Hadronic and New Physics contributions to $b \to s$ transitions

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Based on arXiv:1603.00865, arXiv:1702.02234, arXiv:1705.06274 and arXiv:1806.02791

XIII Meeting on B Physics: Synergy between LHC & SUPERKEKB in the Quest for New Physics

$b \to s$ transitions

Radiative and (semi)leptonic rare B decays are highly sensitive probes for new physics

Inclusive decays $B \to X_s\gamma$ and $B \to X_s\ell^+\ell^-$

- Precise theory calculations
- Heavy mass expansion
- Theoretical description of power corrections available $\to$ they can be calculated or estimated within the theoretical approach
- Full exploitation possible with Belle-II (complete angular analysis)

Exclusive decays

- Leptonic: $B_s \to \mu^+\mu^-$
  $\to$ theory errors under control (decay constant with rather good precision)
- Semileptonic: $B \to K^*\mu^+\mu^-$, $B \to K\mu^+\mu^-$ and $B_s \to \phi\mu^+\mu^-$
  $\to$ many experimentally accessible observables

  $\to$ issue of hadronic uncertainties in exclusive modes

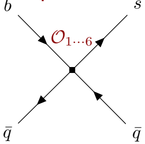
  no theoretical description of power corrections existing within the theoretical framework of QCD factorisation and SCET

Effective field theory

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(\sum_{i=1\cdots 10,S,P} \left(C_i(\mu)\mathcal{O}_i(\mu) + C'_i(\mu)\mathcal{O}'_i(\mu) \right) \right)$$

Operator set for $b \to s$ transitions:

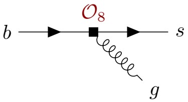
4-quark operators



$\mathcal{O}_{1,2} \propto (\bar{s}\Gamma_\mu c)(\bar{c}\Gamma^\mu b)$

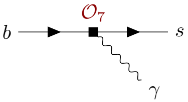
$\mathcal{O}_{3,4} \propto (\bar{s}\Gamma_\mu b)\sum_q(\bar{q}\Gamma^\mu q)$

chromomagnetic dipole operator



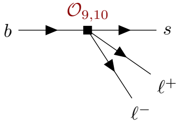
$\mathcal{O}_8 \propto (\bar{s}\sigma^{\mu\nu} T^a P_R) G^a_{\mu\nu}$

electromagnetic dipole operator



$\mathcal{O}_7 \propto (\bar{s}\sigma^{\mu\nu} P_R) F^a_{\mu\nu}$

semileptonic operators



$\mathcal{O}^\ell_9 \propto (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell)$

$\mathcal{O}^\ell_{10} \propto (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\gamma_5 \ell)$

+ the chirality flipped counter-parts of the above operators, $\mathcal{O}'_i$

Wilson coefficients:

The Wilson coefficients are calculated perturbatively and are process independent.
SM contributions known to NNLL **(Bobeth, Misiak, Urban '99; Misiak, Steinhauser '04, Gorbahn, Haisch '04; Gorbahn, Haisch, Misiak '05; Czakon, Haisch, Misiak '06,...)**

$$C_7 = -0.294 \qquad C_9 = 4.20 \qquad C_{10} = -4.01$$

Many observables, with different sensitivities to different Wilson coefficients.

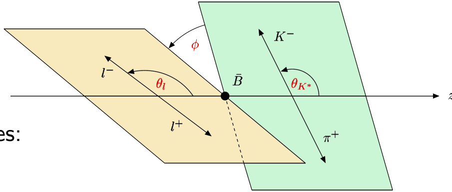
decay	obs	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$
$B \to X_s \gamma$	BR	X		
$B \to K^* \gamma$	BR, $A_{\rm I}$	X		
$B \to X_s \ell^+ \ell^-$	$\mathrm{dBR}/\mathrm{d}q^2$, $A_{\rm FB}$	X	X	X
$B \to K \ell^+ \ell^-$	$\mathrm{dBR}/\mathrm{d}q^2$	X	X	X
$B \to K^* \ell^+ \ell^-$	$\mathrm{dBR}/\mathrm{d}q^2$, angular obs.	X	X	X
$B_s \to \phi \ell^+ \ell^-$	$\mathrm{dBR}/\mathrm{d}q^2$, angular obs.	X	X	X
$B_s \to \mu^+ \mu^-$	BR			X

