Seventh Workshop on Theory, Phenomenology and Experiment in Flavour Physics
8 -10 June 2018, Anacapri, Capri Island, Italy

Status report on b to s anomalies
Tobias Hurth, Johannes Gutenberg University Mainz
Based on

Egede, Hurth, Matias, Ramon, Reece:
New observables in the decay mode $\bar{B}_d \to \bar{K}^* 0 \ell^+ \ell^-$

Egede, Hurth, Matias, Ramon, Reece:
New physics reach of the decay mode $\bar{B} \to \bar{K}^* 0 \ell^+ \ell^-$

Descotes-Genon, Hurth, Matias, Virto:
Optimizing the basis of $B \to K^* \ell \ell$ observables in the full kinematic range

Hurth, Mahmoudi:
On the LHCb anomaly in $B \to K^* \ell^+ \ell^-$

Hurth, Mahmoudi, Neshatpour:
Global fits to $b \to s \ell \ell$ data and signs for lepton non-universality

On the anomalies in the latest LHCb data

Chobanova, Hurth, Mahmoudi, Neshatpour, Martinez Santos:
Large hadronic power corrections or NP in the rare decay $B \to K^* \mu^+ \mu^-$

Hurth, Mahmoudi, Neshatpour, Martinez Santos:
On lepton non-universality in exclusive $b \to s \ell^+ \ell^-$ decays

Arby, Hurth, Mahmoudi, Neshatpour:
Hadronic and NP contributions in $B \to K^* \ell^+ \ell^-$
arXiv:1806.02791
Prologue from my 2016 talk on inclusive semileptonic B decays
Self-consistency of the SM

Do we need new physics beyond the SM?

- It is possible to extend the validity of the SM up to the $M_P$ as weakly coupled theory.

High-energy extrapolation shows that the Yukawa couplings, weak gauge couplings and the Higgs self coupling remain perturbative in the entire energy domain between the electroweak and Planck scale (no Landau poles!).

- Renormalizability implies no constraints on the free parameters of the SM Lagrangian.
Experimental evidence beyond SM

- **Dark matter** (visible matter accounts for only 4% of the Universe)

- **Neutrino masses** (Dirac or Majorana masses ?)

- **Baryon asymmetry of the Universe** (new sources of CP violation needed)

**Caveat:**

Answers perhaps wait at energy scales which we do not reach with present experiments.
The LHCb Anomalies
Anomalies in $B \rightarrow K^* \mu^+ \mu^-$ angular observables, in particular $P_5'$; $S_5$

Long standing anomaly 2-3σ:

- 2013 (1 fb$^{-1}$): disagreement with the SM for $P_2$ and $P_5'$ (PRL 111, 191801 (2013))
- March 2015 (3 fb$^{-1}$): confirmation of the deviations (LHCb-CONF-2015-002)
- Dec. 2015: 2 analysis methods, both show the deviations (JHEP 1602, 104 (2016))

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

- Also measured by ATLAS, CMS and Belle

New Physics or underestimated hadronic uncertainties (form factors, power corrections)?
More details:

**Differential decay rate of $B \rightarrow K^* \ell \ell$**

Assuming the $K^*$ to be on the mass shell, the decay $\bar{B}^0 \rightarrow \bar{K}^* (\rightarrow K^- \pi^+ ) \ell^+ \ell^-$ described by the lepton-pair invariant mass, $s$, and the three angles $\theta_\ell$, $\theta_{K^*}$, $\phi$.

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

\[
J(q^2, \theta_\ell, \theta_{K^*}, \phi) =
J_{1s} \sin^2 \theta_{K^*} + J_{1c} \cos^2 \theta_{K^*} + (J_{2s} \sin^2 \theta_{K^*} + J_{2c} \cos^2 \theta_{K^*}) \cos 2\theta_\ell + J_3 \sin^2 \theta_{K^*} \sin^2 \theta_\ell \cos 2\phi
\]

\[
+ J_4 \sin 2\theta_{K^*} \sin 2\theta_\ell \cos \phi + J_5 \sin 2\theta_{K^*} \sin \theta_\ell \cos \phi + (J_{6s} \sin^2 \theta_{K^*} + J_{6c} \cos^2 \theta_{K^*}) \cos \theta_\ell
\]

\[
+ J_7 \sin 2\theta_{K^*} \sin \theta_\ell \sin \phi + J_8 \sin 2\theta_{K^*} \sin 2\theta_\ell \sin \phi + J_9 \sin^2 \theta_{K^*} \sin^2 \theta_\ell \sin 2\phi
\]

**Large number of independent angular observables**
First measurements of new angular observables LHCb arXiv:1308.1707

SM predictions Descotes-Genon, Hurth, Matias, Virto arXiv:1303.5794

LHCb Anomaly
a statistical fluctuation, an underestimation of $\Lambda/m_b$ corrections or new physics in $C_9$?

\[ C_7 \quad (B \to X_s \gamma) \]

\[ O_7^{(i)} \propto m_b \bar{s}\sigma_{\mu\nu}P_{R(L)} b F_{\mu\nu} \]

\[ O_9^{(i)} \propto \bar{s} \gamma^\mu P_{L(R)} \bar{\ell} \gamma_\mu \ell \]

\[ O_{10}^{(i)} \propto \bar{s} \gamma^\mu P_{L(R)} \bar{\ell} \gamma_\mu \gamma_5 \ell \]

\[ C_{10} \quad (B \to \mu^+\mu^-) \]
Tension seen in $P_5'$ in [PRL 111, 191801 (2013)] confirmed
- [4.0, 6.0] and [6.0, 8.0] GeV$^2$/c$^4$ show deviations of 2.9$\sigma$ each
- Naive combination results in a significance of 3.7$\sigma$
- Compatible with 1 fb$^{-1}$ measurement
Lepton flavour universality in $B^+ \rightarrow K^+ \ell^+ \ell^-$

