Project C3b: New Physics Models for flavour observables

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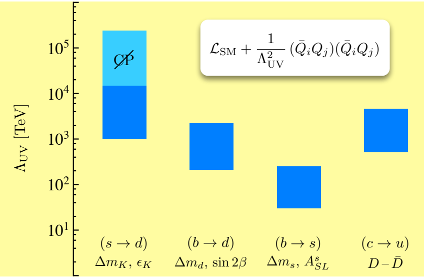
1. Introduction/Motivation

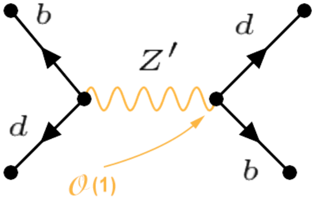
Introduction

- What is the next layer of physics, beyond the standard model (SM)? (We know that the SM is not the final word.)
- high-pT experiments: produce and study new particles directly
  low energy flavour experiments: explore virtual effects of new heavy particles



- FCNC-induced processes probe higher scales than direct searches[1]

[1] plot by M. Neubert



- E.g. Z' model with $\mathcal{O}(1)$ FCNC couplings: $M_{Z'} \gtrsim 100\,\text{TeV}$
- For loop-induced NP effects the probed scales are lower, $\mathcal{O}(1-10\,\text{TeV})$

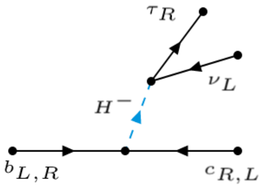
- Several discrepancies between experiment and SM expectations, called 'flavour anomalies'

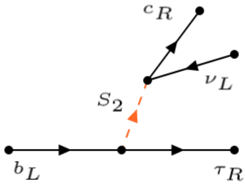
Anomaly	Main observables	Current discrepancy w.r.t. SM	Theor. cleanness[2]
$b \to s\mu^+\mu^-$	P_5', R_K, R_{K^*} ...	$\sim 4-6\,\sigma$	★★[3]
$b \to c\tau\nu$	$\mathcal{R}_D$, $\mathcal{R}_{D^*}$ ...	$\sim 4\,\sigma$	★★★
$(g-2)_\mu$	$(g-2)_\mu$	$\sim 3.7\,\sigma$	★★
ϵ_K'	$K \to \pi\pi$	$2.8\,\sigma$	★

- Bulk of literature invokes ad-hoc explanations, often with a single new particle (Z', leptoquarks)
- Aim: construct viable models that can put such particles into well-motivated theoretical framework(s)

[2] w.r.t. current measurement precision
[3] R_{K,K^*} alone deserve 3 stars

- Charged current processes mediated by W at tree level. Any NP explanation involves new charged heavy particle:





- Not rare processes, but precisely measured. Hadronic uncertainties from form factors under control.
- Data point to NP that violates lepton flavour universality (LFU).
- Deviations from purely left-handed couplings of W to fermions possible, giving rise to new signatures in the future (polarisation observables).

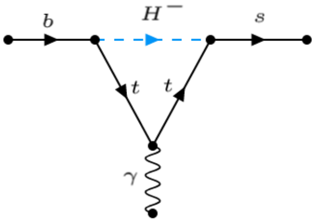
2. Quick review of work packages

Work packages

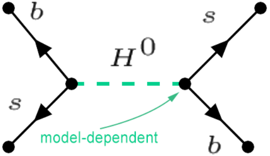
- A model-independent study of BSM effects involves 2499 dimension-6 operators.
  $\rightarrow$ One needs well motivated benchmark models of new physics.
- Such models permit analyses of non-trivial correlations between flavour observables and between flavour and collider physics