The only reason C_9 is the main player to explain the anomalies is that C_7 and C_{10} are severely constrained!

$$\delta \langle P_5' \rangle_{[4.3,8.68]} \simeq -0.52\, \delta C_7 \quad -0.03\, \delta C_8 \quad -0.08\, \delta C_9 \quad -0.03\, \delta C_{10}$$

Angular distributions

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



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}

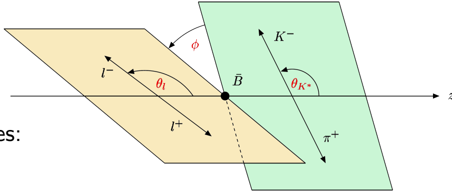
↘ functions of the spin amplitudes A_0, $A_\parallel$, $A_\perp$, A_t, and A_S

Spin amplitudes: functions of Wilson coefficients and form factors

Main operators:

$$\mathcal{O}_9 = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell), \quad \mathcal{O}_{10} = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\gamma_5 \ell)$$

$$\mathcal{O}_S = \frac{e^2}{16\pi^2}(\bar{s}^\alpha_L b^\alpha_R)(\bar{\ell}\,\ell), \quad \mathcal{O}_P = \frac{e^2}{16\pi^2}(\bar{s}^\alpha_L b^\alpha_R)(\bar{\ell}\gamma_5 \ell)$$



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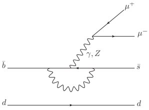
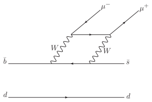




Optimised observables: form factor uncertainties cancel at leading order

$$\langle P_1 \rangle_{\rm bin} = \frac{1}{2} \frac{\int_{\rm bin} dq^2 [J_3 + \bar{J}_3]}{\int_{\rm bin} dq^2 [J_{2s} + \bar{J}_{2s}]} \qquad \langle P_2 \rangle_{\rm bin} = \frac{1}{8} \frac{\int_{\rm bin} dq^2 [J_{6s} + \bar{J}_{6s}]}{\int_{\rm bin} dq^2 [J_{2s} + \bar{J}_{2s}]}$$

$$\langle P'_4 \rangle_{\rm bin} = \frac{1}{\mathcal{N}'_{\rm bin}} \int_{\rm bin} dq^2 [J_4 + \bar{J}_4] \qquad \langle P'_5 \rangle_{\rm bin} = \frac{1}{2\mathcal{N}'_{\rm bin}} \int_{\rm bin} dq^2 [J_5 + \bar{J}_5]$$

$$\langle P'_6 \rangle_{\rm bin} = \frac{-1}{2\mathcal{N}'_{\rm bin}} \int_{\rm bin} dq^2 [J_7 + \bar{J}_7] \qquad \langle P'_8 \rangle_{\rm bin} = \frac{-1}{\mathcal{N}'_{\rm bin}} \int_{\rm bin} dq^2 [J_8 + \bar{J}_8]$$

with

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

$+$ CP violating clean observables and other combinations

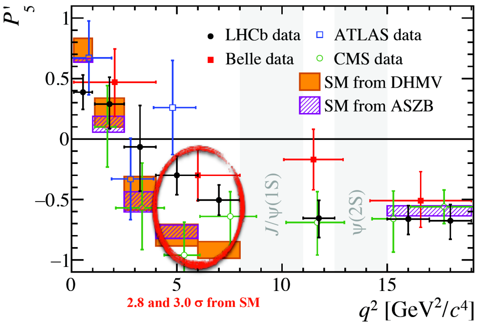
U. Egede et al., JHEP 0811 (2008) 032, JHEP 1010 (2010) 056
J. Matias et al., JHEP 1204 (2012) 104
S. Descotes-Genon et al., JHEP 1305 (2013) 137

Or alternatively:

$$S_i = \frac{J_{i(s,c)} + \bar{J}_{i(s,c)}}{\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}} \,, \qquad P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_L(1-F_L)}}$$

