Rare B decays and search for new physics

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Uppsala – 29 August 2019
Råshult, June 2007
**Why flavour physics?**

**CP violation:**

The only CP violating parameter in the SM is the CKM phase. However, we know from baryogenesis that new sources of CP violation are needed.

**The Standard Model flavour puzzle:**

Why are the flavour parameters small and hierarchical?

**The New Physics flavour puzzle:**

If there is NP at the TeV scale, why are flavour changing neutral current (FCNC) so small? If NP has a generic flavour structure, it should contribute to FCNC processes.

**Flavour physics is sensitive to new physics at \( \Lambda_{NP} \gg E_{\text{experiments}} \)**

Flavour physics can discover new physics or probe it before it is directly observed in experiments:

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$\rightarrow$ ideal probs: rare $B$ decays
→ Interesting interplay between flavour, collider and dark matter searches
Prime example: \( B_s \rightarrow \mu^+\mu^- \), \( A/H \rightarrow \tau^+\tau^- \) and direct dark matter detection
(not covered in this talk)

→ Indirect hints for new physics: Flavour “anomalies”

Deviations from the Standard Model predictions in \( b \rightarrow s\ell\ell \) transitions

Focus of the talk, since there are so few these days and they are still among our best bets!

- Model independent implications
- Model dependent implications
Outline

- Introduction
  - Theoretical framework

- Observables
  - Definitions
  - Recent anomalies

- Theoretical uncertainties
  - Hadronic effects
  - Statistical comparison of NP vs hadronic effects

- NP global fits
  - Model independent implications

- Specific NP models

- Future prospects to understand the source of anomalies

- Conclusions
Effective field theory

\[ \mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left( \sum_{i=1\ldots10,S,P} \left( C_i(\mu)O_i(\mu) + C'_i(\mu)O'_i(\mu) \right) \right) \]

Separation between short distance (Wilson coefficients) and long distance (local operators) effects

**Operator set for** \( b \rightarrow s \) **transitions:**

- **4-quark operators**
  \[ O_{1,2} \propto (\bar{s}\Gamma^\mu c)(\bar{c}\Gamma^\mu b) \]
  \[ O_{3,4} \propto (\bar{s}\Gamma^\mu b)\sum_q(\bar{q}\Gamma^\mu q) \]

- **Chromomagnetic dipole operator**
  \[ O_8 \propto (\bar{s}\sigma^{\mu\nu} T^a P_R) G^{a}_{\mu\nu} \]

- **Electromagnetic dipole operator**
  \[ O_7 \propto (\bar{s}\sigma^{\mu\nu} P_R) F^{a}_{\mu\nu} \]

- **Semileptonic operators**
  \[ O_9 \propto (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\gamma_5 \ell) \]
  \[ O'_{10} \propto (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \gamma_5 \ell) \]

+ the chirality flipped counter-parts of the above operators, \( O'_i \)
Wilson coefficients

The Wilson coefficients are calculated perturbatively up to NNLO

**Two main steps:**

- matching between the effective and full theories $\rightarrow$ extraction of the $C_{i}^{\text{eff}}(\mu)$ at scale $\mu \sim M_W$

$$C_{i}^{\text{eff}}(\mu) = C_{i}^{(0)\text{eff}}(\mu) + \frac{\alpha_s(\mu)}{4\pi} C_{i}^{(1)\text{eff}}(\mu) + \cdots$$

- Evolving the $C_{i}^{\text{eff}}(\mu)$ to the scale relevant for $B$ decays, $\mu \sim m_b$ using the RGE runnings.

The Wilson coefficients are process independent.

**In the SM:**

$$C_7 \sim -0.3 \quad C_9 \sim 4 \quad C_{10} \sim -4$$
The Wilson coefficients are calculated perturbatively up to NNLO

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In the SM:

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C_7 \sim -0.3 \quad C_9 \sim 4 \quad C_{10} \sim -4
\]
**Hadronic quantities**

To compute the amplitudes:

\[
A(A \rightarrow B) = \langle B | H_{\text{eff}} | A \rangle = \frac{G_F}{\sqrt{2}} \sum_i \lambda_i C_i(\mu) \langle B | O_i | A \rangle(\mu)
\]

\[\langle B | O_i | A \rangle: \text{ hadronic matrix element}\]

**How to compute matrix elements?**

→ Model building, Lattice simulations, Light flavour symmetries, Heavy flavour symmetries, ...

→ Describe hadronic matrix elements in terms of **hadronic quantities**

**Two types of hadronic quantities:**

- **Decay constants**: Probability amplitude of hadronising quark pair into a given hadron
- **Form factors**: Transition from a meson to another through flavour change

Once the Wilson coefficients and hadronic quantities calculated, the physical observables (branching fractions,...) can be calculated.
Observables and Anomalies
\(b \rightarrow s\ell^+\ell^-\) transitions: \(B \rightarrow K^* \mu^+\mu^-\)

**Angular distributions**

The full angular distribution of the decay \(\bar{B}^0 \rightarrow \bar{K}^{*0}\ell^+\ell^-\) \((\bar{K}^{*0} \rightarrow K^-\pi^+)\) is completely described by four independent kinematic variables: \(q^2\) (dilepton invariant mass squared), \(\theta_\ell, \theta_{K^*}, \phi\)

**Differential decay distribution:**

\[
\frac{d^4\Gamma}{dq^2 \, d\cos\theta_\ell \, d\cos\theta_{K^*} \, d\phi} = \frac{9}{32\pi} J(q^2, \theta_\ell, \theta_{K^*}, \phi)
\]

\(J(q^2, \theta_\ell, \theta_{K^*}, \phi) = \sum_i J_i(q^2) \, f_i(\theta_\ell, \theta_{K^*}, \phi)\)

↘ angular coefficients \(J_1-9\)

↘ functions of the spin amplitudes \(A_0, A_\parallel, A_\perp, A_t, \text{ and } A_S\)