(1) Multi-Higgs doublet models

- Extra Higgs doublet extensions - new, charged and neutral Higgs bosons



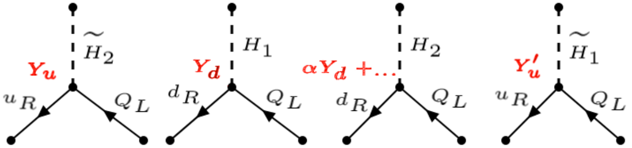
- Neutral Higgs can induce (model dependently) FCNCs transitions



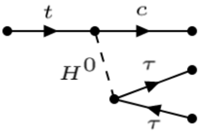
(1) Multi-Higgs doublet models

Symmetry approach to suppress FCNC

- Gauge-kinetic terms in SM obey a $U(3)^5$ symmetry. Yukawa matrices Y_u, Y_d are spurions breaking this symmetry which may well control the NP contributions as well (Minimal Flavour Violation (MFV) ansatz).
- Im multi-Higgs doublet models more spurions are possible, and there are many ways to suppress unwanted FCNC effects in e.g. B mixing.



- Can suppress FCNCs in down-type sector by choosing three spurions Y_d, Y_u, Y'_u, with the third Yukawa coupling expanded as $\alpha Y_d + \beta Y_d Y_u^\dagger Y_u + \ldots$. This still permits e.g. a sizable tcH^0 vertex:

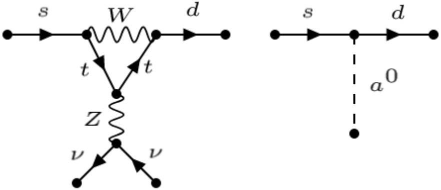


(1) Multi-Higgs doublet models

- Solution to $b \to c\tau\nu$ puzzle?
- Unclear if some multi-Higgs-doublet model can solve this:
- $B_c \to \tau\nu$ problem $\to$ tension with $\mathcal{R}(D^*)$, more on this later

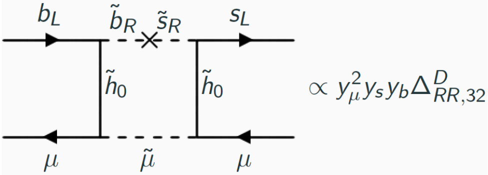
(2) Light neutral scalar(s)

- Spontaneous breaking of global flavour symmetry - massless goldstone boson - 'familon'
- Can obtain small mass via an anomaly
- Interesting flavour patterns $\rightarrow$ 'axiflavon'
- Possible avenue: $K \rightarrow \pi\bar{\nu}\nu$ NA62 (new results this year)



- Explanation of $b \to s\mu^+\mu^-$ anomalies with new particles in loops requires $\mathcal{O}(1)$ couplings, i.e. LFUV at $\mathcal{O}(1)$ level.
- How does this comply with SM LFUV by tiny Yukawa couplings, e.g. $y_\mu \sim 10^{-3}$?
- Could small fermion masses be loop-induced, with underlying $\mathcal{O}(1)$ parameters breaking the SM flavour symmetry?
- First approach: MSSM with VEV $v_d = 0$, thus down-type fermions get VEV from other Higgs doublet H_u through SUSY loop.
  $\Rightarrow \quad y_\mu = \mathcal{O}(1)$ in superpotential possible

MSSM contribution to $b \to s\mu^+\mu^-$:



Work in progress by PhD student Mustafa Tabet

- Default SUSY scenario in collider physics:
  MSSM-scenarios with split squark spectrum, very heavy squarks of first two generations and lighter stops.
- Major motivation for such a scenario - reconciliation of of the gauge hierarchy problem (needs not-too heavy stops) with non-observation of supersymmetry at the LHC
- But: Sizable FCNCs mediated by squarks and gluinos from the diagonalisation of the hierarchical squark mass matrices.
- Goal: study flavour patterns of such MSSM scenarios.