- SM prediction very accurate (leading corrections from QED, giving rise to large logarithms involving the ratio $m_B/m_{\mu,e}$)

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

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

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

Bordone, Isidori, Pattori, arXiv:1605.07633

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

Would be a spectacular fall of the SM!
Lepton flavour universality in $B^0 \to K^{*0}\ell^+\ell^-$

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

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

\begin{align*}
R_{K^*}^{\text{exp,bin1}} &= 0.660^{+0.110}_{-0.070}\quad(\text{stat}) \pm 0.024(\text{syst}) \\
R_{K^*}^{\text{exp,bin2}} &= 0.685^{+0.113}_{-0.069}\quad(\text{stat}) \pm 0.047(\text{syst}) \\
R_{K^*}^{\text{SM,bin1}} &= 0.906 \pm 0.020_{\text{QED}} \pm 0.020_{\text{FF}} \\
R_{K^*}^{\text{SM,bin2}} &= 1.000 \pm 0.010_{\text{QED}}
\end{align*}

Bordone, Isidori, Pattori, arXiv:1605.07633

2.2-2.5σ tension with the SM predictions in each bin

BaBar, PRD 86 (2012) 032012; Belle, PRL 103 (2009) 171801
Theoretical Tools
Theoretical tools for flavour precision observables

Factorization theorems: separating long- and short-distance physics

- Electroweak effective Hamiltonian: \( H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} \sum C_i(\mu, M_{\text{heavy}}) \mathcal{O}_i(\mu) \)

- \( \mu^2 \approx M_{\text{New}}^2 \gg M_W^2 \): 'new physics' effects: \( C_i^{\text{SM}} (M_W) + C_i^{\text{New}} (M_W) \)

How to compute the hadronic matrix elements \( \mathcal{O}_i(\mu = m_b) \)?
Inclusive modes $B \to X_s \gamma$ and $B \to X_s \ell^+ \ell^-$

How to compute the hadronic matrix elements $\mathcal{O}_i(\mu = m_b)$?

Heavy mass expansion for inclusive modes:

$$
\Gamma(\bar{B} \to X_s \gamma) \xrightarrow{m_b \to \infty} \Gamma(b \to X_s^{\text{parton}} \gamma), \quad \Delta^{\text{nonpert.}} \sim \Lambda_{\text{QCD}}^2 / m_b^2
$$

No linear term $\Lambda_{\text{QCD}} / m_b$ (perturbative contributions dominant)

An old story:

- If one goes beyond the leading operator ($\mathcal{O}_7, \mathcal{O}_9$):
  breakdown of local expansion

A new dedicated analysis:

naive estimate of non-local matrix elements leads to 5% uncertainty.

SCET analysis in $B \to X_s \gamma$: Benzke,Lee,Neubert,Paz, arXiv:1003.5012

in $B \to X_s \ell\ell$: Benzke,Hurth,Turczyk, arXiv:1705.10366

In semileptonic case $\mathcal{O}(1/m_b^2)$ contributions numerically relevant

(work in progress)
Exclusive modes $B \to K^{(*)} \ell \ell$

QCD-improved factorization: BBNS 1999

$$T_{a}^{(i)} = C_{a}^{(i)} \xi_{a} + \phi_{B} \otimes T_{a}^{(i)} \otimes \phi_{a,K^*} + O(\Lambda/m_{b})$$

(Soft-collinear effective theory)

- Separation of perturbative hard kernels from process-independent nonperturbative functions like form factors
- Relations between formfactors in large-energy limit
- Limitation: insufficient information on power-suppressed $\Lambda/m_{b}$ terms (breakdown of factorization: 'endpoint divergences')
Exclusive modes $B \rightarrow K^{(*)} \ell \ell$

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- Relations between formfactors in large-energy limit

- Limitation: insufficient information on power-suppressed $\Lambda/m_b$ terms (breakdown of factorization: 'endpoint divergences')

**More details:**

"Full formfactor approach" Altmannshofer et al., arXiv:0811.1214

- we have factorizable and nonfactorizable power corrections
- using full QCD formfactors in the factorization formula takes factorizable power corrections into account automatically
- nonfactorizable contributions generated by four-quark and $O_8$ operators
Exclusive modes $B \rightarrow K^{(*)} \ell \ell$

QCD-improved factorization: BBNS 1999

\[ T_a^{(i)} = C_a^{(i)} \xi_a + \phi_B \otimes T_a^{(i)} \otimes \phi_{a,K^*} + O(\Lambda/m_b) \]  

(Soft-collinear effective theory)

- Separation of perturbative hard kernels from process-independent nonperturbative functions like form factors
- Relations between formfactors in large-energy limit
- Limitation: insufficient information on power-suppressed $\Lambda/m_b$ terms (breakdown of factorization: 'endpoint divergences')

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

(This does not affect $R_K$ and $R_K^*$ of course, but does affect combined fits!)
Effective Hamiltonian for $b \rightarrow sll$ transitions

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

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

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

Transversity amplitudes:

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

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

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

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

$$A_S = N_S (C_S - C_S') A_0(q^2)$$

$$\left( C_i^{\pm} \equiv C_i \pm C_i' \right)$$
Effective Hamiltonian for $b \to s \ell \ell$ transitions

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

\[ \mathcal{H}_{\text{eff}}^{\text{had}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[ \sum_{i=1\ldots6} C_i O_i + C_8 O_8 \right] \]

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

\[ \times \int d^4y e^{iq \cdot y} \langle \vec{K}_\lambda | T \{ j^{\text{em,had,\mu}}(y) \mathcal{H}_{\text{eff}}^{\text{had}}(0) \} | \vec{B} \rangle \]

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

Non-Fact., QCDf

power corrections

Beneke et al.: 106067; 0412400
Model independent Analysis
Model-independent global fits to $b \rightarrow s$ data

Relevant operators: $O_7, O_8, O'_{9\mu,e}, O'_{10\mu,e}$

Scan over the values of $\delta C_i$: $C_i(\mu) = C_i^{SM} + \delta C_i$

More than 100 observables included

Experimental and theoretical correlations considered

Several groups doing global fits.