Spin amplitudes: functions of Wilson coefficients and form factors

**Main operators:**

\(O_9 = \frac{e^2}{(4\pi)^2} (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\ell), \quad O_{10} = \frac{e^2}{(4\pi)^2} (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\gamma_5\ell)\)

\(O_S = \frac{e^2}{16\pi^2} (\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\ell), \quad O_P = \frac{e^2}{16\pi^2} (\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\gamma_5\ell)\)
Angular distributions

The full angular distribution of the decay $B^0 \rightarrow \bar{K}^{*0} \ell^+ \ell^-$ ($\bar{K}^{*0} \rightarrow K^- \pi^+$) is completely described by four independent kinematic variables: $q^2$ (dilepton invariant mass squared), $\theta_\ell$, $\theta_{K^*}$, $\phi$

Differential decay distribution:

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$$J(q^2, \theta_\ell, \theta_{K^*}, \phi) = \sum_i J_i(q^2) f_i(\theta_\ell, \theta_{K^*}, \phi)$$

$\downarrow$ angular coefficients $J_1 - 9$

$\downarrow$ functions of the spin amplitudes $A_0$, $A_\parallel$, $A_\perp$, $A_t$, and $A_S$

Spin amplitudes: functions of Wilson coefficients and form factors

Main operators:

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$$O_S = \frac{e^2}{16\pi^2} (\bar{s}^\alpha L b_R^\alpha)(\bar{\ell} \ell), \quad O_P = \frac{e^2}{16\pi^2} (\bar{s}^\alpha L b_R^\alpha)(\bar{\ell} \gamma_5 \ell)$$
Optimised observables: form factor uncertainties cancel at leading order

$$\langle P_1 \rangle_{\text{bin}} = \frac{1}{2} \int_{\text{bin}} dq^2 [J_3 + \bar{J}_3]$$

$$\langle P_2 \rangle_{\text{bin}} = \frac{1}{8} \int_{\text{bin}} dq^2 [J_{6s} + \bar{J}_{6s}]$$

$$\langle P_4' \rangle_{\text{bin}} = \frac{1}{N'_{\text{bin}}} \int_{\text{bin}} dq^2 [J_4 + \bar{J}_4]$$

$$\langle P_5' \rangle_{\text{bin}} = \frac{1}{2N'_{\text{bin}}} \int_{\text{bin}} dq^2 [J_5 + \bar{J}_5]$$

$$\langle P_6' \rangle_{\text{bin}} = -\frac{1}{2N'_{\text{bin}}} \int_{\text{bin}} dq^2 [J_7 + \bar{J}_7]$$

$$\langle P_8' \rangle_{\text{bin}} = -\frac{1}{N'_{\text{bin}}} \int_{\text{bin}} dq^2 [J_8 + \bar{J}_8]$$

with

$$N'_{\text{bin}} = \sqrt{-\int_{\text{bin}} dq^2 [J_{2s} + \bar{J}_{2s}] \int_{\text{bin}} dq^2 [J_{2c} + \bar{J}_{2c}]}$$

+ CP violating clean observables and other combinations

J. Matias et al., JHEP 1204 (2012) 104
S. Descotes-Genon et al., JHEP 1305 (2013) 137

Or alternatively:

$$S_i = \frac{J_i(s,c) + \bar{J}_i(s,c)}{\frac{d\Gamma}{dq^2} + \frac{d\Gamma}{dq^2}}$$

$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_L(1 - F_L)}}$$
A consistent deviation pattern with the SM predictions in $b \rightarrow s$ measurements with muons in the final state:

- deviations with the SM predictions between 1 and 3.5 $\sigma$
- general trend: EXP $<$ SM in low $q^2$
- ... but the branching ratios have very large theory uncertainties!
LHCb recent anomalies

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- ... but the branching ratios have very large theory uncertainties!
The LHCb anomalies (1)

\( B \rightarrow K^* \mu^+ \mu^- \) angular observables, in particular \( P'_5 / S_5 \)

- 2013 (1 fb\(^{-1}\)): disagreement with the SM for \( P_2 \) and \( P'_5 \) \((\text{PRL 111, 191801 (2013)})\)
- March 2015 (3 fb\(^{-1}\)): confirmation of the deviations \((\text{LHCb-CONF-2015-002})\)
- Dec. 2015: 2 analysis methods, both show the deviations \((\text{JHEP 1602, 104 (2016)})\)

3.7\(\sigma\) deviation in the 3rd bin
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![Graphs showing deviations in angular observables](image-url)

- 3.7σ deviation in the 3rd bin
- 2.9σ in the 4th and 5th bins (3.7σ combined)

Belle supports LHCb \((arXiv:1604.04042)\)

tension at 2.1σ

3.4σ combined fit (likelihood)
The LHCb anomalies (1)

Current picture

The deviations are still there!
Difficulty to think of statistical fluctuations...

LHCb, JHEP 02 (2016) 104; Belle, PRL 118 (2017); ATLAS, ATLAS-CONF-2017-023; CMS, CMS-PAS-BPH-15-008
The LHCb anomalies (2)

$B_s \rightarrow \phi \mu^+ \mu^-$ branching fraction

- Same theoretical description as $B \rightarrow K^* \mu^+ \mu^-$
  - Replacement of $B \rightarrow K^*$ form factors with the $B_s \rightarrow \phi$ ones
  - Also consider the $B_s - \bar{B}_s$ oscillations

- June 2015 (3 fb$^{-1}$): the differential branching fraction is found to be $3.2\sigma$ below the SM predictions in the [1-6] GeV$^2$ bin
The LHCb anomalies (3)

Lepton flavour universality in $B^+ \to K^+ \ell^+ \ell^-$

- Theoretical description similar to $B \to K^* \mu^+ \mu^-$, but different since $K$ is scalar
- June 2014 (3 fb$^{-1}$): measurement of $R_K$ in the [1-6] GeV$^2$ bin

$$R_K = BR(B^+ \to K^+ \mu^+ \mu^-)/BR(B^+ \to K^+ e^+ e^-)$$

$$R_K^{SM} = 1.0006 \pm 0.0004$$

2.6$\sigma$ tension in [1-6] GeV$^2$ bin

$R_K^{exp} = 0.745^{+0.090}_{-0.074}$(stat) $\pm 0.036$(syst)

