Highlights from flavour physics

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Physics beyond the Standard Model?

Many good motivations for BSM physics

- origin of EW symmetry breaking & naturalness
- origin of flavour (hierarchies)
- dark matter & dark energy
- baryon asymmetry of the universe
- ...

... but no discovery yet!

- LHC searches in impressive agreement with SM prediction

Are we following the wrong guiding principles?

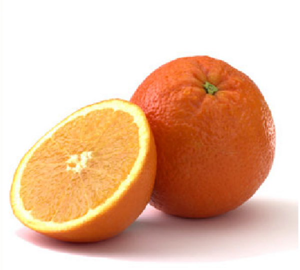
A vast variety of new physics models

Many new physics models on the market. . .

. . . but which is the correct one?

A vast variety of new physics models

Maybe LHC will still 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 in the Standard Model (SM)

Flavour and CP violation in SM described by CKM matrix

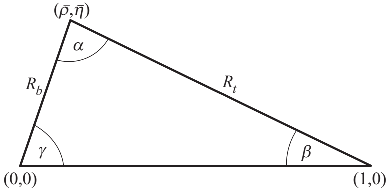
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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

➢ **Unitarity triangle**

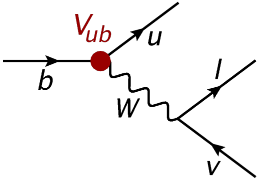
$$R_b = \left| \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right|$$

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



Precision determination of CKM elements

Tree level decays: flavour changing charged current interactions



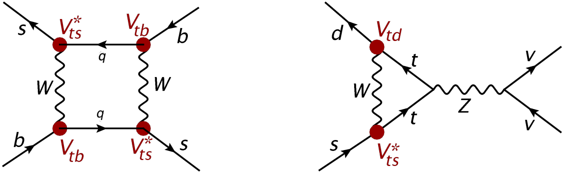
- direct sensitivity to relevant CKM element
- small impact of new physics contributions

➢ model-independent determination of CKM matrix as a **standard candle** of the SM

Flavour changing neutral current processes

strongly suppressed in the SM ➢ **high sensitivity to BSM contributions**

- loop factor
- CKM hierarchy
- chiral structure
- GIM mechanism (CKM unitarity)



CKM hierarchy predicts specific pattern of effects in the SM

$$\underbrace{V_{ts}^* V_{td}}_{K \text{ system}} \sim 5\cdot 10^{-4} \ll \underbrace{V_{tb}^* V_{td}}_{B_d \text{ system}} \sim 10^{-2} < \underbrace{V_{tb}^* V_{ts}}_{B_s \text{ system}} \sim 4\cdot 10^{-2}$$

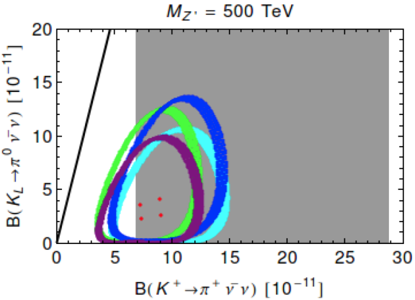
➢ K decays in general most sensitive to BSM physics

A glimpse at the zeptouniverse

Tree level flavour changing Z':

BURAS ET AL. (2014)

- $K \to \pi\nu\bar{\nu}$ decays sensitive to scales up to 2000 TeV if left- and right-handed FV couplings are present
- (fine-tuned) cancellation of effects in $K^0 - \bar{K}^0$ mixing required
- new physics reach of B decays lower by an order of magnitude (~ 100 TeV!)



New Physics – but what next?

Discovering a trace of NP in flavour observables would be exciting!

However it leaves us in the dark about its origin.

Dechiphering NP in flavour observables

Goal: understand the origin of NP flavour violation

- ➢ measure as many observables as possible
- ➢ identify pattern of correlations

↙ ↘

correlations within given meson system give information on BSM operator structure
(chirality, vector vs. scalar etc.)

correlations between different meson systems allow to draw conclusions on underlying flavour symmetry
(MFV, NMFV, $U(2)^3$ etc.)

