New physics effects in $b \to s\ell\ell$ transitions

Nazila Mahmoudi

Lyon University & CERN

Based on arXiv:1603.00865, arXiv:1702.02234 & arXiv:1705.06274 and work in progress

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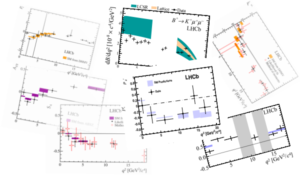
Les Rencontres de Physique de la Vallée d'Aoste: Results and Perspectives in Particle Physics
La Thuile, Feb. 25th - March 3rd, 2018

Introduction

Several tensions with the SM predictions observed in the *bsℓℓ* transitions

→ Flavour anomalies



At the moment amongst the most significant tensions with the SM at the LHC!

Focus of this talk:

→ **Can the deviations be explained by the SM uncertainties?**

→ **If the deviations are due to New Physics, what can we learn in a model independent way?**

Theoretical framework

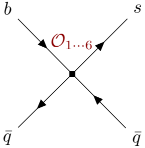
Effective field theory

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

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

Operator set for $b \to s$ transitions:

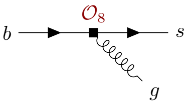
4-quark operators



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

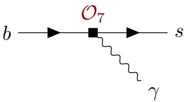
$\mathcal{O}_{3,4} \propto (\bar{s}\Gamma_\mu b)\sum_q(\bar{q}\Gamma^\mu q)$

chromomagnetic dipole operator



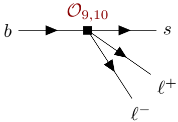
$\mathcal{O}_8 \propto (\bar{s}\sigma^{\mu\nu} T^a P_R) G^a_{\mu\nu}$

electromagnetic dipole operator



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

semileptonic operators



$\mathcal{O}_9^\ell \propto (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell)$

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

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

Theoretical framework

Wilson coefficients:

The Wilson coefficients are calculated perturbatively and are process independent

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

SM contributions known to NNLL

(Bobeth, Misiak, Urban '99; Misiak, Steinhauser '04, Gorbahn, Haisch '04; Gorbahn, Haisch, Misiak '05; Czakon, Haisch, Misiak '06,...)

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

Hadronic quantities:

$$\mathcal{A}(A \to B) = \langle B|\mathcal{H}_{\rm eff}|A\rangle = \frac{G_F}{\sqrt{2}} \sum_i \lambda_i C_i(\mu) \langle B|\mathcal{O}_i|A\rangle(\mu)$$

How to compute matrix elements?

→ Model building, Lattice simulations, light/heavy flavour symmetries, ...

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

↙ Decay constants ↘ Form factors

Main source of uncertainty!

→ design observables where the hadronic uncertainties cancel (ratios,...)

Prime example: $B \to K^* \mu^+ \mu^-$ and its angular ratios P_i'

Theoretical framework

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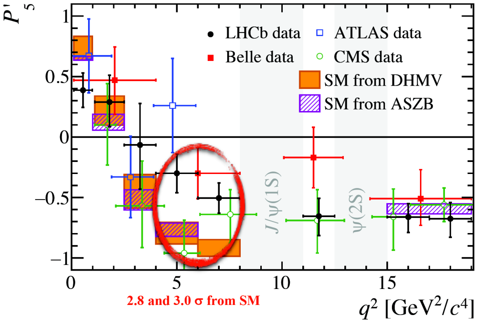
The LHCb anomalies (1)

$B \to K^* \mu^+ \mu^-$ 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

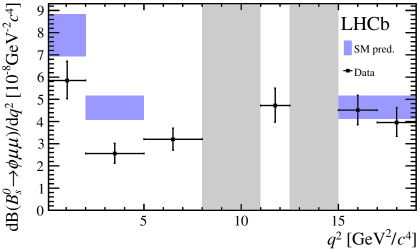
- Also measured by ATLAS, CMS and Belle

The LHCb anomalies (2)

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

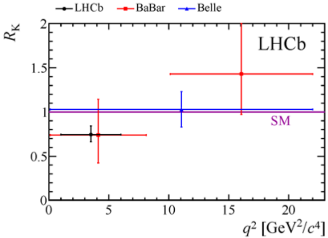


The LHCb anomalies (3)

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

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



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

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

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

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

Bordone, Isidori, Pattori, arXiv:1605.07633

If confirmed this would be a groundbreaking discovery
and a very spectacular fall of the SM

The updated analysis is eagerly awaited!