(5) Extended gauge symmetries

- a) Can leptoquarks that can explain the flavour anomalies be accommodated in a Pati-Salam model $SU(4)_c \times SU(2)_L \times SU(2)_R$? Or even $SO(10)$? (challenging to simultaneously avoid proton decay)
- b) E_6 - Representation **27** contains SM fermions plus additional vector-like fermions
- Explore the phenomenology of such models on LFV decays (preliminary work - master thesis by Thomas Deppisch)

3. Impact of polarization observables and $B_c \to \tau\nu$ on NP in $b \to c\tau\nu$ anomalies,

based on paper *arXiv: 1811.09603 [hep-ph]* done in collaboration with Monika Blanke, Andreas Crivellin, Stefan de Boer, Marta Moscati, Teppei Kitahara and Ulrich Nierste (accepted by PRD)

- The observable ratios:

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

- Measured values higher than the SM expectations:

$$\frac{\mathcal{R}(D)}{\mathcal{R}(D)_{\mathsf{SM}}} = 1.36 \pm 0.13_{\mathsf{stat}}, \pm 0.08_{\mathsf{syst}} \qquad 2.4\,\sigma$$

$$\frac{\mathcal{R}(D^*)}{\mathcal{R}(D^*)_{\mathsf{SM}}} = 1.186 \pm 0.050_{\mathsf{stat}}, \pm 0.027_{\mathsf{syst}} \qquad 3.3\,\sigma$$

- Total discrepancy w.r.t SM predictions at the level of $\sim 4\sigma$.

Effective description

- Use the effective description:

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

with four-fermion operators:

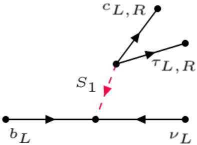
$$O_V^L = (\bar{c}\gamma^\mu P_L b)\,(\bar{\tau}\gamma_\mu P_L \nu_\tau)$$

$$O_S^R = (\bar{c}P_R b)\,(\bar{\tau}P_L \nu_\tau)$$

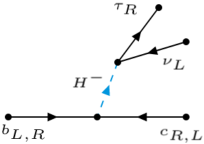
$$O_S^L = (\bar{c}P_L b)\,(\bar{\tau}P_L \nu_\tau)$$

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

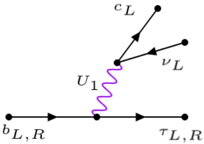
Two-parameter scenarios



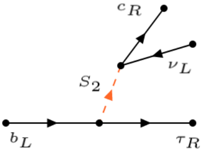
(a)



(b)



(c)



(d)

- We consider combinations of Wilson coefficients that result from exchange of a single heavy intermediate state:

(a) real $(C_V^L,\, C_S^L = -4C_T)$ - scalar leptoquark $S_1(3,1,-1/3)$
(b) real $(C_S^R,\, C_S^L)$ - charged Higgs
(c) real $(C_V^L,\, C_S^R)$ - vector leptoquark $U_1(3,1,2/3)$
(d) $\mathrm{Re}[C_S^L = 4C_T], \mathrm{Im}[C_S^L = 4C_T]$ - scalar leptoquark $S_2(3,2,7/6)$

Observables

We perform the fit for the Wilson coefficients of the four scenarios using the measured observables as inputs:

- In addition to $\mathcal{R}(D^{(*)})$ use τ-polarization asymmetry in $B \to D^* \tau \nu$ (Belle 2016)
- F_L, the longitudinal polarization fraction of D^* (Belle 2018)
- Predict (from the fits) yet unmeasured polarization observables in $B \to D \tau \nu$ and the $\mathcal{R}(\Lambda_c)$ - the analogous ratio for the baryonic modes

