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 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 \textit{charged current} interactions

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

\textit{model-independent} determination of CKM matrix as a \textit{standard candle} of the SM
Flavour changing neutral current processes

**strongly suppressed** in the SM $\rightarrow$ **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

$$V_{ts}^* V_{td} \sim 5 \cdot 10^{-4} \ll V_{tb}^* V_{td} \sim 10^{-2} < V_{tb}^* V_{ts} \sim 4 \cdot 10^{-2}$$

**$K$ decays** in general most sensitive to BSM physics
A glimpse at the zeptouniverse

Tree level flavour changing $Z'$:

- $K \rightarrow \pi \nu \bar{\nu}$ 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 ($\sim 100$ 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
- $4.1\sigma$ anomaly in semi-tauonic $B$ decays
- various consistent $2 - 3\sigma$ deviations in $b \to s\mu^+\mu^-$ transitions
Direct CP violation in $K \rightarrow \pi \pi$ decays

anomalous CP breaking
\( \varepsilon' / \varepsilon \) in the SM

Simple phenomenological expression: \( \text{Buras, Gorbahn, Jäger, Jamin (2015)} \)

\[
\Re(\varepsilon' / \varepsilon) \simeq \frac{\Im(V_{ts}^* V_{td})}{1.4 \cdot 10^{-4}} \cdot 10^{-4} \cdot \left( -3.6 + 21.4 B_6^{(1/2)} + 1.2 - 10.4 B_8^{(3/2)} \right)
\]

- large cancellation between \( A_0 \) and \( A_2 \) amplitudes
- hadronic matrix elements from the lattice \( \text{RBC-UKQCD (2015)} \)

\[
B_6^{(1/2)} = 0.57 \pm 0.19 \quad B_8^{(3/2)} = 0.76 \pm 0.05
\]

consistent with large \( N_c \) bound \( B_6^{(1/2)} < B_8^{(3/2)} < 1 \)

- new lattice results coming soon \( \text{Buras, Gérard (2015,2016)} \)

NLO: \( (1.9 \pm 4.5) \cdot 10^{-4} \) \( \text{BGJJ’15} \)

NNLO: coming soon! \( \text{Cerdà-Sevilla, Gorbahn, Jäger, Kokulu (2016)} \)

\( 2.9 \sigma \) tension with the data! (a bit less with lattice value for \( \Re A_0 \))
Message from a wise man

\[ \varepsilon' / \varepsilon \text{ anomaly is the largest anomaly in flavour physics!} \]

(A.J. Buras)
New physics can induce large deviations from SM in $\varepsilon'/\varepsilon$

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

- in simplified models with flavour changing $Z$ or $Z'$ couplings
  Buras, Buttazzo, Knegjens (2015)
  Ende, Kitahara, Mishima, Yamamoto (2016)

- in 331 models

- 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)
\( \varepsilon'/\varepsilon \) and \( K \to \pi \nu \bar{\nu} \) in simplified \( Z \) and \( Z' \) models

- Tension in \( \varepsilon'/\varepsilon \) can be removed.
- Large effect in \( K_L \to \pi^0 \nu \bar{\nu} \) – suppressed or enhanced, depending on NP coupling structure.

Buras, Buttazzo, Knegjens (2015)
The $K$-Unitarity Triangle


Unitarity Triangle from kaon decay observables

KUT 2015
The $K$-Unitarity Triangle

Lehner, Lunghi, Soni (2015)


Unitarity Triangle from kaon decay observables

KUT 2025?
Quo vadis kaon physics?

Understanding the $\varepsilon'/\varepsilon$ anomaly

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

pattern of observed deviations from SM will give a clear picture of the NP scenario at work
The $b \rightarrow c \tau \nu$ anomaly

anomalous trees
Semi-tauonic decays $B \rightarrow D(\ast)\tau\nu$

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

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

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

**Note:** anomaly mainly driven by leptonic $\tau$ decays
Effective theory for $b \rightarrow c \tau \nu$

Model-independent description by effective four-fermion operators

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

$$\mathcal{O}_{V_{L,R}} = (\bar{c}\gamma^\mu P_{L,R} b)(\bar{\tau}\gamma^\mu P_{L\nu})$$

$$\mathcal{O}_{S_{L,R}} = (\bar{c}P_{L,R} b)(\bar{\tau} P_{L\nu})$$

$$\mathcal{O}_T = (\bar{c}\sigma^{\mu\nu} P_{L} b)(\bar{\tau}\sigma_{\mu\nu} P_{L\nu})$$

