Cornering New Physics at Belle II

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SM flavour in a nutshell

- Quark flavour violation described by CKM matrix

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

- 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
  
  $|V_{us}| = 0.2248 \pm 0.0008$  
  
  According to [Bigi, Gambino, Schacht (2017)]

- $|V_{ub}|$: 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. $\varepsilon_K, K \to \pi \nu \bar{\nu}$

- $\gamma/\phi_3$: increasing precision by LHCb:
  
  $\gamma = (74.0^{+5.0}_{-5.8})^\circ$  
  
  [Brod, Zupan (2013)]

  essentially free from theory uncertainties

future Belle II and LHCb accuracy $\pm 1^\circ$
Implications for the Unitarity Triangle

- ideally determined solely through tree-level measurements
  \[ R_b \sim \frac{|V_{ub}|}{|V_{cb}|} \] not well known due to persisting \( |V_{ub}| \) problem

- some tension in \( R_t \) determined from \( \gamma \) vs. \( \frac{\Delta M_d}{\Delta M_s} \)

MB, Buras (2018)
$\Delta M_{s,d}$ – anomalous boxes?
A Closer Look at $\Delta M_d$ and $\Delta M_s$

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

> emerging anomaly in $\Delta F = 2$?

MB, Buras (2018)
New Physics Pattern in $\Delta F = 2$

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

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

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

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

- $\delta_{s,d} \simeq \pi$ typically requires maximal CP violation in corresponding $\Delta F = 1$ transitions (and/or new operators) \text{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. $3.8\sigma$ 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
$b \rightarrow c\tau\nu$ – anomalous trees
The $\mathcal{R}(D^{(*)})$ Anomaly

Test of lepton flavour universality in semi-leptonic $B$ decays

$$\mathcal{R}(D^{(*)}) = \frac{\text{BR}(B \rightarrow D^{(*)}\tau\nu)}{\text{BR}(B \rightarrow D^{(*)}\ell\nu)} \quad (\ell = e, \mu)$$

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

related observables: $\mathcal{R}(\Lambda_c)$, $F_L(D^*)$, $P_\tau(D^{(*)})$, $\text{BR}(B_c \rightarrow \tau\nu)$...
Effective Hamiltonian

New Physics above $B$ meson scale described model-independently by

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

with the vector, scalar and tensor operators

$$O_V^L = (\bar{c}\gamma^\mu P_L b) (\bar{\tau}\gamma_\mu P_L \nu_\tau)$$
$$O_S^R = (\bar{c}P_R b) (\bar{\tau}P_L \nu_\tau)$$
$$O_T = (\bar{c}\sigma^{\mu\nu} P_L b) (\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau)$$
$$O_S^L = (\bar{c}P_L b) (\bar{\tau}P_L \nu_\tau)$$

Popular BSM scenarios:

- charged Higgs contributions $\Rightarrow C_S^{L,R} \neq 0$
- new charged vector boson $W' \Rightarrow C_V^L \neq 0$
- (scalar or vector) leptoquark $\Rightarrow C_j \neq 0$ (depending on model)
Fit Results: Single Particle Scenarios (I)

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

- **SU(2)$_L$-singlet scalar LQ**
  - $C_S^L = -4C_T$
  - $\text{BR}(B_c \rightarrow \tau \nu) > 10\%$
  - $\text{BR}(B_c \rightarrow \tau \nu) > 60\%$

- **SU(2)$_L$-singlet vector LQ**
  - $C_S^R$
  - $\text{BR}(B_c \rightarrow \tau \nu) > 10\%$
  - $\text{BR}(B_c \rightarrow \tau \nu) > 60\%$