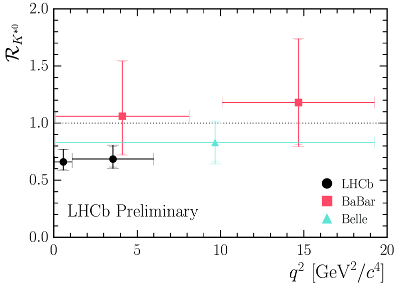
The LHCb anomalies (4)

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



$$R_{K^*}^{\rm exp,bin1} = 0.660^{+0.110}_{-0.070}({\rm stat}) \pm 0.024({\rm syst})$$

$$R_{K^*}^{\rm exp,bin2} = 0.685^{+0.113}_{-0.069}({\rm stat}) \pm 0.047({\rm syst})$$

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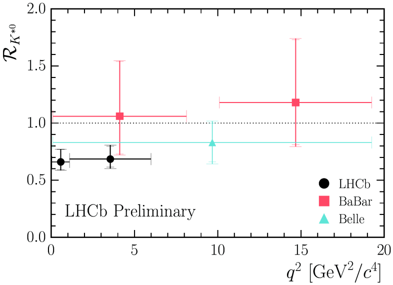

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$$R_{K^*}^{\mathrm{exp,bin2}} = 0.685^{+0.113}_{-0.069}(\mathrm{stat}) \pm 0.047(\mathrm{syst})$$

$$R_{K^*}^{\mathrm{SM,bin1}} = 0.906 \pm 0.020_{\mathrm{QED}} \pm 0.020_{\mathrm{FF}}$$

$$R_{K^*}^{\mathrm{SM,bin2}} = 1.000 \pm 0.010_{\mathrm{QED}}$$

Bordone, Isidori, Pattori, arXiv:1605.07633

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

Issue of the hadronic power corrections

Effective Hamiltonian for $b \to s$ transitions $\qquad \mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm had} + \mathcal{H}_{\rm eff}^{\rm sl}$

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

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

Transversity amplitudes:

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

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

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

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

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

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

$$\mathcal{A}_\lambda^{(\rm had)} = -i \frac{e^2}{q^2} \int d^4x\, e^{-iq\cdot x} \langle \ell^+ \ell^- | j_\mu^{\rm em,lept}(x) | 0 \rangle \times \int d^4y\, e^{iq\cdot y} \langle \bar{K}_\lambda^* | T\{ j^{\rm em,had,\mu}(y) \mathcal{H}_{\rm eff}^{\rm had}(0) \} | \bar{B} \rangle$$

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

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power corrections → **unknown**

only guesstimates possible at present
but estimates possible with some work on the theory side

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$\to$ **unknown**

only guesstimates possible at present
but estimates possible with some work on the theory side

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?

Description in terms of helicity amplitudes:

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

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

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

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

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

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 $h_{\lambda(=+,-,0)}(q^2)$:

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

S. Jäger and J. Camalich, Phys.Rev. D93 (2016) 014028M. Ciuchini et al., JHEP 1606 (2016) 116

Hadronic power correction effect:

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

New Physics effect:

$$\delta H_V^{C_9^{\text{NP}}}(\lambda) = -iN'\tilde{V}_L(q^2)C_9^{\text{NP}} = iN'm_B^2\frac{16\pi^2}{q^2}\left(a_\lambda C_9^{\text{NP}} + q^2b_\lambda C_9^{\text{NP}} + q^4c_\lambda C_9^{\text{NP}}\right)$$

and similarly for C_7

$\Rightarrow$ NP effects can be embedded in the hadronic effects.