PRL 113, 151601 (2014)

BaBar, PRD 86 (2012) 032012; Belle, PRL 103 (2009) 171801
Recent results

\[ R_K = \frac{BR(B^+ \rightarrow K^+ \mu^+ \mu^-)}{BR(B^+ \rightarrow K^+ e^+ e^-)} \]

Run 1 \((PRL \ 113, \ 151601 \ (2014))\):
\[ R_K([1.1, 6.0] \text{ GeV}^2) = 0.717^{+0.083+0.017}_{-0.071-0.016} \]

Run 2 \((arXiv:1903.09252)\):
\[ R_K([1.1, 6.0] \text{ GeV}^2) = 0.928^{+0.089+0.020}_{-0.076-0.017} \]

Combined result \((arXiv:1903.09252)\):
\[ R_K([1.1, 6.0] \text{ GeV}^2) = 0.846^{+0.060+0.016}_{-0.054-0.014} \]

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The LHCb anomalies (4)

Lepton flavour universality in $B \rightarrow K^* \ell^+ \ell^-$

- LHCb measurement (April 2017):
  
  \[ R_{K^*} = \frac{BR(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{BR(B^0 \rightarrow K^{*0} e^+ e^-)} \]

- Two $q^2$ regions: [0.045-1.1] and [1.1-6.0] GeV$^2$

\[ R_{K^*}^{\text{exp,bin1}} = 0.660^{+0.110}_{-0.070} \text{(stat)} \pm 0.024 \text{(syst)} \]
\[ R_{K^*}^{\text{exp,bin2}} = 0.685^{+0.113}_{-0.069} \text{(stat)} \pm 0.047 \text{(syst)} \]

\[ R_{K^*}^{\text{SM,bin1}} = 0.906 \pm 0.028 \]
\[ R_{K^*}^{\text{SM,bin2}} = 1.000 \pm 0.010 \]

2.2-2.5$\sigma$ tension with the SM predictions in each bin

BaBar, PRD 86 (2012) 032012; Belle, PRL 103 (2009) 171801
**Transversity amplitudes**

Effective Hamiltonian for $b \rightarrow s\ell\ell$ transitions

\[ \mathcal{H}_{\text{eff}} = \mathcal{H}_{\text{eff}}^{\text{had}} + \mathcal{H}_{\text{eff}}^{\text{sl}} \]

\[ \mathcal{H}_{\text{eff}}^{\text{sl}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[ \sum_{i=7,9,10} C_i^{(t)} O_i^{(t)} \right] \]

\[ \langle \bar{K}^* | \mathcal{H}_{\text{eff}}^{\text{sl}} | \bar{B} \rangle: \ B \rightarrow K^* \ \text{form factors} \ V, A_{0,1,2}, T_{1,2,3} \]

Transversity amplitudes:

\[ A_{\perp}^{L,R} \approx N_{\perp} \left\{ (C_9^+ + C_{10}^+) \frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2} C_7^+ T_1(q^2) \right\} \]

\[ A_{\parallel}^{L,R} \approx N_{\parallel} \left\{ (C_9^- + C_{10}^-) \frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2} C_7^- T_2(q^2) \right\} \]

\[ A_{0}^{L,R} \approx N_0 \left\{ (C_9^- + C_{10}^-) \left[ (\ldots) A_1(q^2) + (\ldots) A_2(q^2) \right] \right. \]

\[ \left. + \frac{2m_b}{q^2} C_7^- \left[ (\ldots) T_2(q^2) + (\ldots) T_3(q^2) \right] \right\} \]

\[ A_S = N_S (C_S - C_S') A_0(q^2) \quad (C_i^\pm \equiv C_i \pm C_i') \]
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$$\mathcal{H}_{\text{eff}}^{\text{had}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[ \sum_{i=1...6} C_i O_i + C_8 O_8 \right]$$

$$\mathcal{A}^{(\text{had})}_\lambda = -i \frac{e^2}{q^2} \int d^4 x e^{-i q \cdot x} \langle \ell^+ \ell^- | j_{\mu}^{\text{em,lept}}(x) | 0 \rangle$$

$$\times \int d^4 y e^{i q \cdot y} \langle \bar{K}^*_\lambda | T \{ j_{\mu}^{\text{em,had},\mu}(y) \mathcal{H}_{\text{eff}}^{\text{had}}(0) \} | \bar{B} \rangle$$

$$\equiv e^2 q^2 \epsilon_\mu L^\mu_V \left[ \text{LO in } \mathcal{O} \left( \frac{\Lambda}{m_b}, \frac{\Lambda}{E_{K^*}} \right) + \mathcal{O}(q^2) \right]$$

Non-Fact., QCDf

$$h_\lambda(q^2)$$

power corrections

Beneke et al.; 106067; 0412400
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$$\equiv \frac{e^2}{q^2} \epsilon_\mu L^\mu_V \left[ \text{LO in } \mathcal{O} \left( \frac{\Lambda}{m_b}, \frac{\Lambda}{E_{K^*}} \right) + h_\lambda(q^2) \right]$$

\[\text{Non-Fact., QCDf} \]

\[\text{\textup{\rightarrow unknown}} \quad \text{partial calculation: Khodjamirian et al., ...} \]

\[1006.4945 \]

\[\text{Beneke et al.: } 106067; 0412400 \]

\[\text{Nazila Mahmoudi} \quad \text{Uppsala - 29 Aug. 2019} \]
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$$\equiv \frac{e^2}{q^2} \epsilon_\mu L_{\nu}^{\mu} \left[ \text{LO in } \mathcal{O}(\frac{\Lambda}{m_b}, \frac{\Lambda}{E_{K^*}}) + \text{power corrections} \right]$$

The significance of the anomalies depends on the assumptions made for the unknown power corrections!