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))**



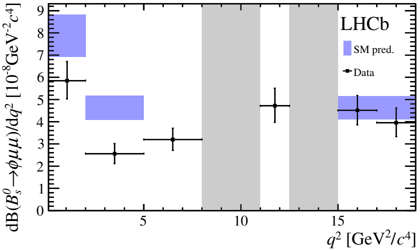
LHCb, JHEP 02 (2016) 104; Belle, PRL 118 (2017); ATLAS, ATLAS-CONF-2017-023; CMS, CMS-PAS-BPH-15-008

- Also measured by ATLAS, CMS and Belle

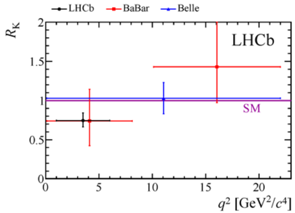
$B_s \to \phi\mu^+\mu^-$ branching fraction

- Same theoretical description as $B \to K^*\mu^+\mu^-$
  - Replacement of $B \to K^*$ form factors with the $B_s \to \phi$ ones
  - Also consider the $B_s - \bar{B}_s$ oscillations
- June 2015 (3 fb^{-1}): the differential branching fraction is found to be **3.2σ** below the SM predictions in the [1-6] GeV^2 bin

JHEP 1509 (2015) 179



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



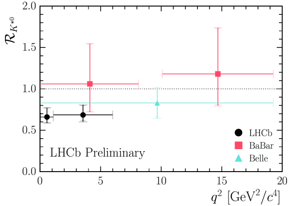
- Theoretical description similar to $B \to K^* \mu^+ \mu^-$, but different since K is scalar
- SM prediction very accurate
- June 2014 (3 fb^{-1}): measurement of

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

in the [1-6] GeV^2 bin: **2.6σ** tension (LHCb, PRL 113, 151601(2014))

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

Lepton flavour universality in $B^0 \to K^{*0} \ell^+ \ell^-$



- LHCb measurement (April 2017): JHEP 08 (2017) 055

$$R_{K^*} = BR(B^0 \to K^{*0} \mu^+ \mu^-)/BR(B^0 \to K^{*0} e^+ e^-)$$

- Two q^2 regions: [0.045-1.1] and [1.1-6.0] GeV^2
- **2.2-2.5σ** tension in each bin

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

If confirmed this would be a groundbreaking discovery!

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

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

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

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

Transversity amplitudes:

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

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

$$A_0^{L,R} \simeq N_0 \Big\{ (C_9^- \mp C_{10}^-) \left[(\ldots) A_1(q^2) + (\ldots) A_2(q^2) \right] + 2m_b C_7^- \left[(\ldots) T_2(q^2) + (\ldots) T_3(q^2) \right] \Big\}$$

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

$$(C_i^\pm \equiv C_i \pm C_i')$$

Issue of hadronic effects

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

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

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

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

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

$$\equiv \frac{e^2}{q^2}\epsilon_\mu L_V^\mu \Big[\underbrace{\text{LO in } \mathcal{O}(\frac{\Lambda}{m_b}, \frac{\Lambda}{E_{K^*}})}_{\text{Non-Fact., QCDf}} + \underbrace{h_\lambda(q^2)}_{\text{power corrections}} \Big]$$

Beneke et al.: 106067; 0412400

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power corrections
$\rightarrow$ **unknown**

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partial calculation: Khodjamirian et al., 1006.4945

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Non-Fact., QCDf

Beneke et al.: 106067; 0412400

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

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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 the combined fits!

New Physics or hadronic effects?

Global fits

Many observables $\rightarrow$ **Global fits** of the latest LHCb data

Relevant $\mathcal{O}$perators:

$$\mathcal{O}_7,\ \mathcal{O}_8,\ \mathcal{O}_{9\mu,e}^{(\prime)},\ \mathcal{O}_{10\mu,e}^{(\prime)} \quad \text{and} \quad \mathcal{O}_{S-P} \propto (\bar{s}P_R b)(\bar{\mu}P_L\mu)$$

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

$$C_i(\mu) = C_i^{\rm SM}(\mu) + \delta C_i$$

- $\rightarrow$ Scans over the values of δC_i
- $\rightarrow$ Calculation of flavour observables
- $\rightarrow$ Comparison with experimental results
- $\rightarrow$ Constraints on the Wilson coefficients C_i

Several groups doing global fits (with similar results):