Recent anomalies in the flavour sector

- tension in CP violation in $K \to \pi\pi$ decays
- 4.1σ anomaly in semi-tauonic B decays
- various *consistent* $2-3\sigma$ deviations in $b \to s\mu^+\mu^-$ transitions

Direct CP violation in $K \to \pi\pi$ decays

anomalous CP breaking

ε'/ε in the SM

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

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

- 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 (2015,2016)

- new lattice results coming soon

NLO: $(1.9 \pm 4.5) \cdot 10^{-4}$ BGJJ'15 $(1.1 \pm 5.1) \cdot 10^{-4}$ KNT'16

NNLO: coming soon! Cerdà-Sevilla, Gorbahn, Jäger, Kokulu (2016)

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

Message from a wise man

ε'/ε **anomaly is the largest anomaly in flavour physics !**

(A.J. Buras)

ε'/ε beyond the SM

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

- in the Littlest Higgs model with T-parity (LHT)

  MB, Buras, Recksiegel (2015)

- in simplified models with flavour changing Z or Z' couplings

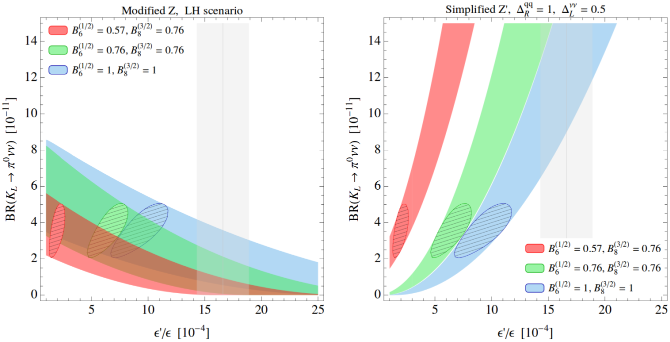
  Buras, Buttazzo, Knegjens (2015)
  Ende, Kitahara, Mishima, Yamamoto (2016)

- in 331 models — Buras, de Fazio (2015), (2016)
- in supersymmetry — Tanimoto, Yamamoto (2016)
  Kitahara, Nierste, Tremper (2016)
  D'Ambrosio et al. (2017)

- in vector-like quark (VLQ) models — Bobeth, Buras, Celis, Jung (2016)
- model-independently — Buras (2016)

ε'/ε and $K \to \pi\nu\bar{\nu}$ in simplified Z and Z' models

Buras, Buttazzo, Knegjens (2015)



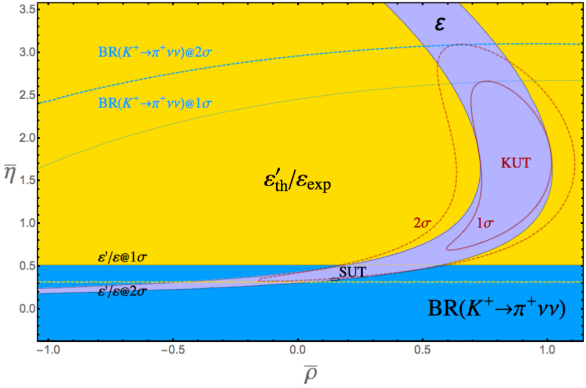
- tension in ε'/ε can be removed
- large effect in $K_L \to \pi^0\nu\bar{\nu}$ – suppressed or enhanced, depending on NP coupling structure

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

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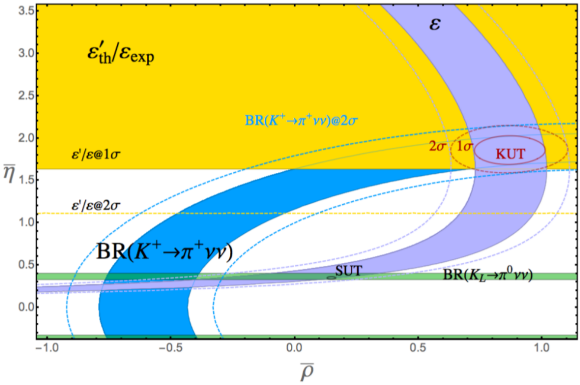


KUT 2025?