This does not affect $R_K$ and $R_{K^*}$
Hadronic effects

Description also possible in terms of helicity amplitudes:

\[ H_V(\lambda) = -i \, N' \left\{ C_9 \tilde{V}_{L\lambda}(q^2) + C'_9 \tilde{V}_{R\lambda}(q^2) + \frac{m_B^2}{q^2} \left[ \frac{2 \hat{m}_b}{m_B} (C_7 \tilde{T}_{L\lambda}(q^2) + C'_7 \tilde{T}_{R\lambda}(q^2)) - 16\pi^2 N_{\lambda}(q^2) \right] \right\} \]

\[ H_A(\lambda) = -i \, N'(C_{10} \tilde{V}_{L\lambda}(q^2) + C'_{10} \tilde{V}_{R\lambda}(q^2)), \]

\[ N_{\lambda}(q^2) = \text{leading nonfact.} + h_{\lambda} \]

\[ H_S = i \, N' \frac{\hat{m}_b}{m_W} (C_S - C'_S) \tilde{S}(q^2) \]

Helicity FFs \( \tilde{V}_{L/R}, \tilde{T}_{L/R}, \tilde{S} \) are combinations of the standard FFs \( V, A_{0,1,2}, T_{1,2,3} \)

A possible parametrisation of the non-factorisable power corrections \( h_{\lambda(=+,-,0)}(q^2) \):

\[ h_{\lambda}(q^2) = h^{(0)}_{\lambda} + \frac{q^2}{1\text{GeV}^2} h^{(1)}_{\lambda} + \frac{q^4}{1\text{GeV}^4} h^{(2)}_{\lambda} \]


M. Ciuchini et al., JHEP 1606 (2016) 116

It seems

\[ h^{(0)}_{\lambda} \rightarrow C_{7}^{NP}, \quad h^{(1)}_{\lambda} \rightarrow C_{9}^{NP} \]

and \( h^{(2)}_{\lambda} \) terms cannot be mimicked by \( C_7 \) and \( C_9 \)

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However, \( \tilde{V}_{L(R)\lambda} \) and \( \tilde{T}_{L(R)\lambda} \) both have a \( q^2 \) dependence!
Description also possible in terms of helicity amplitudes:

\[ H_V(\lambda) = -i N' \left\{ C_9 \tilde{V}_{L\lambda}(q^2) + C'_9 \tilde{V}_{R\lambda}(q^2) + \frac{m_B^2}{q^2} \left[ \frac{2 \hat{m}_b}{m_b} (C_7 \tilde{T}_{L\lambda}(q^2) + C'_7 \tilde{T}_{R\lambda}(q^2)) - 16\pi^2 N_{\lambda}(q^2) \right] \right\} \]

\[ H_A(\lambda) = -i N'(C_{10} \tilde{V}_{L\lambda}(q^2) + C'_{10} \tilde{V}_{R\lambda}(q^2)), \quad N_{\lambda}(q^2) = \text{leading nonfact.} + h_{\lambda} \]

\[ H_S = i N' \frac{\hat{m}_b}{m_W} (C_S - C'_S) \tilde{S}(q^2) \quad \left( N' = -\frac{4G_F m_B}{\sqrt{2}} \frac{e^2}{16\pi^2} V_{tb} V_{ts}^* \right) \]

Helicity FFs \( \tilde{V}_{L/R} \), \( \tilde{T}_{L/R} \), \( \tilde{S} \) are combinations of the standard FFs \( V, A_{0,1,2}, T_{1,2,3} \).

A possible parametrisation of the non-factorisable power corrections \( h_{\lambda(=+, -, 0)}(q^2) \):

\[ h_{\lambda}(q^2) = h_{\lambda}^{(0)} + \frac{q^2}{1\text{GeV}^2} h_{\lambda}^{(1)} + \frac{q^4}{1\text{GeV}^4} h_{\lambda}^{(2)} \]


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Hadronic effects

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However, \( \tilde{V}_{L(R)\lambda} \) and \( \tilde{T}_{L(R)\lambda} \) both have a \( q^2 \) dependence!
Hadronic effects

\[ V^{-}(q^2) + V^{-}(q^2) + V^{0}(q^2) \]

\[ T^{-}(q^2) + T^{-}(q^2) + T^{0}(q^2) \]

\[ q^4 \text{ terms can rise due to terms which multiply Wilson coefficients} \]

\[ \Rightarrow C_7^{NP} \text{ and } C_9^{NP} \text{ can each cause effects similar to } h_{\lambda}^{(0,1,2)} \]
**Hadronic effects**

**Hadronic power correction effect:**

\[ \delta H_{V}^{\text{p.c.}}(\lambda) = iN' m_B^2 \frac{16\pi^2}{q^2} h_{\lambda}(q^2) = iN' m_B^2 \frac{16\pi^2}{q^2} \left( h_{\lambda}^{(0)} + q^2 h_{\lambda}^{(1)} + q^4 h_{\lambda}^{(2)} \right) \]

**New Physics effect:**

\[ \delta H_{V}^{\text{NP}}(\lambda) = -iN' \tilde{V}_{L}(q^2) C_{9}^{\text{NP}} = iN' m_B^2 \frac{16\pi^2}{q^2} \left( a_{\lambda} C_{9}^{\text{NP}} + q^2 b_{\lambda} C_{9}^{\text{NP}} + q^4 c_{\lambda} C_{9}^{\text{NP}} \right) \]

and similarly for \( C_{7} \)

\[ \Rightarrow \] NP effects can be embedded in the hadronic effects.