B. Capdevila, A. Crivellin, S. Descotes-Genon, J. Matias and J. Virto, JHEP 1801 (2018) 093
W. Altmannshofer, P. Stangl and D. M. Straub, Phys. Rev. D 96 (2017) no.5, 055008
G. D'Amico, M. Nardecchia, P. Panci, F. Sannino, A. Strumia, R. Torre and Urbano, JHEP 1709 (2017) 010
G. Hiller and I. Nisandzic, Phys. Rev. D 96 (2017) no.3, 035003
L. S. Geng, B. Grinstein, S. Jager, J. Martin Camalich, X. L. Ren and R. X. Shi, Phys. Rev. D 96 (2017) no.9, 093006
M. Ciuchini, A. M. Coutinho, M. Fedele, E. Franco, A. Paul, L. Silvestrini and M. Valli, Eur. Phys. J. C 77 (2017) no.10, 688
T. Hurth, FM, D. Martinez Santos and S. Neshatpour, Phys. Rev. D 96 (2017) no.9, 095034
...

Theoretical uncertainties and correlations

- Monte Carlo analysis
- variation of the "standard" input parameters: masses, scales, CKM, ...
- decay constants taken from the latest lattice results
- use for the $B_{(s)} \to V$ form factors of the lattice+LCSR combinations from 1503.05534, including correlations
- $B \to K$ form factors are obtained from the lattice+LCSR combinations (1411.3161, 1503.05534), including all the correlations
- for $B_s \to \phi\mu^+\mu^-$, mixing effects taken into account
- Parameterisation of uncertainties from power corrections:

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

↘ Leading Order QCDf of non-factorisable piece

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

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

Global fits

Global fits of the observables obtained by minimisation of

$$\chi^2 = \left(\vec{O}^{\rm th} - \vec{O}^{\rm exp}\right) \cdot (\Sigma_{\rm th} + \Sigma_{\rm exp})^{-1} \cdot \left(\vec{O}^{\rm th} - \vec{O}^{\rm exp}\right)$$

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

More than 100 observables relevant for leptonic and semileptonic decays:

- $\mathrm{BR}(B \to X_s\gamma)$
- $\mathrm{BR}(B \to X_d\gamma)$
- $\mathrm{BR}(B \to K^*\gamma)$
- $\Delta_0(B \to K^*\gamma)$
- $\mathrm{BR}^{\rm low}(B \to X_s\mu^+\mu^-)$
- $\mathrm{BR}^{\rm high}(B \to X_s\mu^+\mu^-)$
- $\mathrm{BR}^{\rm low}(B \to X_s e^+e^-)$
- $\mathrm{BR}^{\rm high}(B \to X_s e^+e^-)$
- $\mathrm{BR}(B_s \to \mu^+\mu^-)$
- $\mathrm{BR}(B_d \to \mu^+\mu^-)$
- $\mathrm{BR}(B \to K^0\mu^+\mu^-)$
- $\mathrm{BR}(B \to K^{*+}\mu^+\mu^-)$
- $\mathrm{BR}(B \to K^+\mu^+\mu^-)$
- $\mathrm{BR}(B \to K^* e^+e^-)$
- R_K
- R_{K^*}
- $B \to K^{*0}\mu^+\mu^-$: 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^2bins
- $B_s \to \phi\mu^+\mu^-$: BR, F_L, S_3, S_4, S_7
  in 3 low q^2 and 2 high q^2bins

Computations performed using SuperIso public program

NP Fit results: single operator

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

All $b \to s$ data except $R_{K^{(*)}}$		$(\chi^2_{\rm SM} = 98.1)$	
	b.f. value	$\chi^2_{\rm min}$	$\mathrm{Pull}_{\rm SM}$
δC_9	-1.02 ± 0.20	79.7	4.3σ
δC_{10}	0.18 ± 0.25	97.6	0.8σ
δC_9^μ	-1.05 ± 0.19	77.5	4.5σ
δC_9^e	0.72 ± 0.58	96.9	1.1σ
δC_{10}^μ	0.27 ± 0.25	96.8	1.1σ
δC_{10}^e	-0.56 ± 0.50	97.1	1.0σ