Quo vadis kaon physics?

Understanding the ε'/ε anomaly

- establish tension by more precise calculations of relevant hadronic matrix elements, and independent confirmation
- measurements of $K_L \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$ branching ratios
- improved SM predictions by more precise CKM determinations ($|V_{cb}|$, also γ)
- lattice determination of long-distance contributions to $K^+ \to \pi^+ \nu\bar{\nu}$ and ΔM_K

➢ pattern of observed deviations from SM will give a clear picture of the NP scenario at work

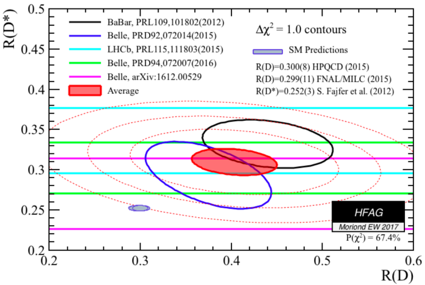
The $b \to c\tau\nu$ anomaly

anomalous trees

Semi-tauonic decays $B \to D^{(*)}\tau\nu$

Test of lepton flavour universality (LFU) in semi-leptonic B decays

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



- theoretically clean, as hadronic uncertainties largely cancel in ratio
- measurements by BaBar, Belle, and LHCb ($R(D^*)$ only)
- 3.9σ tension between HFAG fit and SM value
- supported by recent $R_{J/\psi}$ measurement (LHCb)

Note: anomaly mainly driven by leptonic τ decays

Effective theory for $b \to c\tau\nu$

Model-independent description by effective four-fermion operators

$$\mathcal{L}_{\text{eff}}^{b\to c\tau\nu} = -\frac{4G_F}{\sqrt{2}} V_{cb} \sum_j C_j \mathcal{O}_j$$

$$\mathcal{O}_{V_{L,R}} = (\bar{c}\gamma^\mu P_{L,R} b)(\bar{\tau}\gamma_\mu P_L \nu)$$
$$\mathcal{O}_{S_{L,R}} = (\bar{c} P_{L,R} b)(\bar{\tau} P_L \nu)$$
$$\mathcal{O}_T = (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu)$$

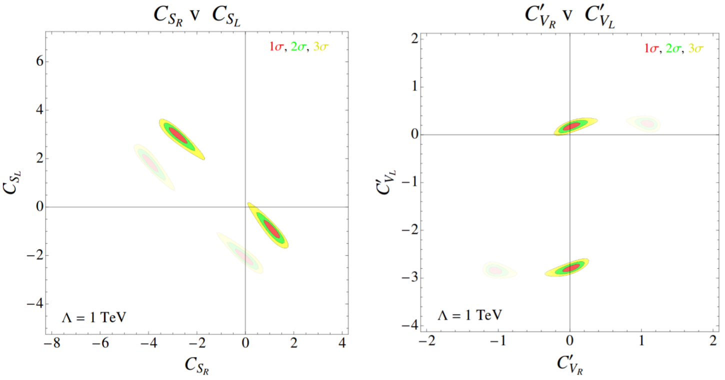
SM: tree-level $W^\pm$ exchange ➢ $C_{V_L} = 1$, $C_{j\neq V_L} = 0$

BSM scenarios:

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

Global fit of Wilson coefficients

Freytsis, Ligeti, Ruderman (2015)
see also Bardhan, Byakti, Ghosh (2016)



➢ **good fit for $\delta C_{S_R} \simeq -\delta C_{S_L} \neq 0$ or $\delta C_{V_L} \neq 0$**
but rather large NP contribution required

Constraints on NP explanations

Scalar models ($\delta C_{S_R} \simeq -\delta C_{S_L} \neq 0$)

- large $B_c \to \tau\nu$ decay rate, in tension with B_c lifetime

  Alonso, Grinstein, Camalich (2016)

- issues with differential q^2 distribution in $B \to D\tau\nu$

  Celis, Jung, Li, Pich (2016)

Vector models ($\delta C_{V_L} \neq 0$)

- tension with $\tau \to \mu\nu\bar{\nu}$ and $Z \to \ell\bar{\ell}$ Feruglio, Paradisi, Pattori (2016)

Generally: **watch out for $SU(2)_L$ symmetry**

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

  Faroughy, Greljo, Kamenik (2016)

- large impact on $B_s \to \tau^+\tau^-$, $B \to K\tau^+\tau^-$, $B \to K^{(*)}\nu\bar{\nu}$ etc.