Global fits to $\leq 2016$ data

Hurth et al. arXiv:1603.00865
Descotes-Genon et al. arXiv:1510.04239
Ciuchini et al. arXiv:1512.07157
Beaujean et al. arXiv:1508.01526
Alonso et al. arXiv:1407.7044

Fits to the data including $R_{K^*}$ of 2017

Capdevilla et al. arXiv:1704.05340
Geng et al. arXiv:1704.05446
Altmannshofer et al. arXiv:1704.05435
D’Amico et al. arXiv:1704.05438
Ciuchini et al. arXiv:1704.05447
Hurth et al. arXiv:1705.06274
Fit results for two operators

The assumption on the power correction errors have a rather mild impact on the constraints of the allowed region.
Fits assuming different form factor uncertainties

The size of the form factor errors has a crucial role in constraining the allowed region.

$S_5$ is not the only observable which drives $\frac{\delta C_9}{C_9^{\text{SM}}}$ to negative values.
The hadronic contributions (in terms of helicity amplitudes) appear in:

$$H_V(\lambda) = -i \, N' \left\{ C_9^{\text{eff}} \tilde{V}_\lambda(q^2) + \frac{m_B^2}{q^2} \left[ \frac{2 \hat{m}_b}{m_B} C_7^{\text{eff}} \tilde{T}_\lambda(q^2) - 16\pi^2 \mathcal{N}_\lambda(q^2) \right] \right\}$$

$$N' = -\frac{4G_F m_B}{\sqrt{2}} \frac{e^2}{16\pi^2} v_{tb} v_{ts}^*$$

$$\mathcal{N}_\lambda(q^2) = \text{leading nonfact.} + h_\lambda$$

Helicity FFs $\tilde{V}_{L/R}, \tilde{T}_{L/R}$ are combinations of the standard FFs $V, A_{0,1,2}, T_{1,2,3}$. 
The hadronic contributions (in terms of helicity amplitudes) appear in:

\[ H_V(\lambda) = -i \, N' \left\{ C_9^{\text{eff}} \tilde{\nu}_{\lambda}(q^2) + \frac{m_B^2}{q^2} \left[ 2 \frac{m_b}{m_B} C_7^{\text{eff}} \tilde{T}_{\lambda}(q^2) - 16\pi^2 \mathcal{N}_{\lambda}(q^2) \right] \right\} \]

\[ N' = -\frac{4G_F m_B}{\sqrt{2}} \frac{e^2}{16\pi^2} V_{tb} V_{ts}^* \]

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

The most general parametrisation up to higher order terms in \( q^2 \) of the non-factorisable power corrections \( h_{\lambda(\pm,+,0)}(q^2) \) which is compatible with the analyticity structure is:

\[ \delta H_V^{\text{PC}}(\lambda = \pm) = i N' m_B^2 \frac{16\pi^2}{q^2} h_{\lambda}(q^2) = i N' m_B^2 16\pi^2 \left( \frac{h_{\lambda}^{(0)}}{q^2} + h_{\lambda}^{(1)} + q^2 h_{\lambda}^{(2)} \right) \]

\[ \delta H_V^{\text{PC}}(\lambda = 0) = i N' m_B^2 \frac{16\pi^2}{\sqrt{q^2}} \left( h_{0}^{(0)} + q^2 h_{0}^{(1)} + q^4 h_{0}^{(2)} \right) \]
New physics or hadronic effects

Hurth, Mahmoudi, Neshatpour, Chobanova, Martinez Santos arXiv:1702.02234
Arby, Hurth, Mahmoudi, Neshatpour arXiv: 1806.02791

The hadronic contributions (in terms of helicity amplitudes) appear in:

\[ H_V(\lambda) = -iN' \left\{ C_9^{\text{eff}} \tilde{V}_\lambda(q^2) + \frac{m_B^2}{q^2} \left[ \frac{2 \hat{m}_b}{m_B} C_7^{\text{eff}} \tilde{T}_\lambda(q^2) - 16\pi^2 N_\lambda(q^2) \right] \right\} \]

\[ (N' = -\frac{4G_F m_B}{\sqrt{2}} \frac{e^2}{16\pi^2} V_{tb} V_{ts}^* ) \]

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

The most general parametrisation up to higher order terms in \( q^2 \) of the non-factorisable power corrections \( h_\lambda(=+, -, 0)(q^2) \) which is compatible with the analyticity structure is:

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

\[ \delta H_V^{PC}(\lambda = 0) = iN' m_B^2 \frac{16\pi^2}{\sqrt{q^2}} \left( h_0^{(0)} + q^2 h_0^{(1)} + q^4 h_0^{(2)} \right) \]

New Physics effect:

\[ \delta H_V^{\text{NP}}(\lambda = \pm) = -iN' \tilde{V}_L(q^2) C_9^{\text{NP}} = -iN' \left( a_\lambda C_9^{\text{NP}} + q^2 b_\lambda C_9^{\text{NP}} \right) \]

and similarly for \( \lambda = 0 \) and for \( C_7 \)

\[ \Rightarrow \text{NP effects can be embedded in the hadronic effects.} \]
Wilk’s test