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

**BSM scenarios:**

- charged Higgs contributions $\Rightarrow \delta C_{S_{L,R}} \neq 0$
- new charged vector boson $W'$ $\Rightarrow \delta C_{V_{L,R}} \neq 0$
- (scalar or vector) leptoquark $\Rightarrow \delta C_{j} \neq 0$ (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** $(\delta C_{SR} \simeq -\delta C_{SL} \neq 0)$
- large $B_c \to \tau \nu$ decay rate, in tension with $B_c$ lifetime
  \textit{Alonso, Grinstein, Camalich (2016)}
- issues with differential $q^2$ distribution in $B \to D\tau\nu$
  \textit{Celis, Jung, Li, Pich (2016)}

**Vector models** $(\delta C_{VL} \neq 0)$
- tension with $\tau \to \mu\nu\bar{\nu}$ and $Z \to \ell\bar{\ell}$
  \textit{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
  \textit{Faroughy, Greljo, Kamenik (2016)}
- large impact on $B_s \to \tau^+\tau^-, B \to K\tau^+\tau^-, B \to K(\ast)\nu\bar{\nu}$ etc.
  \textit{Crivellin, Müller, Ota (2017)}
- contributions to $\Upsilon \to \tau^+\tau^-$ and $\psi \to \tau^+\tau^-$
  \textit{Aloni et al. (2017)}

$\Rightarrow$ NP resolution of $R(D(\ast))$ anomaly challenging
Semileptonic $b \rightarrow s$ transitions

anomalous penguins
The $b \rightarrow s\mu^+\mu^-$ transitions and LFU

Highlights from flavour physics
The $b \rightarrow s\mu^+\mu^-$ transitions and LFU

Various $2 - 3\sigma$ tensions showing consistent NP pattern
Theoretical description

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

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

where the operators most sensitive to new physics are

$O_{7}^{(i)}$  

$O_{9,10}^{(i)}$  

$O_{S,P}^{(i)}$

SM:
### Sensitivity to Wilson coefficients

#### Complementary sensitivity

<table>
<thead>
<tr>
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<th>$C_7^{(')}$</th>
<th>$C_9^{(')}$</th>
<th>$C_{10}^{(')}$</th>
<th>$C_{S,P}^{(')}$</th>
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<td>$B \to X_s \gamma$</td>
<td>X</td>
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<tr>
<td>$B \to K^* \gamma$</td>
<td>X</td>
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<tr>
<td>$B \to X_s \ell^+ \ell^-$</td>
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<td>$B \to K^{(*)} \ell^+ \ell^-$</td>
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<tr>
<td>$B_s \to \phi \ell^+ \ell^-$</td>
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<tr>
<td>$B_s \to \mu^+ \mu^-$</td>
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<td>X</td>
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- 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 $B \rightarrow K^{(*)} \mu^+ \mu^-$

$B \rightarrow K^*$ 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 $P_i, P'_i$
- 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

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

(and similar for other f.s. mesons)
- theoretically extremely clean

Matias et al. (2012)
consistent fit for $C_9^{\text{NP}} \approx -1$, non-zero $C_9^{\text{NP}}$, $C_{10}^{\text{NP}}$ 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 accommodated
- potential relation to $(g - 2)_\mu$ anomaly
Loop induced NP?

Large $C_9^{NP}$ as model-killer

- 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
- box contribution

Altmannshofer, Straub (2013)

$Z'$ penguin effect

Bélanger, Delaunay, Westhoff (2015)
Kamenik, Soreq, Zupan (2017)

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 $b \rightarrow s \nu \bar{\nu}$
  - $B_c$ life-time under control

- such leptoquark is predicted from Pati-Salam gauge group
  \[ G_{PS} = SU(4) \times SU(2)_L \times SU(2)_R \]

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 $\mu$ and $\tau$ decays
  - tests of LFU: $(g-2)_\mu$, $K \to (\pi)\ell\nu$, $\tau$ decays etc.

if anomalies persist, we expect New Physics in the reach of the LHC
Currently, flavour physics offers the most intriguing hints for the presence of New Physics!

The present anomalies in $\varepsilon'/\varepsilon$, semileptonic $b \to s$ transitions and LFU observables require further experimental and theoretical investigation.

If eventually confirmed, their New Physics origin can be disentangled by complementary measurements in the flavour sector, but also in high-$p_T$ searches.