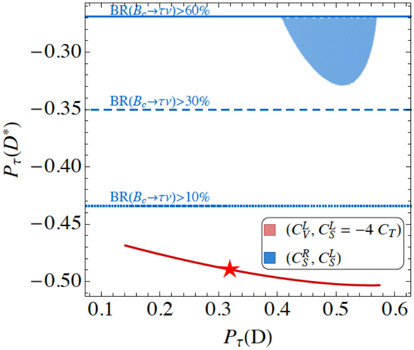
- Charged Higgs explanation under pressure from B_c-lifetime that constraints yet unmeasured $BR(B_c \to \tau\nu)$.
- $B_c \to \tau\nu$ is affected by the same pseudoscalar Wilson coefficient $C_S^R - C_S^L$ that enters $\mathcal{R}(D^*)$.
- Total width $\Gamma_{\text{tot}}(B_c)$ known from measured lifetime and $\Gamma(B_c \to \tau\nu) = \Gamma_{\text{tot}} \times BR(B_c \to \tau\nu)$
- $\mathcal{R}(D^*)$ data compatible only with excessive enhancement of $BR(B_c \to \tau\nu)$ over its SM value $BR(B_c \to \tau\nu)_{\text{SM}} = 2\%$ Alonso, Grinstein, Martin Camalich 2015
- An upper bound $BR(B_c \to \tau\nu) < 10\%$ inferred from non-observation of $Z \to b\bar{b}[B_c \to \tau\nu]$ at LEP using the estimate of the ratio f_c/f_u of $b \to B_c$ and $b \to B_u$ fragmentation probabilities from pp, $p\bar{p}$ data Akeroyd, Chen 2017.
- pp and $\bar{p}p$ collisions produce B_c through mechanisms that have no counterpart in Z-decays
- We chose three cases in our analysis: $BR(B_c \to \tau\nu) < 10\%$, $BR(B_c \to \tau\nu) < 30\%$, $BR(B_c \to \tau\nu) < 60\%$.

As an example, compare the two scenarios $C_V^L, C_S^L = -4C_T$ (from leptoquark S_1) and $C_S^{L,R}$ (from charged Higgs)

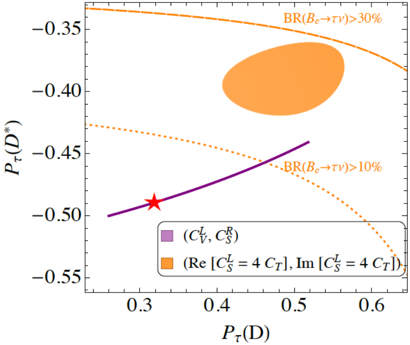
2D hyp.	best-fit	p-value percent	pull$_{SM}$	$\mathcal{R}(D)$	$\mathcal{R}(D^*)$	$F_L(D^*)$	$P_\tau(D^*)$	$P_\tau(D)$	$\mathcal{R}(\Lambda_c)$
$(C_V^L, C_S^L = -4C_T)$	$(0.08, 0.05)$	**22.0**	4.2	0.394 $-0.3\,\sigma$	0.308 $+0.2\,\sigma$	**0.45** $-1.7\,\sigma$	-0.50 $-0.2\,\sigma$	0.40	0.41
$(C_S^R, C_S^L)\vert_{60\%}$	$(-0.19, -0.74)$ $(0.34, -0.22)$	**68.5**	4.5	0.412 $+0.1\,\sigma$	0.299 $-0.5\,\sigma$	**0.54** $-0.7\,\sigma$	-0.27 $+0.2\,\sigma$	0.50	0.40
$(C_S^R, C_S^L)\vert_{30\%}$	$(-0.30, -0.64)$ $(0.24, -0.11)$	11.8	4.1	0.423 $+0.4\,\sigma$	0.280 $-1.8\,\sigma$	0.51 $-1.0\,\sigma$	-0.35 0.0 σ	0.51	0.39
$(C_S^R, C_S^L)\vert_{10\%}$	$(0.14, 0.00)$ $(-0.40, -0.55)$	0.6	3.4	0.433 $+0.6\,\sigma$	**0.263** $-2.9\,\sigma$	0.48 $-1.4\,\sigma$	-0.44 $-0.1\,\sigma$	0.53	0.38

- S_1 performs well, with F_L and the predicted value of $P_\tau(D^*)$ SM-like
- F_L favors charged-Higgs solution
- If this scenario is true then either $\mathcal{R}(D^*)$ will go down towards its SM value or $BR(B_c \to \tau\nu) \gtrsim 30\%$

Use the results of the fits to predict correlations between observables for different scenarios, e.g.