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

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New Physics effect:

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and similarly for C_7

$\Rightarrow$ 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 $C_i^{\rm NP}$(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):

	2 (δC_9)	4 ($\delta C_7, \delta C_9$)	18 ($h_{+,-,0}^{(0,1,2)}$)
0	3.7×10^{-5} (4.1σ)	6.3×10^{-5} (4.0σ)	6.1×10^{-3} (2.7σ)
2	–	0.13 (1.5σ)	0.45 (0.76σ)
4	–	–	0.61 (0.52σ)

→ Adding δC_9 improves over the SM hypothesis by 4.1σ
→ Including in addition δC_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

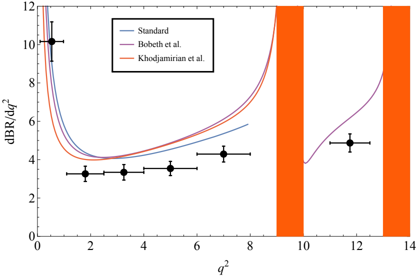
The situation is still inconclusive

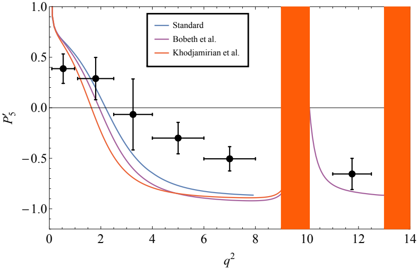
Estimates of hadronic effects

Various methods for hadronic effects

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

	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





Estimates of hadronic effects

Various methods for hadronic effects

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

	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

One operator fit

		SM	C_9	C_{10}	C_9'	C_{10}'
Standard	χ^2	60.7	45.6(3.9σ)	60.7 (0.0σ)	54.2(2.6σ)	53.8(2.6σ)
Khodjamirian et al.	χ^2	79.6	52.9(5.2σ)	74.1(2.3σ)	73.0(2.6σ)	76.8(1.7σ)
Bobeth et al.	χ^2	53.7	45.4(2.9σ)	52.5(1.1σ)	53.1(0.8σ)	52.9(0.9σ)

NP Implications

Global fits

Many observables → **Global fits**

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

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

→ Scans over the values of δC_i
→ Calculation of flavour observables

Theoretical uncertainties and correlations

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

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

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

⇒ 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:

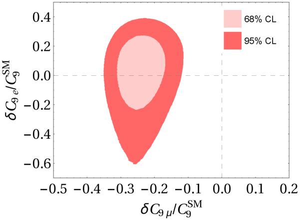
- $\mathrm{BR}(B \to X_s\gamma)$
- $\mathrm{BR}(B \to X_d\gamma)$
- $\Delta_0(B \to K^*\gamma)$
- $\mathrm{BR}^{\rm low}(B \to X_s\mu^+\mu^-)$
- $\mathrm{BR}^{\rm high}(B \to X_s\mu^+\mu^-)$
- $\mathrm{BR}^{\rm low}(B \to X_s e^+e^-)$
- $\mathrm{BR}^{\rm high}(B \to X_s e^+e^-)$
- $\mathrm{BR}(B_s \to \mu^+\mu^-)$
- $\mathrm{BR}(B_d \to \mu^+\mu^-)$
- $\mathrm{BR}(B \to K^0\mu^+\mu^-)$
- $\mathrm{BR}(B \to K^{*+}\mu^+\mu^-)$
- $\mathrm{BR}(B \to K^+\mu^+\mu^-)$
- $\mathrm{BR}(B \to K^* e^+e^-)$
- 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

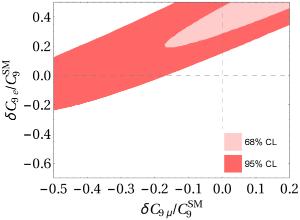
Computations performed using SuperIso public program

Fit results for two operators

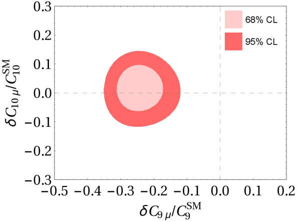
using all but R_K and R_{K^*} | using only R_K and R_{K^*}

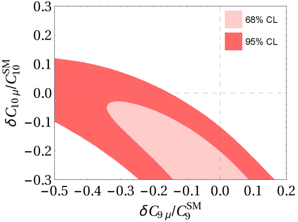
$(C_9^\mu - C_9^e)$





$(C_9^\mu - C_{10}^\mu)$





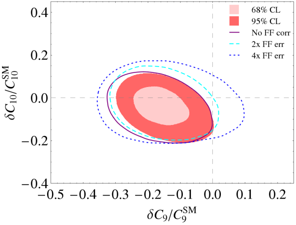
The two sets are compatible at least at the 2σ level.