We can do a fit for both (hadronic quantities \( h_{+,-,0}^{(0,1,2)} \) (18 parameters) and Wilson coefficients \( C_{i}^{\text{NP}} \) (2 or 4 parameters))

Due to this embedding the two fits can be compared with the Wilk’s test.
Hadronic effects

Hadronic power correction effect:

\[ \delta H_{V}^{\text{P.c.}}(\lambda) = iN' m_B^2 \frac{16\pi^2}{q^2} h_\lambda(q^2) = iN' m_B^2 \frac{16\pi^2}{q^2} \left( h^{(0)}_\lambda + q^2 h^{(1)}_\lambda + q^4 h^{(2)}_\lambda \right) \]

New Physics effect:

\[ \delta H_{V}^{C_{9}^{\text{NP}}}(\lambda) = -iN' \tilde{V}_L(q^2) C_{9}^{\text{NP}} = iN' m_B^2 \frac{16\pi^2}{q^2} \left( a_{\lambda} C_{9}^{\text{NP}} + q^2 b_{\lambda} C_{9}^{\text{NP}} + q^4 c_{\lambda} C_{9}^{\text{NP}} \right) \]

and similarly for \( C_{7} \)

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Due to this embedding the two fits can be compared with the Wilk’s test
Wilk’s test

SM vs 2 parameters and 4 parameters p-values were independently computed through 2D profile likelihood integration, and they give similar results

For low $q^2$ (up to 8 GeV$^2$):

<table>
<thead>
<tr>
<th></th>
<th>$2 (\delta C_9)$</th>
<th>$4 (\delta C_7, \delta C_9)$</th>
<th>$18 (h_{+,-,0}^{0,1,2})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$3.7 \times 10^{-5}$ (4.1σ)</td>
<td>$6.3 \times 10^{-5}$ (4.0σ)</td>
<td>$6.1 \times 10^{-3}$ (2.7σ)</td>
</tr>
<tr>
<td>2</td>
<td>−</td>
<td>0.13 (1.5σ)</td>
<td>0.45 (0.76σ)</td>
</tr>
<tr>
<td>4</td>
<td>−</td>
<td>−</td>
<td>0.61 (0.52σ)</td>
</tr>
</tbody>
</table>

→ Adding $\delta C_9$ improves over the SM hypothesis by 4.1σ
→ Including in addition $\delta C_7$ or hadronic parameters improves the situation only mildly
→ One cannot rule out the hadronic option

**Adding 16 more parameters does not really improve the fits**

The situation is still inconclusive
Estimates of hadronic effects

Various methods for hadronic effects

$$\frac{e^2}{q^2} \epsilon^\mu L^\lambda_V \left[ Y(q^2) \tilde{V}_\lambda + \text{LO in } \mathcal{O}(\frac{\Lambda}{m_b}, \frac{\Lambda}{E_{K^*}}) + h_\lambda(q^2) \right]$$

<table>
<thead>
<tr>
<th></th>
<th>factorisable</th>
<th>non-factorisable</th>
<th>power corrections (soft gluon)</th>
<th>region of calculation</th>
<th>physical region of interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>✔</td>
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<td>✗</td>
<td>$q^2 \lesssim 7 \text{ GeV}^2$</td>
<td>directly</td>
</tr>
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<td>✗</td>
<td>✔</td>
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</tr>
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<td>✔</td>
<td>$q^2 &lt; 0 \text{ GeV}^2$</td>
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Estimates of hadronic effects

Various methods for hadronic effects

\[ \frac{e^2}{q^2} \varepsilon_{\mu} L^\mu_V \left[ Y(q^2) \tilde{V}_\lambda + \text{LO in } \mathcal{O}(\frac{\Lambda}{m_b}, \frac{\Lambda}{E_{K^*}}) + h_\lambda(q^2) \right] \]

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</tr>
</tbody>
</table>
Global fits
Many observables $\rightarrow$ **Global fits** of the latest LHCb data

Relevant $\mathcal{O}$perators:

\[ \mathcal{O}_7, \mathcal{O}_8, \mathcal{O}^{(')}_{9\mu,e}, \mathcal{O}^{(')}_{10\mu,e} \quad \text{and} \quad \mathcal{O}_{S-P} \propto (\bar{s} \mathcal{P}_R b)(\bar{\mu} \mathcal{P}_L \mu) \equiv \mathcal{O}_0 \]

NP manifests itself in the shifts of the individual coefficients with respect to the SM values:

\[ C_i(\mu) = C_i^{SM}(\mu) + \delta C_i \]

$\rightarrow$ Scans over the values of $\delta C_i$

$\rightarrow$ Calculation of flavour observables

$\rightarrow$ Comparison with experimental results

$\rightarrow$ Constraints on the Wilson coefficients $C_i$
Global fits

Theoretical uncertainties and correlations

- Monte Carlo analysis
- variation of the “standard” input parameters: masses, scales, CKM, ...
- decay constants taken from the latest lattice results
- $B \rightarrow K^{(*)}$ and $B_s \rightarrow \phi$ form factors are obtained from the lattice+LCSR combinations (1411.3161, 1503.05534), including all the correlations
- Parameterisation of uncertainties from power corrections:

$$A_k \rightarrow A_k \left(1 + a_k \exp(i\phi_k) + \frac{q^2}{6 \text{ GeV}^2} b_k \exp(i\theta_k)\right)$$

$|a_k|$ between 10 to 60%, $b_k \sim 2.5a_k$
Low recoil: $b_k = 0$

$\Rightarrow$ Computation of a (theory + exp) correlation matrix
Global fits

Global fits of the observables obtained by minimisation of

$$\chi^2 = (\vec{O}^\text{th} - \vec{O}^\text{exp}) \cdot (\Sigma^\text{th} + \Sigma^\text{exp})^{-1} \cdot (\vec{O}^\text{th} - \vec{O}^\text{exp})$$

$$(\Sigma^\text{th} + \Sigma^\text{exp})^{-1}$$ is the inverse covariance matrix.