$\rightarrow$ C_9 and C_9^μ solutions are favoured with SM pulls of 4.3 and 4.5σ

$\rightarrow$ C_{10}-like solutions do not play a role

NP Fit results: single operator

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

All $b \to s$ data except $R_{K^{(*)}}$	($\chi^2_{\rm SM} = 98.1$)		
	b.f. value	$\chi^2_{\rm min}$	${\rm Pull}_{\rm SM}$
δC_9	-1.02 ± 0.20	79.7	4.3σ
δC_{10}	0.18 ± 0.25	97.6	0.8σ
δC_9^μ	-1.05 ± 0.19	77.5	4.5σ
δC_9^e	0.72 ± 0.58	96.9	1.1σ
δC_{10}^μ	0.27 ± 0.25	96.8	1.1σ
δC_{10}^e	-0.56 ± 0.50	97.1	1.0σ

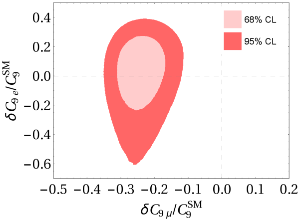
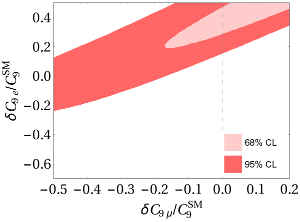
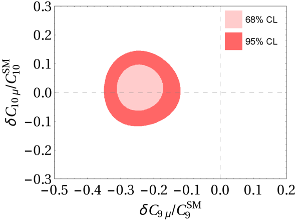
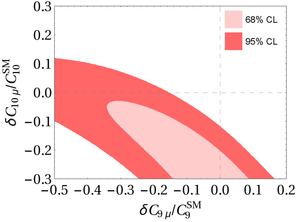
→ C_9 and C_9^μ solutions are favoured with SM pulls of 4.3 and 4.5σ

→ C_{10}-like solutions do not play a role

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

Only R_K and R_{K^*}	($\chi^2_{\rm SM} = 18.7$)		
	b.f. value	$\chi^2_{\rm min}$	${\rm Pull}_{\rm SM}$
δC_9	-1.99 ± 5.81	18.6	0.3σ
δC_{10}	4.09 ± 12.23	18.5	0.5σ
δC_9^μ	-1.47 ± 0.52	5.3	3.7σ
δC_9^e	1.58 ± 0.49	3.6	3.9σ
δC_{10}^μ	1.38 ± 0.44	2.8	4.0σ
δC_{10}^e	-1.44 ± 0.44	2.3	4.1σ

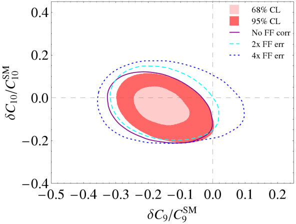
→ NP in C_9^e, C_9^μ, C_{10}^e, or C_{10}^μ are favoured by the $R_{K^{(*)}}$ ratios (significance: $3.7 - 4.1\sigma$)

	using all but R_K and R_{K^*}	using only R_K and R_{K^*}
$(C_9^\mu - C_9^e)$		
$(C_9^\mu - C_{10}^\mu)$		

The two sets are compatible at least at the 2σ level.

Fits with different assumptions for the form factor uncertainties:

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



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

Fit results for two operators: dependence on hadronic uncertainties

Fits with different assumptions for the form factor uncertainties:

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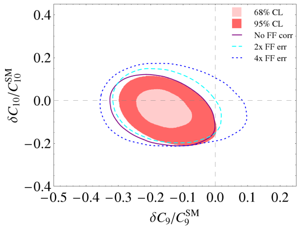
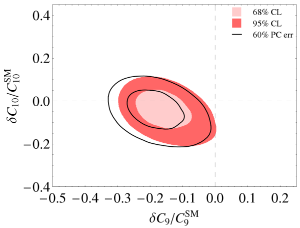


The size of the form factor errors has a crucial role in constraining the allowed region!

Fits assuming different power correction uncertainties:

- 10% uncertainty (filled areas)
- 60% uncertainty (solid line)



60% power correction uncertainty leads to only 17-20% error at the observable level.
Significance of the tension depends on the assumption on the size of the power corrections

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

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

$\left(N' = -\frac{4 G_F m_B}{\sqrt{2}}\frac{e^2}{16\pi^2} V_{tb}V_{ts}^*\right)$ $\mathcal{N}_\lambda(q^2) =$ **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 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:

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

$$\delta H_V^{\rm PC}(\lambda=0) = i\,N' m_B^2 \frac{16\pi^2}{\sqrt{q^2}}\left(h_0^{(0)} + q^2\,h_0^{(1)} + q^4\,h_0^{(2)}\right)$$

New Physics effect:

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

and similarly for $\lambda = 0$ and for C_7

⇒ NP effects can be embedded in the hadronic effects.