Form factor dependence

Global fit using all $bs\ell\ell$ observables

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

$(C_9 - C_{10})$ $(C_9 - C_9')$ $(C_9^e - C_9^\mu)$

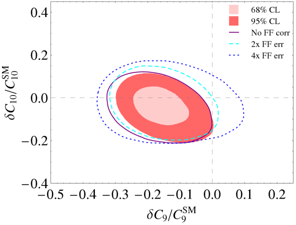


Form factor dependence

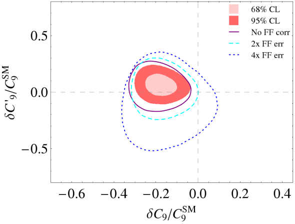
Global fit using all $bs\ell\ell$ observables

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

$(C_9 - C_{10})$



$(C_9 - C_9')$

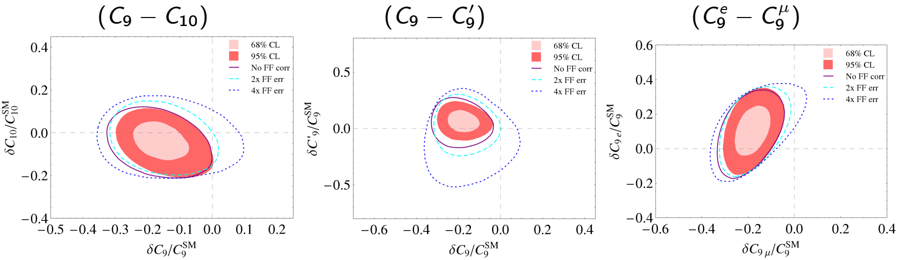


$(C_9^e - C_9^\mu)$

Form factor dependence

Global fit using all $bs\ell\ell$ observables

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



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

Fit results with more than two operators

Wilson coefficients sensitive to NP:

$$C_7, C_8, C_9^\ell, C_{10}^\ell, C_S^\ell, C_P^\ell$$

$\rightarrow$ 10 independent WC (considering $\ell = e, \mu$)

+ 10 primed Wilson coefficents

In the general case, the WC can be complex

$\rightarrow$ 40 independent real parameters!

Fit results with more than two operators: All observables

Preliminary!

107 observables

Set of WC	Nb parameters	χ^2_{min}	Pull$_{SM}$	Improv.
SM	0	105.56	-	-
$C_9^{(e,\mu)}$ real	2	79.84	4.70σ	4.70σ
$C_7, C_8, C_9^{(e,\mu)}, C_{10}^{(e,\mu)}$ real	6	79.03	3.75σ	0.08σ
All non-primed WC real	10	78.20	3.05σ	0.07σ
All WC real (incl. primed)	20	75.90	1.78σ	0.01σ
All WC complex (incl. primed)	40	67.20	0.61σ	0.01σ

- No real improvement in the fits when going beyond the $C_9^{(e,\mu)}$ case
- Pull with the SM below 1σ when all WC are varied
- Many parameters are not constrained, in particular the imaginary parts
- Significant contribution also from the electron scalar coefficient

Fit results with more than two operators: All observables

Preliminary!

All observables ($\chi^2_{\rm SM} = 105.6$, $\chi^2_{\rm min} = 67.2$)

	δC_7	δC_8
Re(δC_i)	0.02 ± 0.01	0.03 ± 0.35
Im(δC_i)	0.01 ± 0.17	-1.10 ± 0.68
	$\delta C'_7$	$\delta C'_8$
Re(δC_i)	0.02 ± 0.03	-0.13 ± 1.18
Im(δC_i)	-0.07 ± 0.02	-0.45 ± 1.50