(a)



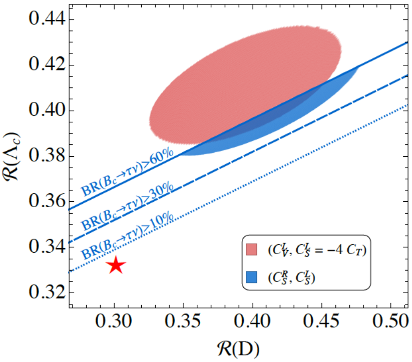
(b)

(a) leptoquark S_1
charged Higgs

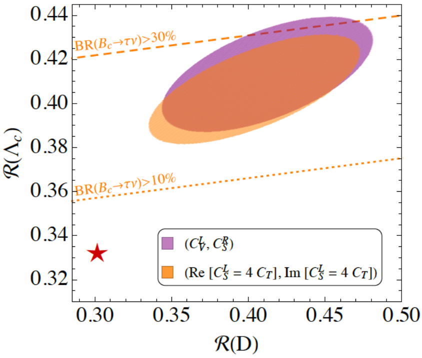
(b) leptoquark U_1
leptoquark S_2

Regions on the plots from 1σ ranges of Wilson coefficients.

Correlations involving $\mathcal{R}(\Lambda_c)$



(a)



(b)

(a) leptoquark S_1
charged Higgs

(b) leptoquark U_1
leptoquark S_2

- In fact, in all scenarios with good p-values the $\mathcal{R}(\Lambda_c)$ has essentially the same value
- Inspecting the formulas for the observables in terms of Wilson coefficients we find a sum-rule:

$$\frac{\mathcal{R}(\Lambda_c)}{\mathcal{R}_{\rm SM}(\Lambda_c)} = 0.262\frac{\mathcal{R}(D)}{\mathcal{R}_{\rm SM}(D)} + 0.738\frac{\mathcal{R}(D^*)}{\mathcal{R}^{\rm SM}(D^*)} + x$$

The remainder x is function of Wilson coefficients C_i^j - stays small $|x| < 0.05$ for C_i^j in their 1σ ranges.
For the current data:

$$\begin{aligned}\mathcal{R}(\Lambda_c) &= \mathcal{R}(\Lambda_c)_{\mathsf{SM}}(1.24 \pm 0.06)\\ &= 0.41 \pm 0.02_{\mathsf{exp}} \pm 0.03_{\mathsf{th}}\end{aligned}$$

in any model of NP.

- $\mathcal{R}(\Lambda_c)$ is an important 'redundant' observable whose measurement could (in)validate the $b \to c\tau\nu$ anomalies.

- All possible new physics in all possible observables of $b \to c\tau\nu$ decays can be parametrized in terms of four complex coefficients C_V^L, C_S^R, C_S^L, C_T.
- Charged-Higgs scenario (with non-zero $C_S^{L,R}$) not ruled out yet.
- Scalar leptoquark S_1 and vector LQ U_1 provide good fits.
- Measurements of polarization observables could differentiate between scenarios.
- $\mathcal{R}(\Lambda_c)$ is an important crosscheck of the consistency of the measurements

Objectives of C3b

- Find dynamics of new physics behind the flavour anomalies
- Link flavour anomalies to other puzzles like:
  - electroweak symmetry breaking ($\rightarrow$ Higgs sector)
  - origin of gauge sector ($\rightarrow$ gauge unification)
  - gauge hierarchy problem ($\rightarrow$ supersymmetry)
- Correlate precision observables in models of new physics aiming at predictions for LHCb, Belle II and other experiments