- Good fit for both $(C_V^L, C_S^L = -4C_T)$ and $(C_V^L, C_S^R)$
- Small impact of $\text{BR}(B_c \rightarrow \tau \nu)$ 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 $(C^R_S, C^L_S)$, but only allowed for $\text{BR}(B_c \to \tau\nu) \lesssim 60\%$
- Good fit for $(C^L_S = 4C_T)$, unless $\text{BR}(B_c \to \tau\nu) < 10\%$ is imposed
The \( \Lambda_b \rightarrow \Lambda_c \tau \nu \) 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:

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

- enhancement of \( \mathcal{R}(D^{(*)}) \) implies \( \mathcal{R}(\Lambda_c) > \mathcal{R}_{SM}(\Lambda_c) = 0.33 \pm 0.01 \)
- 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 \( \text{LHCb (soon)} \)
Flavour Observables to Test NP in $\mathcal{R}(D^{(*)})$

Direct probes of NP structure

- $\text{BR}(B_c \to \tau\nu)$ 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-$\tau$ at ATLAS and CMS
  Faroughy, Greljo, Kamenik (2016); Altmannshofer, Dev, Soni (2017)
  Greljo, Martin Camalich, Ruiz-Alvarez (2018)

⚠️ full NP resolution of $\mathcal{R}(D^{(*)})$ anomaly challenging
$b \to s\mu\mu$ – anomalous penguins
The $b \rightarrow s\mu^+\mu^-$ Transitions and LFU

$P_5'$

$q^2$ [GeV$^2$/c$^4$]

$R_K$

$B_s \rightarrow \phi\mu\mu$

$\Delta B(B_s^0)$

$dB(B_s^0 \rightarrow \phi\mu\mu)/dq^2 \times [10^{-8}\text{GeV}^2c^4]$
New Physics in $b \rightarrow s\mu^+\mu^-$

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)

- $C^\text{NP}_9 \sim -1.2$ ➤ LH quark current, muon vector current
- $C^\text{NP}_9 = -C^\text{NP}_{10} \sim -0.7$ ➤ 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)

One-particle solution to both anomalies: \( SU(2)_L \)-singlet vector LQ

- evades stringent constraints from \( B_s \) mixing and \( b \to s\mu\bar{\nu} \)
- \( B_c \) life-time under control
- beware of loop effects!

Crivellin, Greub, Saturnino, Müller (2018)

Model building challenges

- identify UV origin of such vector LQ \( \Rightarrow \) 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  

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

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

Simplest realisation

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

\( \Rightarrow \) extend model to achieve \textbf{flavour-dependent couplings} and lower LQ mass to \textbf{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)
MB, Crivellin (2018)
Greljo, Stefanek (2018)
Heeck, Teresi (2018)
Balaji, Foot, Schmidt (2018)

... 

This talk: two examples

- three-site model with $PS^3$ symmetry


- Pati-Salam in Randall-Sundrum background

MB, Crivellin (2018)
The PS$^3$ Model

model sketch from Isidori, CKM’18

High-scale [$\sim 10^3$ TeV]
“vertical” breaking

$\Sigma_1 \rightarrow \Psi_1$

$\Phi^R_{12} \Phi^L_{12}$

$\Omega_{12}$

$\Phi^R_{23} \Phi^L_{23}$

$\Omega_{23}$

$PS_1 \rightarrow SM_1$

$PS_i \times PS_j \rightarrow PS_{i+j}$

Low-scale “vertical”
Breaking [$EWSB$]

$SM_3 \rightarrow QED_3$

SM ($\rightarrow$ QED)
**Key Features of PS³**


**common to all PS-type models**
- TeV-scale LQ, colour-octet vector and $Z'$
- decent fit to low-energy data
- large $\tau \rightarrow \mu$ LFV effects

**specific to PS³**
- 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:

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

\[
\begin{align*}
&y = 0 \\
&y = L
\end{align*}
\]

- 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 \( G_{PS} \), incl. LQ
  - flavor-dependent couplings from localisation of SM fermions in 5D bulk

MB, Crivellin (2018)
Key Features of Warped PS

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

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

$b \rightarrow c$

$b \rightarrow s$

$b \rightarrow d$

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