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

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

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 (plain SM)</td>
<td>4.2σ</td>
<td>4.1σ</td>
<td>3.1σ</td>
</tr>
<tr>
<td>2 (\delta C_9)</td>
<td>−</td>
<td>1.4σ</td>
<td>1.1σ</td>
</tr>
<tr>
<td>4 (\delta C_7, \delta C_9)</td>
<td>−</td>
<td>−</td>
<td>0.95σ</td>
</tr>
</tbody>
</table>

→ Adding $\delta C_9$ improves over the SM hypothesis by 4.2σ
→ 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 fit

The situation is still inconclusive

(LHCb upgrade prospects: NP versus hadronic effects 34 σ)
Separate NP fits with a single operator

Hurth, Mahmoudi, Martinez Santos, Neshatpour arXiv: 1705.06274

Best fit values in the one operator fit considering only $R_K$ and $R_K^*$

<table>
<thead>
<tr>
<th></th>
<th>b.f. value</th>
<th>$\chi^2_{\text{min}}$</th>
<th>Pull_{SM}</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta C_9$</td>
<td>$-0.48$</td>
<td>18.3</td>
<td>0.3$\sigma$</td>
</tr>
<tr>
<td>$\Delta C_9^\prime$</td>
<td>$+0.78$</td>
<td>18.1</td>
<td>0.6$\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{10}$</td>
<td>$-1.02$</td>
<td>18.2</td>
<td>0.5$\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{10}^\prime$</td>
<td>$+1.18$</td>
<td>17.9</td>
<td>0.7$\sigma$</td>
</tr>
<tr>
<td>$\Delta C_9^{\mu}$</td>
<td>$-0.35$</td>
<td>5.1</td>
<td>3.6$\sigma$</td>
</tr>
<tr>
<td>$\Delta C_9^\theta$</td>
<td>$+0.37$</td>
<td>3.5</td>
<td>3.9$\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{10}^{\mu}$</td>
<td>$-1.66$</td>
<td>2.7</td>
<td>4.0$\sigma$</td>
</tr>
<tr>
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<td>$-0.34$</td>
<td></td>
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<tr>
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<td>$-2.36$</td>
<td>2.2</td>
<td>4.0$\sigma$</td>
</tr>
</tbody>
</table>

→ NP in $C_9^\theta$, $C_9^{\mu}$, $C_{10}^\theta$, or $C_{10}^{\mu}$ are favoured by the $R_K^{(*)}$ ratios (significance: 3.6 – 4.0$\sigma$)

→ NP contributions in primed operators do not play a role.

Best fit values considering all observables besides $R_K$ and $R_K^*$ (under the assumption of 10% non-factorisable power corrections)

<table>
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<tr>
<td>$\Delta C_9$</td>
<td>$-0.24$</td>
<td>70.5</td>
<td>4.1$\sigma$</td>
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<tr>
<td>$\Delta C_9^\prime$</td>
<td>$-0.02$</td>
<td>87.4</td>
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</tr>
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</tr>
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<td>$\Delta C_9^{\mu}$</td>
<td>$-0.25$</td>
<td>68.2</td>
<td>4.4$\sigma$</td>
</tr>
<tr>
<td>$\Delta C_9^\theta$</td>
<td>$+0.18$</td>
<td>86.2</td>
<td>1.2$\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{10}^{\mu}$</td>
<td>$-0.05$</td>
<td>86.8</td>
<td>0.8$\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{10}^\theta$</td>
<td>$-2.14$</td>
<td>86.3</td>
<td>1.1$\sigma$</td>
</tr>
</tbody>
</table>

→ $C_9$ and $C_9^{\mu}$ solutions are favoured with SM pulls of 4.1 and 4.4$\sigma$

→ Primed operators have a very small SM pull

→ $C_{10}$-like solutions do not play a role
Separate NP fits with a single operator

Hurth, Mahmoudi, Martinez Santos, Neshatpour arXiv: 1705.06274

data of 2017 (with $R_{K^*}$ !)

Best fit values in the one operator fit considering only $R_K$ and $R_{K^*}$

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<tr>
<td>$\Delta C_{10}'$</td>
<td>$+1.18$</td>
<td>17.9</td>
<td>0.7$\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{10}^{\mu}$</td>
<td>$-0.35$</td>
<td>5.1</td>
<td>3.6$\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{10}^{e}$</td>
<td>$+0.37$</td>
<td>3.5</td>
<td>3.9$\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{10}^{\mu}$</td>
<td>$-1.66$</td>
<td>2.7</td>
<td>4.0$\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{10}^{e}$</td>
<td>$-0.34$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta C_{10}^{e}$</td>
<td>$-2.36$</td>
<td>2.2</td>
<td>4.0$\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{10}^{e}$</td>
<td>$+0.35$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Best fit values considering all observables besides $R_K$ and $R_{K^*}$
(under the assumption of 10% non-factorisable power corrections)

<table>
<thead>
<tr>
<th></th>
<th>b.f. value</th>
<th>$\chi^2_{\text{min}}$</th>
<th>PullSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta C_9$</td>
<td>$-0.24$</td>
<td>70.5</td>
<td>4.1$\sigma$</td>
</tr>
<tr>
<td>$\Delta C_9'$</td>
<td>$-0.02$</td>
<td>87.4</td>
<td>0.3$\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{10}$</td>
<td>$-0.02$</td>
<td>87.3</td>
<td>0.4$\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{10}'$</td>
<td>$+0.03$</td>
<td>87.0</td>
<td>0.7$\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{10}^{\mu}$</td>
<td>$-0.25$</td>
<td>68.2</td>
<td>4.4$\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{10}^{e}$</td>
<td>$+0.18$</td>
<td>86.2</td>
<td>1.2$\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{10}^{\mu}$</td>
<td>$-0.05$</td>
<td>86.8</td>
<td>0.8$\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{10}^{e}$</td>
<td>$-2.14$</td>
<td>86.3</td>
<td>1.1$\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{10}^{e}$</td>
<td>$+0.14$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Slight decoherence between the two subsets
Separate NP fits with a single operator

Hurth, Mahmoudi, Martinez Santos, Neshatpour arXiv: 1705.06274

data of 2017 (with $R_K^*$ !)