  Crivellin, Müller, Ota (2017)

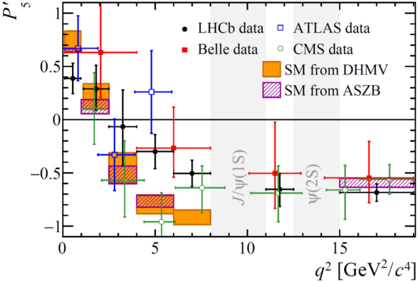
- contributions to $\Upsilon \to \tau^+\tau^-$ and $\psi \to \tau^+\tau^-$ Aloni et al. (2017)

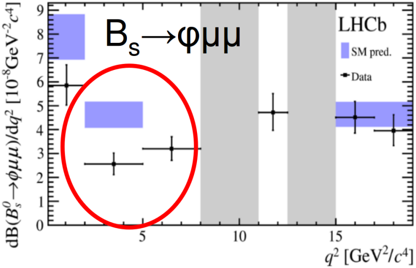
➢ **NP resolution of $R(D^{(*)})$ anomaly challenging**

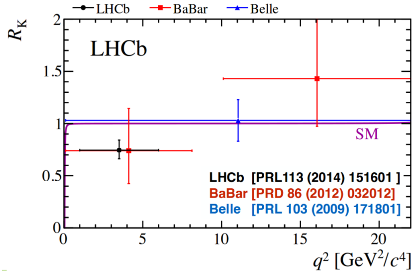
Semileptonic $b \to s$ transitions

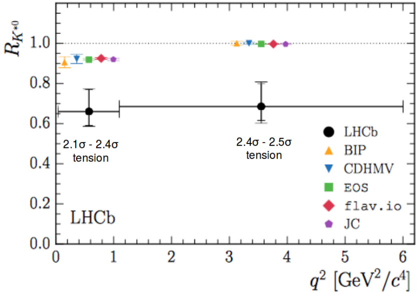
anomalous penguins

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

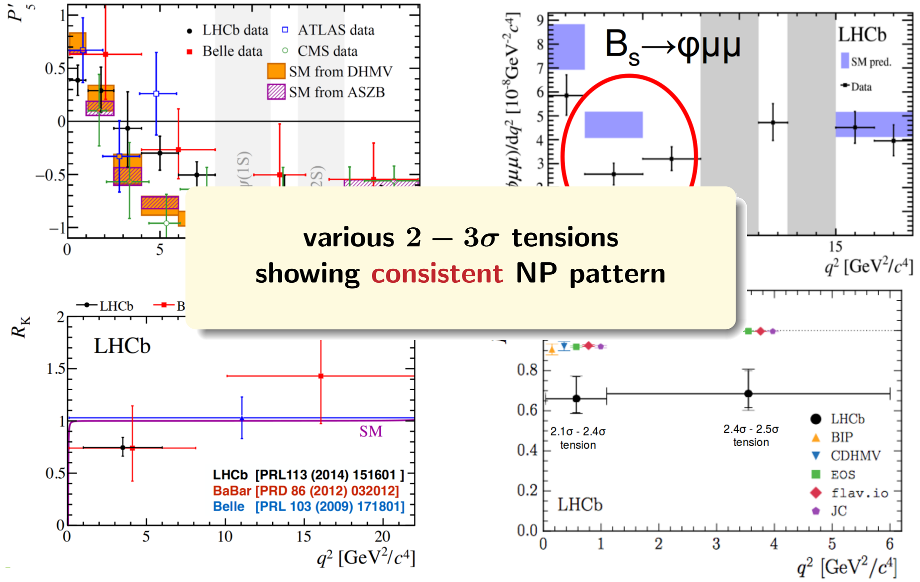








The $b \to s\mu^+\mu^-$ transitions and LFU



various $2-3\sigma$ tensions
showing consistent NP pattern

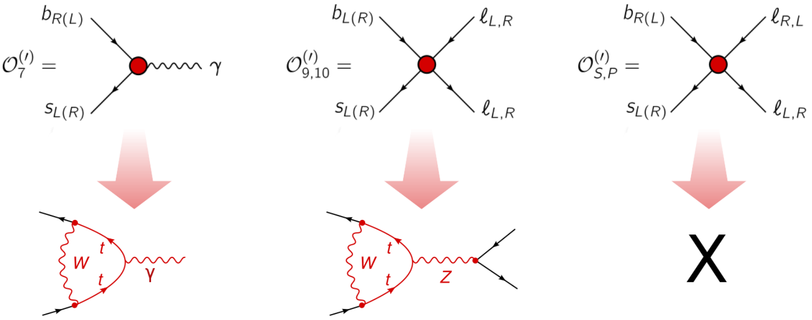
Theoretical description

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

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

where the operators most sensitive to new physics are

SM:



Sensitivity to Wilson coefficients

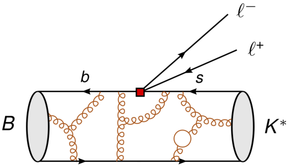
Complementary sensitivity

	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$	$C_{S,P}^{(\prime)}$
$B \to X_s \gamma$	X			
$B \to K^* \gamma$	X			
$B \to X_s \ell^+ \ell^-$	X	X	X	
$B \to K^{(*)} \ell^+ \ell^-$	X	X	X	
$B_s \to \phi \ell^+ \ell^-$	X	X	X	
$B_s \to \mu^+ \mu^-$			X	X