New physics or hadronic effects?

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Wilks' test

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

Due to this embedding the two fits can be compared with the Wilks' test

nr. of parameters	1 (Real δC_9)	2 (Real $\delta C_7, \delta C_9$)	2 (Complex δC_9)	4 (Complex $\delta C_7, \delta C_9$)	18 (Complex $h_{+,-,0}^{(0,1,2)}$)
0 (plain SM)	4.1σ	4.0σ	4.2σ	4.1σ	3.1σ
1 (Real δC_9)	–	1.5σ	2.1σ	2.0σ	1.5σ
2 (Real $\delta C_7, \delta C_9$)	–	–	–	1.9σ	1.4σ
2 (Complex δC_9)	–	–	–	1.4σ	1.1σ
4 (Complex $\delta C_7, \delta C_9$)	–	–	–	–	0.95σ

→ Adding δC_9 improves over the SM hypothesis by 4.1σ

→ Including in addition δC_7, imaginary parts or hadronic parameters improves the situation only mildly

→ One cannot rule out the hadronic option

Adding 17 more parameters does not improve the fits significantly

The situation is still inconclusive

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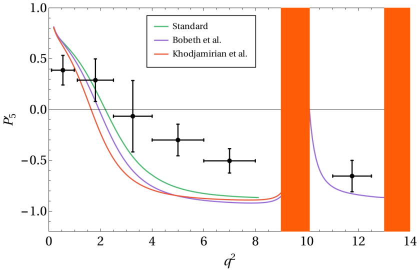
Various methods for hadronic effects

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

	factorisable	non-factorisable	power corrections (soft gluon)	region of calculation	physical region of interest
Standard	✓	✓	✗	$q^2 \lesssim 7$ GeV^2	directly
Khodjamirian et al. [1006.4945]	✓	✗	✓	$q^2 < 1$ GeV^2	extrapolation by dispersion relation
Bobeth et al. [1707.07305]	✓	✓	✓	$q^2 < 0$ GeV^2	extrapolation by analyticity



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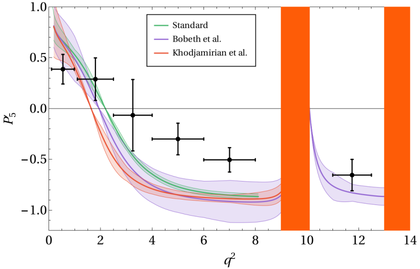

More realistic analyses

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 correct picture!

$C_{S,P}$ are usually assumed to be highly constrained by BR($B_s \to \mu^+\mu^-$)

$\to$ not considered in the global fits

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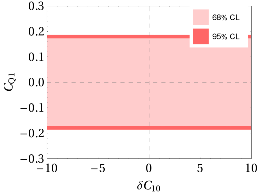
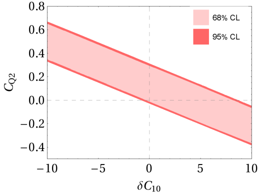
More realistic fits

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





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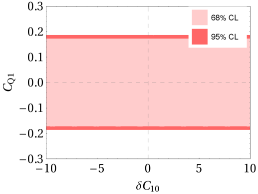
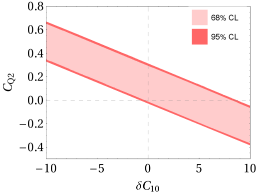
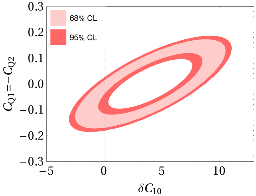




Even if $C_S = -C_P$, allowing for small variations of $C_{S,P}$ alleviates the constraints from $B_s \to \mu^+\mu^-$ on C_{10}



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.