Best fit values in the one operator fit considering only $R_K$ and $R_K^*$

Best fit values considering all observables besides $R_K$ and $R_K^*$
(under the assumption of 10% non-factorisable power corrections)

Within chiral basis: Slight decoherence between the two subsets again

<table>
<thead>
<tr>
<th>$\Delta C_{9}^{\mu}$ = $\Delta C_{10}^{\mu}$ ($\Delta C_{LL}^{\mu}$)</th>
<th>b.f. value</th>
<th>$\chi^2_{\text{min}}$</th>
<th>Pull$_{\text{SM}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta C_{9}^{\mu}$ = $\Delta C_{10}^{\mu}$ ($\Delta C_{LL}^{\mu}$)</td>
<td>$-0.16$</td>
<td>$3.4$</td>
<td>$3.9\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{9}^{e}$ = $\Delta C_{10}^{e}$ ($\Delta C_{LL}^{e}$)</td>
<td>$+0.19$</td>
<td>$2.8$</td>
<td>$4.0\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{9}^{\mu}$ = $\Delta C_{10}^{\mu}$ ($\Delta C_{RL}^{\mu}$)</td>
<td>$-0.01$</td>
<td>$18.3$</td>
<td>$0.4\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{9}^{e}$ = $\Delta C_{10}^{e}$ ($\Delta C_{RL}^{e}$)</td>
<td>$+0.01$</td>
<td>$18.3$</td>
<td>$0.4\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{9}^{\mu}$ = $\Delta C_{10}^{\mu}$ ($\Delta C_{LR}^{\mu}$)</td>
<td>$+0.09$</td>
<td>$17.5$</td>
<td>$1.0\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{9}^{e}$ = $\Delta C_{10}^{e}$ ($\Delta C_{LR}^{e}$)</td>
<td>$-0.55$</td>
<td>$1.4$</td>
<td>$4.1\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{9}^{\mu}$ = $\Delta C_{10}^{\mu}$ ($\Delta C_{RR}^{\mu}$)</td>
<td>$-0.01$</td>
<td>$18.4$</td>
<td>$0.2\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{9}^{e}$ = $\Delta C_{10}^{e}$ ($\Delta C_{RR}^{e}$)</td>
<td>$+0.61$</td>
<td>$2.0$</td>
<td>$4.1\sigma$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\Delta C_{9}^{\mu}$ = $\Delta C_{10}^{\mu}$ ($\Delta C_{LL}^{\mu}$)</th>
<th>b.f. value</th>
<th>$\chi^2_{\text{min}}$</th>
<th>Pull$_{\text{SM}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta C_{9}^{\mu}$ = $\Delta C_{10}^{\mu}$ ($\Delta C_{LL}^{\mu}$)</td>
<td>$-0.10$</td>
<td>$79.4$</td>
<td>$2.8\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{9}^{e}$ = $\Delta C_{10}^{e}$ ($\Delta C_{LL}^{e}$)</td>
<td>$+0.08$</td>
<td>$86.3$</td>
<td>$1.1\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{9}^{\mu}$ = $\Delta C_{10}^{\mu}$ ($\Delta C_{RL}^{\mu}$)</td>
<td>$-0.01$</td>
<td>$87.3$</td>
<td>$0.4\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{9}^{e}$ = $\Delta C_{10}^{e}$ ($\Delta C_{RL}^{e}$)</td>
<td>$-0.01$</td>
<td>$87.0$</td>
<td>$0.7\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{9}^{\mu}$ = $\Delta C_{10}^{\mu}$ ($\Delta C_{LR}^{\mu}$)</td>
<td>$+0.12$</td>
<td>$79.5$</td>
<td>$2.8\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{9}^{e}$ = $\Delta C_{10}^{e}$ ($\Delta C_{LR}^{e}$)</td>
<td>$+0.50$</td>
<td>$85.8$</td>
<td>$1.3\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{9}^{\mu}$ = $\Delta C_{10}^{\mu}$ ($\Delta C_{RR}^{\mu}$)</td>
<td>$-1.12$</td>
<td>$86.7$</td>
<td>$0.9\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{9}^{e}$ = $\Delta C_{10}^{e}$ ($\Delta C_{RR}^{e}$)</td>
<td>$+0.03$</td>
<td>$87.1$</td>
<td>$0.6\sigma$</td>
</tr>
<tr>
<td>$\Delta C_{9}^{\mu}$ = $\Delta C_{10}^{\mu}$ ($\Delta C_{RR}^{\mu}$)</td>
<td>$-0.54$</td>
<td>$86.3$</td>
<td>$1.1\sigma$</td>
</tr>
</tbody>
</table>

Adding the observable $B_s \rightarrow \mu\mu$ as $C_{10}$-discriminator

to ratios has only a very mild effect.
Separate NP fits with two operators

Hurth, Mahmoudi, Martinez Santos, Neshatpour arXiv: 1705.06274

\[(C_9^\mu - C_9^e)\]

using only \(R_K\) and \(R_{K^*}\)

\[(C_9^\mu - C_9^\mu)\]

using all but \(R_K\) and \(R_{K^*}\)

The two sets are compatible at least at the 2 \(\sigma\) level
Global fit to $108 \ b \rightarrow s$ observable with 20 operators