More than 100 observables relevant for leptonic and semileptonic decays:

- $\text{BR}(B \to X_s \gamma)$
- $\text{BR}(B \to X_d \gamma)$
- $\Delta_0(B \to K^* \gamma)$
- $\text{BR}^\text{low}(B \to X_s \mu^+ \mu^-)$
- $\text{BR}^\text{high}(B \to X_s \mu^+ \mu^-)$
- $\text{BR}^\text{low}(B \to X_s e^+ e^-)$
- $\text{BR}^\text{high}(B \to X_s e^+ e^-)$
- $\text{BR}(B_s \to \mu^+ \mu^-)$
- $\text{BR}(B_d \to \mu^+ \mu^-)$
- $\text{BR}(B \to K^0 \mu^+ \mu^-)$
- $\text{BR}(B \to K^* \mu^+ \mu^-)$
- $\text{BR}(B \to K^+ \mu^+ \mu^-)$
- $\text{BR}(B \to K^* e^+ e^-)$
- $R_K$
- $B \to K^{*0} \mu^+ \mu^-$: $\text{BR}$, $F_L$, $A_{FB}$, $S_3$, $S_4$, $S_5$, $S_7$, $S_8$, $S_9$
  in 8 low $q^2$ and 4 high $q^2$ bins
- $B_s \to \phi \mu^+ \mu^-$: $\text{BR}$, $F_L$, $S_3$, $S_4$, $S_7$
  in 3 low $q^2$ and 2 high $q^2$ bins
Single operator fits

Comparison of one-operator NP fits:

(under the assumption of 10% non-factorisable power corrections)

<table>
<thead>
<tr>
<th>All observables except $R_K, R_K^*$</th>
<th>$\chi^2_{SM} = 100.2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta C_9$</td>
<td>$-1.00 \pm 0.20$</td>
</tr>
<tr>
<td>$\delta C_9^\mu$</td>
<td>$-1.03 \pm 0.20$</td>
</tr>
<tr>
<td>$\delta C_9^e$</td>
<td>$0.72 \pm 0.58$</td>
</tr>
<tr>
<td>$\delta C_{10}$</td>
<td>$0.25 \pm 0.23$</td>
</tr>
<tr>
<td>$\delta C_{10}^\mu$</td>
<td>$0.32 \pm 0.22$</td>
</tr>
<tr>
<td>$\delta C_{10}^e$</td>
<td>$-0.56 \pm 0.50$</td>
</tr>
<tr>
<td>$\delta C_{LL}^\mu$</td>
<td>$-0.48 \pm 0.15$</td>
</tr>
<tr>
<td>$\delta C_{LL}^e$</td>
<td>$0.33 \pm 0.29$</td>
</tr>
</tbody>
</table>

| $\chi^2_{min}$                       | 82.5                   |
| $\text{Pull}_{SM}$                   | $4.2\sigma$            |
|                                      | 98.9                   |
| $\delta C_{10}$                      | $1.1\sigma$            |
| $\delta C_{10}^\mu$                  | $1.5\sigma$            |
| $\delta C_{10}^e$                    | $1.0\sigma$            |
| $\delta C_{LL}$                      | $3.3\sigma$            |
| $\delta C_{LL}^\mu$                  | $1.1\sigma$            |

<table>
<thead>
<tr>
<th>Only $R_K, R_K^*$</th>
<th>$\chi^2_{SM} = 16.9$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta C_9$</td>
<td>$-2.04 \pm 5.93$</td>
</tr>
<tr>
<td>$\delta C_9^\mu$</td>
<td>$-0.74 \pm 0.28$</td>
</tr>
<tr>
<td>$\delta C_9^e$</td>
<td>$0.79 \pm 0.29$</td>
</tr>
<tr>
<td>$\delta C_{10}$</td>
<td>$4.10 \pm 11.87$</td>
</tr>
<tr>
<td>$\delta C_{10}^\mu$</td>
<td>$0.77 \pm 0.26$</td>
</tr>
<tr>
<td>$\delta C_{10}^e$</td>
<td>$-0.78 \pm 0.27$</td>
</tr>
<tr>
<td>$\delta C_{LL}^\mu$</td>
<td>$-0.37 \pm 0.12$</td>
</tr>
<tr>
<td>$\delta C_{LL}^e$</td>
<td>$0.41 \pm 0.15$</td>
</tr>
</tbody>
</table>

$\delta C_{LL}^\mu$ basis corresponds to $\delta C_9^\mu = -\delta C_{10}^\mu$.

$\rightarrow C_9$ and $C_9^\mu$ solutions are favoured with SM pulls of $4.2$ and $4.5\sigma$

$\rightarrow$ Good fits possible for $R_K(\ast)$ ratios with NP in $C_9^{e/\mu}$, $C_{10}^{e/\mu}$ or $C_{LL}^{e/\mu}$
Two operator fits

all observables except $R_K$ and $R_{K^*}$ (with the assumption of 10% power corrections)

Pull: $4.1\sigma$  $4.1\sigma$  $1.1\sigma$
Two operator fits

all observables except $R_K$ and $R_{K^*}$ (with the assumption of 10% power corrections)

Pull: $4.1\sigma$

Using only the data on $R_K$ and $R_{K^*}$

Pull: $3.1\sigma$
Using all the relevant data on $b \rightarrow s$ transitions:

assuming 10% error for the power corrections

<table>
<thead>
<tr>
<th>All observables ($\chi^2_{SM} = 117.03$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>b.f. value</td>
</tr>
<tr>
<td>$\delta C_9$</td>
</tr>
<tr>
<td>$\delta C_9^\mu$</td>
</tr>
<tr>
<td>$\delta C_9^e$</td>
</tr>
<tr>
<td>$\delta C_{10}$</td>
</tr>
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</tr>
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</tr>
</tbody>
</table>

The NP significance is reduced by at least 0.5$\sigma$ compared to before.

In cases of flavour-symmetric $C_9$ and $C_{10}$, which are independent from the changes in the ratios, one finds the same NP significance as expected.
More complete analyses

In a New Physics model:
- new vector bosons: $C_7, C_9, C_{10}$
- new fermions: $C_7, C_8, C_9, C_{10}$
- extended Higgs sector/new scalars: $C_S, C_P$

E.g. in the MSSM, 2HDM, ...: $C_7, C_8, C_9, C_{10}, C_S, C_P$

Considering only one or two Wilson coefficients may not give the full picture!