- different observables constrain different operators
- global analysis can be used to resolve ambiguities
- apparent deviation from the SM in one observable can be cross-checked in related modes

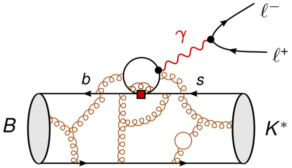
Hadronic uncertainties in $B \to K^{(*)}\mu^+\mu^-$

$B \to K^*$ form factors



- from lattice QCD and light-cone sume rules
- systematic improvements possible

non-factorisable corrections



- "charm loops" at low q^2 and broad $c\bar{c}$ resonances
- dominant uncertainty, no systematic theory description

➢ **construct observables in which these uncertainties cancel**

Clean observables

Optimised observables P_i, P_i' Matias et al. (2012)

- describe angular distribution in $B \to K^* \mu^+ \mu^-$
- designed to be form-factor-free at leading order
- still susceptible to non-factorisable corrections

Lepton flavour universality (LFU) ratios Hiller, Krüger (2003)

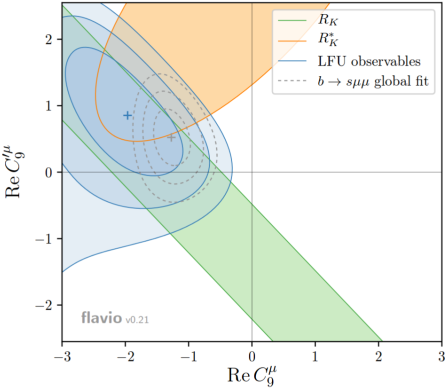
$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)} \mu^+ \mu^-)}{\mathcal{B}(B \to K^{(*)} e^+ e^-)}$$

(and similar for other f. s. mesons)

- theoretically extremely clean

Global analysis

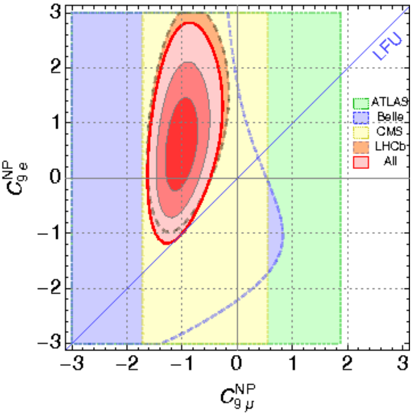
Altmannshofer, Stangl, Straub (2017)
see also Capdevila et al. (2017)