Arby, Hurth, Mahmoudi, Neshatpour arXiv: 1806.02791

20 Wilson coefficients sensitive to NP: $C_7, C_8, C_9^\ell, C_{10}^\ell, C_{Q1}^\ell, C_{Q2}^\ell$

→ 10 independent WC (considering $\ell = e, \mu$) + 10 primed

<table>
<thead>
<tr>
<th>Set of WC</th>
<th>Nr. parameters</th>
<th>$\chi^2_{\text{min}}$</th>
<th>Pull$_{\text{SM}}$</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td>0</td>
<td>118.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$C_9^{\mu}$</td>
<td>1</td>
<td>84.6</td>
<td>5.8$\sigma$</td>
<td>5.8$\sigma$</td>
</tr>
<tr>
<td>$C_9^{(e, \mu)}$</td>
<td>2</td>
<td>83.3</td>
<td>5.6$\sigma$</td>
<td>1.1$\sigma$</td>
</tr>
<tr>
<td>$C_7, C_8, C_9^{(e, \mu)}, C_{10}^{(e, \mu)}$</td>
<td>6</td>
<td>80.1</td>
<td>4.9$\sigma$</td>
<td>0.6$\sigma$</td>
</tr>
<tr>
<td>All non-primed WC</td>
<td>10</td>
<td>78.2</td>
<td>4.3$\sigma$</td>
<td>0.3$\sigma$</td>
</tr>
<tr>
<td>All WC (incl. primed)</td>
<td>20</td>
<td>70.2</td>
<td>3.5$\sigma$</td>
<td>0.5$\sigma$</td>
</tr>
</tbody>
</table>

- 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 not constrained

NP significance of 5.8$\sigma$ in $C_9^{\mu}$ is based on the assumption of 10% error for power corrections
Future prospects
Future LHCb prospects for ratios $R_K$ and $R_{K^*}$

Hurth, Mahmoudi, Martinez Santos, Neshatpour arXiv: 1705.06274

Pull$_{SM}$ for the fit to $\Delta C^\mu_9$ based on the ratios $R_K$ and $R_{K^*}$ for the LHCb upgrade

Assuming current central values remain.

<table>
<thead>
<tr>
<th>$\Delta C^\mu_9$</th>
<th>Syst. Pull$_{SM}$</th>
<th>Syst./2 Pull$_{SM}$</th>
<th>Syst./3 Pull$_{SM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 fb$^{-1}$</td>
<td>6.1$\sigma$ (4.3$\sigma$)</td>
<td>7.2$\sigma$ (5.2$\sigma$)</td>
<td>7.4$\sigma$ (5.5$\sigma$)</td>
</tr>
<tr>
<td>50 fb$^{-1}$</td>
<td>8.2$\sigma$ (5.7$\sigma$)</td>
<td>11.6$\sigma$ (8.7$\sigma$)</td>
<td>12.9$\sigma$ (9.9$\sigma$)</td>
</tr>
<tr>
<td>300 fb$^{-1}$</td>
<td>9.4$\sigma$ (6.5$\sigma$)</td>
<td>15.6$\sigma$ (12.3$\sigma$)</td>
<td>19.5$\sigma$ (16.1$\sigma$)</td>
</tr>
</tbody>
</table>

(): assuming 50% correlation between each of the $R_K$ and $R_{K^*}$ measurements

There is the possibility to establish NP already with 12 fb$^{-1}$
Future LHCb prospects for ratios $R_K$ and $R_{K^*}$

Hurth, Mahmoudi, Martinez Santos, Neshatpour arXiv: 1705.06274

Pull$_{SM}$ for the fit to $\Delta C^\mu_9$ based on the ratios $R_K$ and $R_{K^*}$ for the LHCb upgrade

Assuming current central values remain.

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<tr>
<th>$\Delta C^\mu_9$</th>
<th>Syst. Pull$_{SM}$</th>
<th>Syst./2 Pull$_{SM}$</th>
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</thead>
<tbody>
<tr>
<td>12 fb$^{-1}$</td>
<td>$6.1\sigma$ (4.3$\sigma$)</td>
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<td>$7.4\sigma$ (5.5$\sigma$)</td>
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<tr>
<td>50 fb$^{-1}$</td>
<td>$8.2\sigma$ (5.7$\sigma$)</td>
<td>$11.6\sigma$ (8.7$\sigma$)</td>
<td>$12.9\sigma$ (9.9$\sigma$)</td>
</tr>
<tr>
<td>300 fb$^{-1}$</td>
<td>$9.4\sigma$ (6.5$\sigma$)</td>
<td>$15.6\sigma$ (12.3$\sigma$)</td>
<td>$19.5\sigma$ (16.1$\sigma$)</td>
</tr>
</tbody>
</table>

(): assuming 50% correlation between each of the $R_K$ and $R_{K^*}$ measurements

However, with $R_K$ and $R_{K^*}$ only, significance for all 6 favored NP scenarios, $\Delta C^e_9, \Delta C^e_{10}, \Delta C^e_{LL}$ very similar.

$B_s \rightarrow \mu\mu$ will not help in the future to decide which NP option is realized!
$B_s \rightarrow \mu \mu$ will not help in the future to decide which NP option is realized!

<table>
<thead>
<tr>
<th>LHCb lum.</th>
<th>$\text{Pull}_{\text{SM}}$ with $R_K$ and $R_K^*$ [$+ \text{BR}(B_s \rightarrow \mu^+ \mu^-)$] prospects</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 fb$^{-1}$</td>
<td>$7.4\sigma$ [7.4$\sigma$]</td>
</tr>
<tr>
<td>50 fb$^{-1}$</td>
<td>$8.1\sigma$ [7.6$\sigma$]</td>
</tr>
<tr>
<td>300 fb$^{-1}$</td>
<td></td>
</tr>
</tbody>
</table>

For $R_K$ and $R_K^*$ in each of the upgraded luminosities we have assumed the optimistic scenario with systematic errors reduced by a factor 3 with no correlation among the errors.

