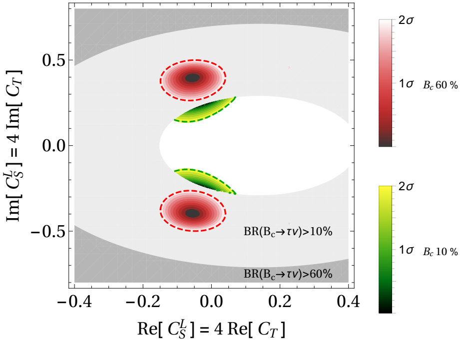
Fit Results: Single Particle Scenarios (II)

MB, Crivellin, de Boer, Kitahara, Moscati, Nierste, Nišandžić (2018)

charged Higgs



$SU(2)_L$-doublet scalar LQ w/ CPV



- very good fit for (C_S^R, C_S^L), but only allowed for BR$(B_c \to \tau\nu) \lesssim 60\%$
- good fit for $(C_S^L = 4C_T)$, unless BR$(B_c \to \tau\nu) < 10\%$ is imposed

The $\Lambda_b \to \Lambda_c \tau\nu$ Sum Rule

MB, Crivellin, de Boer, Kitahara, Moscati, Nierste, Nišandžić (2018)

From the phenomenological expressions for $\mathcal{R}(D^{(*)})$ and $\mathcal{R}(\Lambda_c)$, we derive an **approximate sum rule**:

$$\frac{\mathcal{R}(\Lambda_c)}{\mathcal{R}_{\rm SM}(\Lambda_c)} \simeq 0.262\frac{\mathcal{R}(D)}{\mathcal{R}_{\rm SM}(D)} + 0.738\frac{\mathcal{R}(D^*)}{\mathcal{R}^{\rm SM}(D^*)} + \mathcal{O}(10^{-2})$$

- ➢ enhancement of $\mathcal{R}(D^{(*)})$ implies $\mathcal{R}(\Lambda_c) > \mathcal{R}_{\rm SM}(\Lambda_c) = 0.33 \pm 0.01$
- ➢ model-independent prediction from current $\mathcal{R}(D^{(*)})$ data:

$$\mathcal{R}(\Lambda_c) = 0.41 \pm 0.02_{\mathcal{R}(D^{(*)})} \pm 0.01_{\text{form factors}}$$

➢ **experimental cross-check of $\mathcal{R}(D^{(*)})$ anomaly** LHCb (soon)

Flavour Observables to Test NP in $\mathcal{R}(D^{(*)})$

Direct probes of NP structure

- BR$(B_c \to \tau\nu)$ Alonso, Grinstein, M. Camalich (2016); Akeroyd, Chen (2017)
- $B \to D^{(*)}\tau\nu$ differential distributions, angular and polarisation observables see also Celis, Jung, Li, Pich (2016); Fedele et al. (soon)

Additionally: implied by $SU(2)_L$ symmetry

- large impact on $B \to K^{(*)}\nu\bar{\nu}$ (Belle II exclusive, golden modes!), $B_s \to \tau^+\tau^-$, $B \to K\tau^+\tau^-$, etc. Crivellin, Müller, Ota (2017)
- contributions to $\Upsilon \to \tau^+\tau^-$ and $\psi \to \tau^+\tau^-$ Aloni et al. (2017)

Complementary probes by the LHC

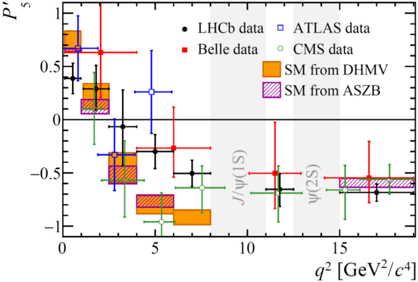
- strong constraints from $b\bar{b} \to \tau\bar{\tau}$ and mono-τ at ATLAS and CMS

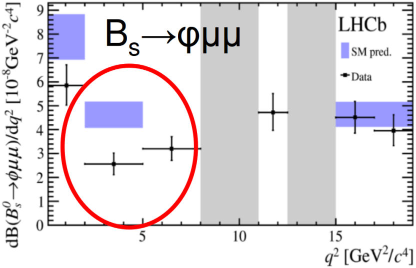
Faroughy, Greljo, Kamenik (2016); Altmannshofer, Dev, Soni (2017)
Greljo, Martin Camalich, Ruiz-Alvarez (2018)