➢ **consistent fit for $C_9^{\mathrm{NP}} \simeq -1$,** non-zero $C_9^{\prime\mathrm{NP}}$, C_{10}^{NP} possible
$\sim 4 - 5\sigma$ deviation from SM

Yet not quite global experimentally

CAPDEVILA ET AL. (2017)
see also ALTMANNSHOFER, STANGL, STRAUB (2017)

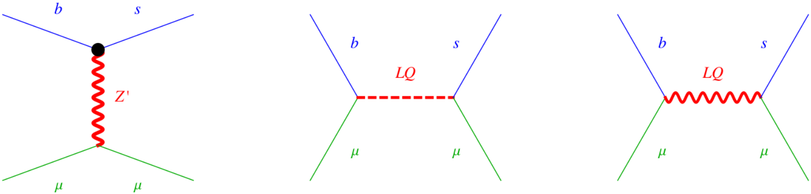


➢ **dominated by LHCb – we need independent cross-check!**

Who ordered that?

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

The usual suspects: Z' and leptoquarks



- tree level NP competing with SM one-loop diagrams
- constraints from $B_s - \bar{B}_s$ mixing can be accomodated
- potential relation to $(g-2)_\mu$ anomaly

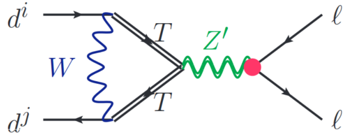
Loop induced NP?

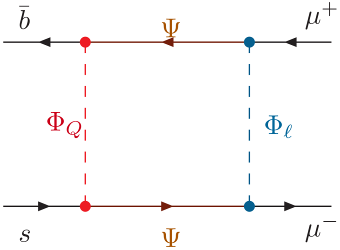
Large C_9^{NP} as model-killer — ALTMANNSHOFER, STRAUB (2013)

- new contributions to Z penguin (e. g. in the MSSM) don't yield required NP pattern – also no LFU violation

Viable setups

- Z' penguin effect — BÉLANGER, DELAUNAY, WESTHOFF (2015); KAMENIK, SOREQ, ZUPAN (2017)
- box contribution — GRIPAIOS, NARDECCHIA, RENNER (2015); ARNAN ET AL. (2016)





A combined resolution of the B decay anomalies?

- several attempts to attribute the B decay anomalies to a *common* NP origin

- $SU(2)$ singlet vector leptoquark appears most promising:
  - evades stringent constraints from B_s mixing and $b \to s\nu\bar{\nu}$
  - B_c life-time under control

- such leptoquark is predicted from Pati-Salam gauge group

$$G_{\text{PS}} = SU(4) \times SU(2)_L \times SU(2)_R$$

Model building challenges

- generate flavour non-universal LQ couplings
- avoid re-introduction of constraints due to additional particles present in UV-complete model

Barbieri, Murphy, Senia (2016)
Di Luzio, Greljo, Nardecchia (2017)
Calibbi, Crivellin, Li (2017)

Quo vaditis B decays?

Understanding the B anomalies

- establish experimental measurements
  - ➢ investigation of potentially underestimated systematics
  - ➢ independent cross-checks
  - ➢ study further related observables
- improve theoretical predictions
  - ➢ form factors
  - ➢ non-factorisable corrections
  - ➢ viable New Physics models
- identify deviations also in other LFU and LFV observables
  - ➢ LFV μ and τ decays
  - ➢ tests of LFU: $(g-2)_\mu$, $K \to (\pi)\ell\nu$, τ decays etc.

➢ if anomalies persist, we expect
New Physics in the reach of the LHC

Summary & outlook

1. Currently, flavour physics offers the most intriguing hints for the presence of New Physics!
2. The present anomalies in ε'/ε, semileptonic $b \to s$ transitions and LFU observables require further experimental and theoretical investigation.
3. If eventually confirmed, their New Physics origin can be disentangled by complementary measurements in the flavour sector, but also in high-p_T searches.