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

effective degrees of freedom (e-dof): degrees of freedom minus the parameters δC_i only weakly affecting the χ^2, defined such as

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Effective number of degrees of freedom

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Fit results with more than two operators: All observables

Set: real C_7, C_8, C_9^ℓ, C_{10}^ℓ, C_S^ℓ, C_P^ℓ + primed coefficients

20 degrees of freedom, 108 observables

Set of WC	Nr. parameters (e-dof)	$\chi^2_{\rm min}$	Pull$_{\rm SM}$	Improvement
SM	0	118.8	-	-
C_9^μ	1	85.1	5.8σ	5.8σ
$C_9^{(e,\mu)}$	2	83.9	5.6σ	1.1σ
$C_7, C_8, C_9^{(e,\mu)}, C_{10}^{(e,\mu)}$	6	81.2	4.8σ	0.5σ
All non-primed WC	10 (8)	81.0	$4.1\,(4.5)\sigma$	$0.0\,(0.1)\sigma$
All WC (incl. primed)	20 (16)	70.2	$3.6\,(4.1)\sigma$	$0.9\,(1.2)\sigma$

- No real improvement in the fits when going beyond the $C_9^{(e,\mu)}$ case
- Pull with the SM decreases when all WC are varied
- Many parameters are very weakly constrained

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Fit results with more than two operators: All observables

All observables with $\chi^2_{\rm SM} = 118.8$ ($\chi^2_{\rm min} = 70.2$; ${\rm Pull}_{\rm SM} = 3.5\,(4.1)\sigma$)

δC_7	δC_8
-0.01 ± 0.05	0.89 ± 0.81
$\delta C_7'$	$\delta C_8'$
0.01 ± 0.03	-1.70 ± 0.46

δC_9^μ	δC_9^e	δC_{10}^μ	δC_{10}^e
-1.40 ± 0.26	-4.02 ± 5.58	-0.07 ± 0.28	1.32 ± 2.02
$\delta C_9'^\mu$	$\delta C_9'^e$	$\delta C_{10}'^\mu$	$\delta C_{10}'^e$
0.23 ± 0.65	-1.10 ± 5.98	-0.16 ± 0.38	2.70 ± 2

$C_{Q_1}^\mu$	$C_{Q_1}^e$	$C_{Q_2}^\mu$	$C_{Q_2}^e$
-0.13 ± 1.86	undetermined	-0.05 ± 0.58	undetermined
$C_{Q_1}'^\mu$	$C_{Q_1}'^e$	$C_{Q_2}'^\mu$	$C_{Q_2}'^e$
0.01 ± 1.87	undetermined	-0.18 ± 0.62	undetermined

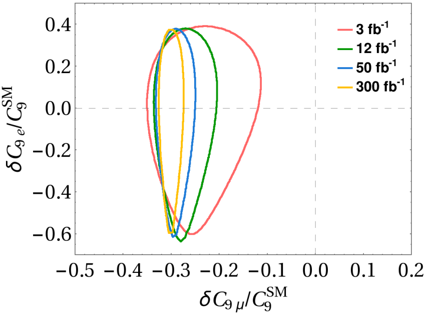
- No real improvement in the fits when going beyond the $C_9^{(e,\mu)}$ case
- Pull with the SM decreases when all WC are varied
- Many parameters are very weakly constrained

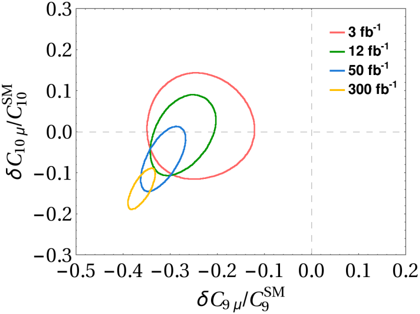
Future prospects

1) Future LHCb prospects

Global fits using the angular observables only (NO theoretically clean R ratios)

Considering several luminosities, assuming the current central values





LHCb may be able to establish new physics within the angular observables even in the pessimistic case that there will be no theoretical progress on non-factorisable power corrections!