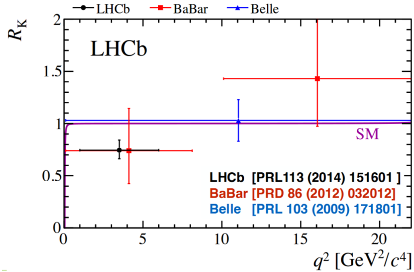
➢ **full NP resolution of $R(D^{(*)})$ anomaly challenging**

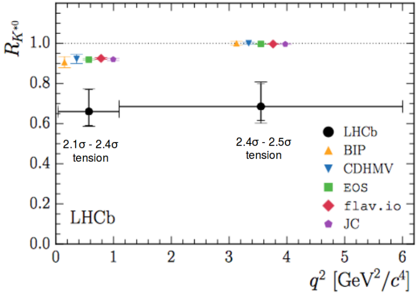
$b \to s\mu\mu$ – anomalous penguins

The $b \to s\mu^+\mu^-$ Transitions and LFU









New Physics in $b \to s\mu^+\mu^-$

Effective Hamiltonian

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

Good global fit solutions:

Altmannshofer, Stangl, Straub (2017)
Capdevila, Crivellin, Descotes-Genon, Matias, Virto (2017)

- $C_9^{\text{NP}} \sim -1.2$ ➢ LH quark current, muon vector current
- $C_9^{\text{NP}} = -C_{10}^{\text{NP}} \sim -0.7$ ➢ LH quark and lepton currents

The usual suspects

- new heavy neutral gauge boson Z'
- or again some leptoquark?

Altmannshofer, Straub (2013); Hiller, Schmaltz (2014)
Altmannshofer et al. (2014); Altmannshofer, Carena, Crivellin (2016)
D'Amico et al. (2017); Di Chiara et al. (2017)
Becirevic et al. (2018); Fajfer et al. (2018) ...

One Leptoquark to Explain Them All?

Alonso, Grinstein, M. Camalich (2015); Calibbi, Crivellin, Ota (2015)
Fajfer, Kosnik (2015); Barbieri, Isidori, Pattori, Senia (2016)
Buttazzo, Greljo, Isidori, Marzocca (2017)
Angelescu, Becirevic, Faroughy, Sumensari (2018) ...

One-particle solution to both anomlies: $SU(2)_L$-singlet vector LQ

- evades stringent constraints from B_s mixing and $b \to s\nu\bar{\nu}$
- B_c life-time under control
- beware of loop effects! Crivellin, Greub, Saturnino, Müller (2018)

Model building challenges

- identify UV origin of such vector LQ ➢ gauge symmetry?
- generate flavour non-universal LQ couplings
- avoid re-introduction of constraints due to additional particles present in UV-complete model

Back to the 70s: Pati-Salam

Recall: Pati-Salam (PS) model — Pati, Salam (1974)

- unification of quarks and leptons by introducing lepton number as fourth colour
- gauge group $G_{\text{PS}} = SU(4) \times SU(2)_L \times SU(2)_R$

  ➢ $SU(4)$ contains $SU(2)_L$-singlet vector leptoquark in addition to gluons and $B - L$ gauge boson

Simplest realisation

- LQ couplings are gauge couplings ➢ flavour-universal
- $m_{\text{LQ}} > \mathcal{O}(10^3\,\text{TeV})$ from $K_L \to \mu e$ and $K \to \pi\mu e$

➢ extend model to achieve **flavour-dependent couplings** and lower LQ mass to **TeV scale**

Recent Model-Building Efforts

quite some activity in this model-building challenge:

Barbieri, Murphy, Senia (2016)
Di Luzio, Greljo, Nardecchia (2017)
Calibbi, Crivellin, Li (2017)
Bordone, Cornella, Fuentes-Martin, Isidori (2017)
MB, Crivellin (2018)
Greljo, Stefanek (2018)
Heeck, Teresi (2018)
Balaji, Foot, Schmidt (2018)

...