For $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$ we have considered the absolute experimental error to be $3.8 \times 10^{-10}$, $3.2 \times 10^{-10}$, $2.6 \times 10^{-10}$ from the prospected LHCb results with 12, 50 and 300 fb$^{-1}$ luminosity as well as the prospected ATLAS and CMS results.

Side remark: Restricting power of $B \rightarrow \mu \mu$ is related to $C_{10}$, but also to $C_{Q_1}$, $C_{Q_2}$
Other ratios allow to discriminate between the NP options

Hurth, Mahmoudi, Martinez Santos, Neshatpour arXiv: 1705.06274

<table>
<thead>
<tr>
<th>Obs.</th>
<th>$C_9^{\mu}$</th>
<th>$C_9^e$</th>
<th>$C_{10}^{\mu}$</th>
<th>$C_{10}^e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{F_L}^{[1,1,6.0]}$</td>
<td>[0.785, 0.913]</td>
<td>[0.909, 0.933]</td>
<td>[1.005, 1.042]</td>
<td>[1.001, 1.018]</td>
</tr>
<tr>
<td>$R_{A_{FB}}^{[1,1,6.0]}$</td>
<td>[6.048, 14.819]</td>
<td>[−0.288, −0.153]</td>
<td>[0.816, 0.928]</td>
<td>[0.974, 1.061]</td>
</tr>
<tr>
<td>$R_{S_b}^{[1,1,6.0]}$</td>
<td>[−0.787, 0.394]</td>
<td>[0.603, 0.697]</td>
<td>[0.881, 1.002]</td>
<td>[1.053, 1.146]</td>
</tr>
<tr>
<td>$R_{F_L}^{[15,19]}$</td>
<td>[0.999, 0.999]</td>
<td>[0.998, 0.998]</td>
<td>[0.997, 0.998]</td>
<td>[0.998, 0.998]</td>
</tr>
<tr>
<td>$R_{A_{FB}}^{[15,19]}$</td>
<td>[0.616, 0.927]</td>
<td>[1.002, 1.061]</td>
<td>[0.860, 0.994]</td>
<td>[1.046, 1.131]</td>
</tr>
<tr>
<td>$R_{S_b}^{[15,19]}$</td>
<td>[0.615, 0.927]</td>
<td>[1.002, 1.061]</td>
<td>[0.860, 0.994]</td>
<td>[1.046, 1.131]</td>
</tr>
<tr>
<td>$R_{K}^{[15,19]}$</td>
<td>[0.621, 0.803]</td>
<td>[0.577, 0.771]</td>
<td>[0.589, 0.778]</td>
<td>[0.586, 0.770]</td>
</tr>
<tr>
<td>$R_{K^*}^{[15,19]}$</td>
<td>[0.597, 0.802]</td>
<td>[0.590, 0.778]</td>
<td>[0.659, 0.818]</td>
<td>[0.632, 0.805]</td>
</tr>
<tr>
<td>$R_{\phi}^{[1,1,6.0]}$</td>
<td>[0.748, 0.852]</td>
<td>[0.620, 0.805]</td>
<td>[0.578, 0.770]</td>
<td>[0.578, 0.764]</td>
</tr>
<tr>
<td>$R_{\phi}^{[15,19]}$</td>
<td>[0.623, 0.803]</td>
<td>[0.577, 0.771]</td>
<td>[0.586, 0.776]</td>
<td>[0.583, 0.769]</td>
</tr>
</tbody>
</table>

see also Capdevila et al., arXiv:1605.03156; Serra et al., arXiv:1610.08761
Back to the problem of nonfactorizable power corrections in angular observables
Crosscheck with $R_{\mu,e}$ ratios

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

NP in the ratios would indirectly confirm the NP interpretation of the anomalies in the angular observables

(if there is a coherent picture)
Calculations beyond guessing numbers

Any unreasonable calculation is better than a fit (M.B.).

Methods offered in the analysis of $B \rightarrow K\ell^+\ell^-$ to calculate power corrections Kjodjamirian et al. arXiv: 1211.0234, also 1006.4945

Most recently: Estimate of power corrections based on analyticity structure Bobeth et al. arXiv:1707.07305
Towards complete SM predictions for the angular observables

LCOPE in the euclidean and then analytical continuation to the physical region (dispersion relation or z-expansion).

\[
\frac{e^2}{q^2} \epsilon_\mu L_\nu^\mu \left[ Y(q^2) V_\lambda + \text{LO in } \mathcal{O} \left( \frac{\Lambda}{m_b}, \frac{\Lambda}{E_{K^*}} \right) + h_\lambda(q^2) \right]
\]

<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>
<td>✓</td>
<td>✗</td>
<td>(q^2 \lesssim 7 \text{ GeV}^2)</td>
<td>directly</td>
</tr>
<tr>
<td>Khodjamirian et al.</td>
<td>✓</td>
<td>✗</td>
<td>✓</td>
<td>(q^2 &lt; 1 \text{ GeV}^2)</td>
<td>extrapolation by dispersion relation</td>
</tr>
<tr>
<td>[1006.4945]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bobeth et al.</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>(q^2 &lt; 0 \text{ GeV}^2)</td>
<td>extrapolation by analyticity</td>
</tr>
<tr>
<td>[1707.07305]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Extrapolation by dispersion relation misses leading nonfact. QCDf contribution (not recommended in Khodjamirian et al. arXiv:1006.4945)

- Adding the QCDf piece in physical region after extrapolation is problematic (see i.e. PMD method in Ciuchini et al. arXiv:1704.05447)

- Bobeth et al. method is most complete and promising approach (see recent paper on convergence of z-expansion arXiv:1805.06378)
Correlations of theory errors are not given in Bobeth et al.
Comparison of various approaches

Correlations of theory errors are not given in Bobeth et al.