A generic set of Wilson coefficients:

complex $C_7, C_8, C_9^\ell, C_{10}^\ell, C_S^\ell, C_P^\ell$ + primed coefficients

The available observables are mainly insensitive to the imaginary parts, one can limit the set to

real $C_7, C_8, C_9^\ell, C_{10}^\ell, C_S^\ell, C_P^\ell$ + primed coefficients

corresponding to 20 degrees of freedom.
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e.g. in the MSSM, 2HDM, ...: \( C_7, C_8, C_9, C_{10}, C_S, C_P \)

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A generic set of Wilson coefficients:

\[
\text{complex } C_7, C_8, C_9^\ell, C_{10}^\ell, C_S^\ell, C_P^\ell + \text{primed coefficients}
\]

The available observables are mainly insensitive to the imaginary parts, one can limit the set to

\[
\text{real } C_7, C_8, C_9^\ell, C_{10}^\ell, C_S^\ell, C_P^\ell + \text{primed coefficients}
\]

corresponding to 20 degrees of freedom.
Full fit - results

Set: real $C_7, C_8, C_9^\ell, C_{10}^\ell, C_S^\ell, C_P^\ell$ + primed coefficients ($20$ ($16$) degrees of freedom)

<table>
<thead>
<tr>
<th>$\delta C_7$</th>
<th>$\delta C_8$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-0.01 \pm 0.04$</td>
<td>$0.82 \pm 0.72$</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th>$\delta C_7'$</th>
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</thead>
<tbody>
<tr>
<td>$0.01 \pm 0.03$</td>
<td>$-1.65 \pm 0.47$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\delta C_9^\mu$</th>
<th>$\delta C_9^e$</th>
<th>$\delta C_{10}^\mu$</th>
<th>$\delta C_{10}^e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-1.37 \pm 0.25$</td>
<td>$-6.55 \pm 2.37$</td>
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<tr>
<th>$\delta C_{9}^{\prime\mu}$</th>
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<th>$\delta C_{10}^{\prime\mu}$</th>
<th>$\delta C_{10}^{\prime e}$</th>
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<tr>
<td>$0.23 \pm 0.62$</td>
<td>$0.75 \pm 2.82$</td>
<td>$-0.16 \pm 0.36$</td>
<td>$1.67 \pm 3.05$</td>
</tr>
</tbody>
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<table>
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<tr>
<th>$C_{Q_1}^\mu$</th>
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<th>$C_{Q_2}^\mu$</th>
<th>$C_{Q_2}^e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-0.01 \pm 0.09$</td>
<td>undetermined</td>
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<td>undetermined</td>
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</table>

<table>
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<td>undetermined</td>
</tr>
</tbody>
</table>

Wilks’ test:
- No real improvement in the fits when going beyond the $C_9^\mu$ case
- Pull with the SM decreases when all WC are varied
- Many parameters are very weakly constrained
NP scenarios
Global fits: New physics is likely to appear in $C_9$:

\[ O_9 = \frac{e^2}{(4\pi)^2} (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell) \]

It can also affect other Wilson coefficients in a lesser extent.

However, difficult to generate $\delta C_9 \sim -1$ at loop level...

Very difficult in the MSSM!
Fit results in the pMSSM
Fit results in the pMSSM

- Graph 1: $p_s$ vs $q^2$ (GeV$^2$)
- Graph 2: $p_s$ bin vs BR($b\rightarrow s\gamma$)
Fit results in the pMSSM
MSSM and $C_9$

Contributions to $C_9$ and $C'_9$ can come from $Z$ and photon penguins, and box diagrams

- $Z$-penguins suppressed by small vector coupling
- charged Higgs contributions proportional to $1/\tan^2\beta$
- other penguin diagrams suppressed by the LHC squark and gluino mass limits
- in any case, only box diagrams can lead to lepton flavour non-universality...
- … but box diagrams suppressed by the LEP slepton and chargino mass bounds
Global fits: New physics is likely to appear in $C_9$:

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However, difficult to generate $\delta C_9 \sim -1$ at loop level...

→ Need for tree level diagrams...

Mainstream scenarios:

- $Z'$ bosons
- leptoquarks
- composite models
$Z'$ bosons

$Z'$ obvious candidate to generate the $O_9$ operator

Needs:
- Flavour-changing couplings to left-handed quarks
- Vector-like couplings to leptons
- Flavour violation or non-universality in the lepton sector

Strong constraints from $B_s - \bar{B}_s$ mixing and LEP contact interactions.

Anomalies consistent with a $Z'$ of 1 to 10 TeV

Can appear in many models, like 331 models, gauge $L_\mu - L_\tau$ models, ...

See e.g. Altmannshofer et al. 1308.1501, Gauld et al. 1308.1959, Buras et al. 1309.2466, Gauld et al. 1310.1082, Buras et al. 1311.6729, Altmannshofer et al. 1403.1269, Buras et al. 1409.4557, Glashow et al. 1411.0565, Crivellin et al. 1501.00993, Altmannshofer et al. 1411.3161, Crivellin et al. 1503.03477, Niehoff et al. 1503.03865, Crivellin et al. 1505.02026, Celis et al. 1505.03079, ...
Leptoquarks

- t-channel diagrams
- Different possible representations, can be scalar (spin 0) or vector (spin 1)
- Cannot alter only $C_9$, but both $C_9$ and $C_{10} (= -C_9)$
- Cannot be lepton flavour non-universal and conserve lepton number simultaneously

Model can be tested with $R_{K(*)}$ measurements and searches for $b \rightarrow s \mu^\pm e^\mp$ and $\mu \rightarrow e\gamma$

Possible scenario: two leptoquarks coupling to one lepton type only.

See e.g. Hiller et al. 1408.1627, Biswas et al. 1409.0882, Buras et al. 1409.4557, Sahoo et al. 1501.05193, Hiller et al. 1411.4773, Becirevic et al. 1503.09024, Alonso et al. 1505.05164, ...
Neutral resonance $\rho_\mu$ coupling to the muons via composite elementary mixing requires some compositeness for the muons can allow for lepton flavour violating couplings constrained by the LEP $Z$-width measurements and $B_s - \bar{B}_s$ mixing

Nonperturbative physics, making predictions more difficult...