This talk: two examples

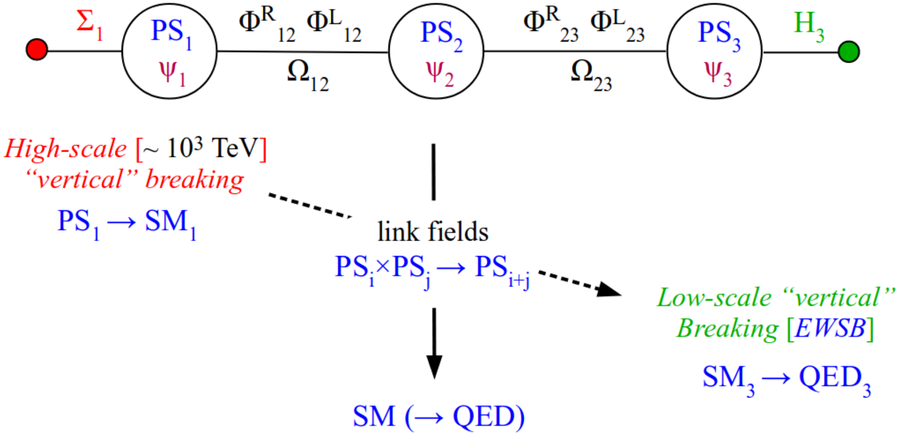
- three-site model with PS^3 symmetry

  Bordone, Cornella, Fuentes-Martin, Isidori (2017)

- Pati-Salam in Randall-Sundrum background MB, Crivellin (2018)

The PS^3 Model

Bordone, Cornella, Fuentes-Martin, Isidori (2017)
model sketch from Isidori, CKM'18



Key Features of PS^3

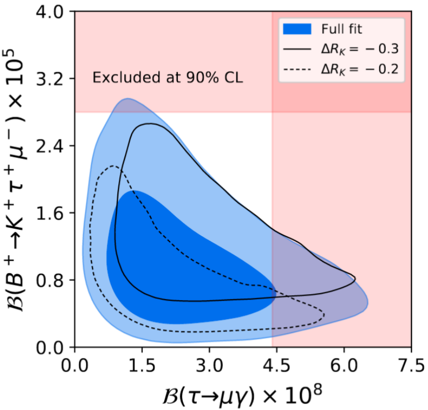
Bordone, Cornella, Fuentes-Martin, Isidori (2017), (2018)

common to all PS-type models

- TeV-scale LQ, colour-octet vector and Z'
- decent fit to low-energy data
- large $\tau \to \mu$ LFV effects

specific to PS^3

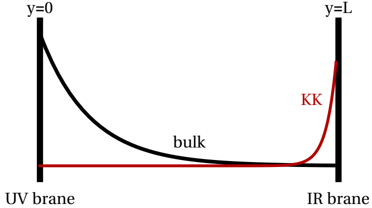
- hierarchical symmetry breaking pattern relates flavour-dependent LQ couplings to Yukawa hierarchies
- LQ coupling also to right-handed fermions



Pati-Salam in the Randall-Sundrum Background

Model in a nutshell: MB, Crivellin (2018)

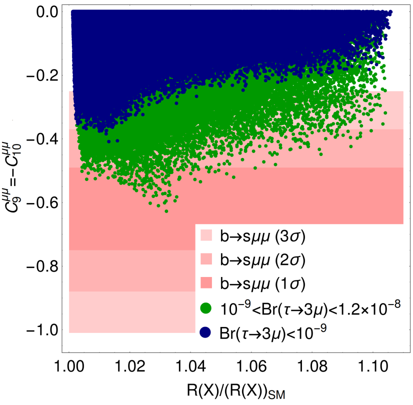
- embed PS gauge symmetry in 5D warped model described by Randall-Sundrum metric



- symmetry breaking by boundary conditions to SM gauge group, instead of sophisticated Higgs sector
  - massless zero modes for SM particles only
  - TeV-scale KK resonances for all degrees of freedom of $G_{\rm PS}$, incl. LQ
  - flavor-dependent couplings from localisation of SM fermions in 5D bulk

Key Features of Warped PS

MB, Crivellin (2018)



- less parametric freedom due to geometric origin of symmetry breaking ➢ predictive
- full resolution of $b \to s\mu\mu$ anomaly
- noticeable improvement in $b \to c\tau\nu$, supported by W' contribution in addition to LQ
- CPV in $D - \bar{D}$ mixing on the verge of discovery
- observable rate for $\tau \to 3\mu$

Outlook

At the dawn of the Belle II era
we are facing a set of intriguing anomalies in B decays

$b \to c$

$b \to s$

$b \to d$

Which one – if any of these – will guide us to New Physics?