NP significance

<table>
<thead>
<tr>
<th></th>
<th>SM</th>
<th>$\delta C_7$</th>
<th>$\delta C_9$</th>
<th>$\delta C_{10}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>b.f. value</td>
<td>b.f. value</td>
<td>$\chi^2_{\text{min}}$</td>
<td>b.f. value</td>
</tr>
<tr>
<td>QCDf</td>
<td>60.9</td>
<td>$-0.03 \pm 0.02$</td>
<td>58.9 (1.4$\sigma$)</td>
<td>$-1.05 \pm 0.21$</td>
</tr>
<tr>
<td>&quot;+10%&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bobeth et al.</td>
<td>54.8</td>
<td>$-0.03 \pm 0.03$</td>
<td>53.5 (1.1$\sigma$)</td>
<td>$-1.26 \pm 0.28$</td>
</tr>
</tbody>
</table>

Arby, Hurth, Mahmoudi, Neshatpour arXiv: 1806.02791
Global fits using the angular observables only (NO theoretically clean $R$ ratios)

Considering several luminosities, assuming the current central values

LHCb upgrade will be able to distinguish between NP and hadronic effects within the angular observables – even without any theoretical progress
Crosscheck of LHCb anomalies with inclusive modes

Hurth, Mahmoudi, Neshatpour, arXiv:1410.4545

if SM deviations in $R_K$ and $P'_5$ persist until Belle-II

If NP then the effect of $C_9$ and $C'_9$ are large enough to be checked at Belle-II with theoretically clean modes.

Hurth, Mahmoudi, arXiv:1312.5267 Experimental extrapolation by Kevin Flood
Extra
New physics explanations \((1\sigma\) solutions\)

Difficult to generate \(\delta C_9 = -1\) at loop level (MSSM with MFV)

Various models under discussion (tree level contributions):

- **\(Z'\) bosons**

  \[
  \begin{align*}
  s_L & \quad \mu^- \\
  b_L & \quad \mu^+
  \end{align*}
  \]

- **Leptoquarks**

  \[
  \begin{align*}
  b & \quad \mu^+ \\
  s & \quad \mu^-
  \end{align*}
  \]

  LQ

References:

- Altmannshofer, Straub arXiv:1308.1501
- Gauld, Goertz, Haisch arXiv:1308.1959;1310.1082
- Buras, De Fazio, Girrbach arXiv:1311.6729
- Altmannshofer, Gori, Pospelov, Yavin arXiv:1403.1269
- Sahoo, Mohanta arXiv:1501.05193
- Becirevic, Fajfer, Kosnik arXiv:1503.09024

...
Model explaining all anomalies by one leptoquark

\[ R_{D^{(*)}}^{\tau/l} = \frac{\mathcal{B}(\bar{B} \rightarrow D^{(*)}\tau\bar{\nu})}{\mathcal{B}(\bar{B} \rightarrow D^{(*)}l\bar{\nu})} / \mathcal{B}(\bar{B} \rightarrow D^{(*)}l\bar{\nu})_{SM} \]

3.9\sigma deviation from \( \tau - \mu/e \) universality

\[ R_{K}^{\mu/e} = \frac{\mathcal{B}(B \rightarrow K\mu^+\mu^-)}{\mathcal{B}(B \rightarrow Ke^+e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036 \]

2.6\sigma deviation from \( \mu - e \) universality

\[ (g - 2)_{\mu} \]

Problem with \( R_{D}^{\mu/e} \)?

Becirevic et al. arXiv:1608.07583
Previous predictions versus LHCb Monte Carlo (10 fb$^{-1}$)


- unknown $\Lambda/m_b$ power corrections

$$A_{\perp,\parallel,0} = A_{\perp,\parallel,0}^0 \left(1 + c_{\perp,\parallel,0}\right)$$ vary $c_i$ in a range of $\pm 10\%$ and also of $\pm 5\%$

Guesstimate

The experimental errors assuming SUSY scenario (b) with large-gluino mass and positive mass insertion, is compared to the theoretical errors assuming the SM.

This was the dream in 2008

see also Altmannshofer et al., arXiv:0811.1214; Bobeth et al., arXiv:0805.2525
Fit the unknown power corrections to the data

data of 2015/2016
Leading SCET amplitude with general ansatz with 18 parameters for power corrections

Camalich, Jäger arXiv:1212.2263

Fit needs 20 – 50% power corrections (on the observable level)

No sign for $q^2$ dependence in the theory-independent fit

Significant $q^2$ dependence if power corrections are fixed at 1GeV via result of LCSR calculation

Kjodjamirian et al. arXiv:1211.0234
Power corrections in QCD improved factorization

\[ T_a^{(i)} = \xi_a C_a^{(i)} + \phi_B \otimes T_a^{(i)} \otimes \phi_{a,K} + \mathcal{O}(1/m_b) \]

BBNS 1999

Power corrections cannot be calculated within QCDf in general.

→ Significance of the tensions in the angular observables depend on the assumptions on the power corrections.

Fit of the power corrections to the data:

Variation of power corrections \((1 + C_i)\) or more sophisticated ansatz:
Hurth et al. (arXiv:1603.00865): Assumption of 60\% (10\%) nonfact. power corrections on the amplitude level lead to 17-20\% (3\%) on the observable level \((S_3, S_4, S_5)\) only.

Do large power corrections at \(\mathcal{O}(50\%)\) - on the observable level - question the validity of the QCDf ansatz?