$\mathrm{Pull_{SM}}$ for the fit to ΔC_9^μ based on R_K and R_{K^*} only for the LHCb upgrade

Assuming current central values remain

ΔC_9^μ	Syst. $\mathrm{Pull_{SM}}$	Syst./2 $\mathrm{Pull_{SM}}$	Syst./3 $\mathrm{Pull_{SM}}$
12 fb^{-1}	6.1σ (4.3σ)	7.2σ (5.2σ)	7.4σ (5.5σ)
50 fb^{-1}	8.2σ (5.7σ)	11.6σ (8.7σ)	12.9σ (9.9σ)
300 fb^{-1}	9.4σ (6.5σ)	15.6σ (12.3σ)	19.5σ (16.1σ)

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

Only a small part of the 50 fb^{-1} is needed to establish NP in the $R_{K^{(*)}}$ ratios even in the pessimistic case that the systematic errors are not reduced by then at all.

This is independent of the hadronic uncertainties!

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:

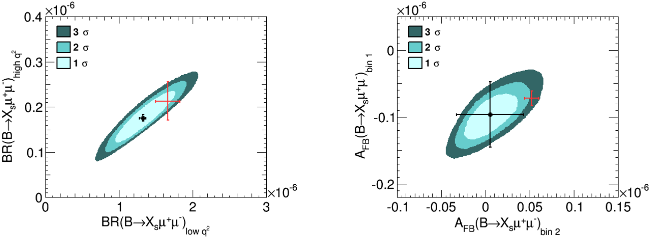
	Predictions assuming 12 fb^{-1} luminosity			
Obs.	C_9^μ	C_9^e	C_{10}^μ	C_{10}^e
$R_{F_L}^{[1.1,6.0]}$	$[0.785, 0.913]$	$[0.909, 0.933]$	$[1.005, 1.042]$	$[1.001, 1.018]$
$R_{A_{FB}}^{[1.1,6.0]}$	$[6.048, 14.819]$	$[-0.288, -0.153]$	$[0.816, 0.928]$	$[0.974, 1.061]$
$R_{S_5}^{[1.1,6.0]}$	$[-0.787, 0.394]$	$[0.603, 0.697]$	$[0.881, 1.002]$	$[1.053, 1.146]$
$R_{F_L}^{[15,19]}$	$[0.999, 0.999]$	$[0.998, 0.998]$	$[0.997, 0.998]$	$[0.998, 0.998]$
$R_{A_{FB}}^{[15,19]}$	$[0.616, 0.927]$	$[1.002, 1.061]$	$[0.860, 0.994]$	$[1.046, 1.131]$
$R_{S_5}^{[15,19]}$	$[0.615, 0.927]$	$[1.002, 1.061]$	$[0.860, 0.994]$	$[1.046, 1.131]$
$R_{K^*}^{[15,19]}$	$[0.621, 0.803]$	$[0.577, 0.771]$	$[0.589, 0.778]$	$[0.586, 0.770]$
$R_K^{[15,19]}$	$[0.597, 0.802]$	$[0.590, 0.778]$	$[0.659, 0.818]$	$[0.632, 0.805]$
$R_\phi^{[1.1,6.0]}$	$[0.748, 0.852]$	$[0.620, 0.805]$	$[0.578, 0.770]$	$[0.578, 0.764]$
$R_\phi^{[15,19]}$	$[0.623, 0.803]$	$[0.577, 0.771]$	$[0.586, 0.776]$	$[0.583, 0.769]$

A confirmation of the deviations in the ratios would indirectly confirm the NP interpretation of the anomalies in the angular observables!

3) 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 $b \to s\ell\ell$:



T. Hurth, FM, JHEP 1404 (2014) 097

T. Hurth, FM, S. Neshatpour, JHEP 1412 (2014) 053

Predictions based on our model-independent analysis

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

red cross: SM predictions

$\to$ Belle-II will check the NP interpretation with theoretically clean modes

Conclusion

- The full LHCb Run 1 results still show some tensions with the SM predictions
- Significance of the anomalies depends on the assumptions on the power corrections
- Model independent fits point to about 25% reduction in C_9, and new physics in muonic C_9^μ is preferred
- The tension with the SM including all observables (assuming 10% non-factorisable power corrections) and all relevant Wilson coefficents is at the 4σ level at the moment.
- We can compare the fits for NP and hadronic parameters using the Wilks' test

  $\rightarrow$ At the moment adding the hadronic parameters does not improve the fit compared to the new physics fit, but the situation is inconclusive
- The LHCb upgrade will have enough precision to distinguish between NP and power corrections