See e.g. Gripaios et al. 1412.1791, Niehoff, et al. 1503.03865, Niehoff et al. 1508.00569, Carmona et al. 1510.07658, ...
Future prospects
How to resolve the issue?

1) Improving the precision of the theoretical calculations

- still some QCD ingredients unknown, or only partially known
  → New methods and alternative approaches are required
  → Several attempts already in the literature

2) Cross-check with other $R_{\mu/e}$ ratios

- $R_K$ and $R_{K^*}$ ratios are theoretically very clean
- The tensions cannot be explained by hadronic uncertainties

Cross-checks needed with other ratios:

<table>
<thead>
<tr>
<th>Obs.</th>
<th>Predictions assuming 12 fb$^{-1}$ luminosity</th>
</tr>
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<tbody>
<tr>
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A confirmation of the deviations in the ratios would indirectly confirm the NP interpretation of the anomalies in the angular observables!
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<td>[0.632, 0.805]</td>
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<td>$R_{[1, 1, 6, 0]}$</td>
<td>[0.748, 0.852]</td>
<td>[0.620, 0.805]</td>
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A confirmation of the deviations in the ratios would indirectly confirm the NP interpretation of the anomalies in the angular observables!
3) Future LHCb prospects

Global fits using the angular observables only (NO theoretically clean $R$ ratios)
Considering several luminosities, assuming the current central values

LHCb will be able to establish new physics within the angular observables
even in the pessimistic case that there will be no theoretical improvements!
How to resolve the issue?

4) Cross-check with inclusive modes

Inclusive decays are theoretically cleaner (see e.g. T. Huber, T. Hurth, E. Lunghi, JHEP 1506 (2015) 176)

At Belle-II, for inclusive $b \to s \ell \ell$:

Predictions based on our model-independent analysis

black cross: future measurements at Belle-II assuming the best fit solution
red cross: SM predictions

→ Belle-II will check the NP interpretation with theoretically clean modes
Cooking a New Physics scenario
Cooking scenarios

Cooking a New Physics scenario

Model-independent approach

gives us the ingredients

$C_9$, a bit of $C_{10},...$
Cooking a New Physics scenario

Model-independent approach

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$C_9$, a bit of $C_{10}$, ...

Simplified models

$Z'$, Lepto quarks, ...
Cooking a New Physics scenario

Model-independent approach

\[ C_9, \text{a bit of } C_{10}, \ldots \]

Simplified models

\[ Z', \text{Lepto quarks, } \ldots \]

UV-complete theory

The real model
Final remarks

Could the anomalies be explained by:

- Statistical fluctuations alone?
- Experimental issues alone?
- Underestimated theoretical uncertainties alone?
- Unknown pieces in the theoretical calculations alone?

▶ Combination of above?

▶ New Physics option?
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Could the anomalies be explained by:

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Could the anomalies be explained by:

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The next round of LHCb results will give us the verdict!

Nazila Mahmoudi
Uppsala - 29 Aug. 2019
Could the anomalies be explained by:

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Is Nature teasing us?

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Or teaching us?

The next round of LHCb results will give us the verdict!
We may be in such a situation:

Columbus had Toscanelli’s map.
It was terribly wrong, but served the purpose!
Backup
$B \rightarrow D^{(*)} \ell \nu$

### Graphical Representation

- **HFLAV average**
- **$\Delta \chi^2 = 1.0$ contours**

### Data Points
- **LHCb15**
- **LHCb18**
- **BaBar12**
- **Belle19**
- **Belle15**
- **Belle17**

### Parameters
- Average of SM predictions:
  - $R(D) = 0.299 \pm 0.003$
  - $R(D^*) = 0.258 \pm 0.005$

### Statistical Test
- $P(\chi^2) = 27\%$
Fit results for two operators: form factor dependence

Fits with different assumptions for the form factor uncertainties:

- correlations ignored (solid line)
- normal form factor errors (filled areas)
- $2 \times$ form factor errors (dashed line)
- $4 \times$ form factor errors (dotted line)

\[
(C_9 - C_{10}) \quad (C_9 - C'_9) \quad (C_9^e - C_9^\mu)
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\[(C_9 - C_{10})\]  
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The size of the form factor errors has a crucial role in constraining the allowed region!
The role of (pseudo)scalar operators

Imposing $\text{BR}(B_s \rightarrow \mu^+\mu^-)$, if $C_S$ and $C_P$ independent, there exists a degeneracy between $C_{10}$ and $C_P$ so that large values for $C_P$ are possible.
The role of (pseudo)scalar operators

Imposing BR\( (B_s \rightarrow \mu^+ \mu^-) \), if \( C_S \) and \( C_P \) independent, there exists a degeneracy between \( C_{10} \) and \( C_P \) so that large values for \( C_P \) are possible.

Even if \( C_S = -C_P \), allowing for small variations of \( C_{S,P} \) alleviates the constraints from \( B_s \rightarrow \mu^+ \mu^- \) on \( C_{10} \).
A generic set of Wilson coefficients:

\[ \text{complex } C_7, C_8, C_9^\ell, C_{10}^\ell, C_5^\ell, C_P^\ell + \text{primed coefficients} \]

The available observables are mainly insensitive to the imaginary parts, one can limit the set to

\[ \text{real } C_7, C_8, C_9^\ell, C_{10}^\ell, C_5^\ell, C_P^\ell + \text{primed coefficients} \]

corresponding to 20 degrees of freedom.

Some of the coefficients may have only weak effects on the observables, and affect the number of dof without affecting the \( \chi^2 \), acting as spurious degrees of freedom.

**effective degrees of freedom** (e-dof): degrees of freedom minus the parameters \( \delta C_i \) only weakly affecting the \( \chi^2 \), defined such as

\[ |\chi^2(\delta C_i = 1) - \chi^2(\delta C_i = 0)| < 1 \]
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