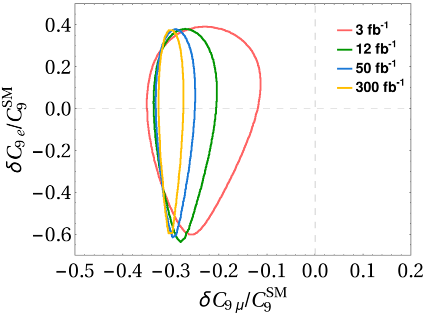
	δC_9^μ	δC_9^e	δC_{10}^μ	δC_{10}^e
Re(δC_i)	-1.25 ± 0.17	-0.45 ± 0.54	-0.20 ± 0.20	4.39 ± 3.27
Im(δC_i)	0.40 ± 4.27	-2.54 ± 0.47	0.02 ± 2.55	-0.29 ± 3.00
	$\delta C_9^{\prime\mu}$	$\delta C_9^{\prime e}$	$\delta C_{10}^{\prime\mu}$	$\delta C_{10}^{\prime e}$
Re(δC_i)	0.10 ± 0.31	0.00 ± 1.41	-0.10 ± 0.17	0.00 ± 1.41
Im(δC_i)	0.43 ± 0.59	0.32 ± 4.63	-0.14 ± 0.24	0.00 ± 5.01
	$\delta C_{Q_1}^\mu$	$\delta C_{Q_1}^e$	$\delta C_{Q_2}^\mu$	$\delta C_{Q_2}^e$
Re(δC_i)	-0.07 ± 0.02	-3.57 ± 0.96	0.10 ± 0.14	-0.01 ± 10.58
Im(δC_i)	0.00 ± 0.19	-3.53 ± 0.48	-0.01 ± 0.11	-0.02 ± 7.77
	$\delta C_{Q_1}^{\prime\mu}$	$\delta C_{Q_1}^{\prime e}$	$\delta C_{Q_2}^{\prime\mu}$	$\delta C_{Q_2}^{\prime e}$
Re(δC_i)	0.07 ± 0.02	0.00 ± 1.41	-0.06 ± 0.14	0.00 ± 1.41
Im(δC_i)	0.00 ± 0.19	-3.61 ± 0.94	0.02 ± 0.11	-0.07 ± 9.58

- No real improvement in the fits when going beyond the $C_9^{(e,\mu)}$ case
- Pull with the SM below 1σ when all WC are varied
- Many parameters are not constrained, in particular the imaginary parts
- Significant contribution also from the electron scalar coefficient

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 progress on non-factorisable power corrections!

Future LHCb prospects

Global fits to ΔC_9^μ using the ratios R_K and R_{K^*} only

Assuming current central values remain

ΔC_9^μ	Syst. Pull$_{\rm SM}$	Syst./2 Pull$_{\rm SM}$	Syst./3 Pull$_{\rm SM}$
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!

Conclusion

- The full LHCb Run 1 results show several consistent 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
- Comparing the fits for NP and hadronic parameters through the Wilk's test shows that at the moment adding the hadronic parameters does not improve the fit compared to the new physics fit, but the situation is inconclusive
- The size of the form factor errors has a significant impact in the fits
- When adding more parameters in the fit, no significant improvement is obtained
- With the full set of free parameters, the tensions with the SM fall below 1σ

Thank you for your attention!

Backup

New physics scenarios

$$\delta\langle P_2\rangle_{[0.1,2]} \simeq +0.37\,\delta C_7 \quad +0.02\,\delta C_8 \quad -0.03\,\delta C_{10}$$

$$\delta\langle P_2\rangle_{[2,4.3]} \simeq -2.48\,\delta C_7 \quad -0.10\,\delta C_8 \quad -0.17\,\delta C_9 \quad +0.03\,\delta C_{10}$$

$$\delta\langle P_2\rangle_{[4.3,8.68]} \simeq -0.71\,\delta C_7 \quad -0.04\,\delta C_8 \quad -0.09\,\delta C_9 \quad -0.04\,\delta C_{10}$$

$$\delta\langle P_4'\rangle_{[0.1,2]} \simeq +0.59\,\delta C_7 \quad -0.08\,\delta C_9 \quad -0.13\,\delta C_{10}$$

$$\delta\langle P_4'\rangle_{[2,4.3]} \simeq +2.45\,\delta C_7 \quad +0.11\,\delta C_8 \quad +0.06\,\delta C_9 \quad -0.14\,\delta C_{10}$$

$$\delta\langle P_4'\rangle_{[4.3,8.68]} \simeq +0.33\,\delta C_7 \quad +0.01\,\delta C_8 \quad +0.01\,\delta C_9$$

$$\delta\langle P_5'\rangle_{[0.1,2]} \simeq -0.91\,\delta C_7 \quad -0.04\,\delta C_8 \quad -0.12\,\delta C_9 \quad -0.03\,\delta C_{10}$$

$$\delta\langle P_5'\rangle_{[2,4.3]} \simeq -3.04\,\delta C_7 \quad -0.14\,\delta C_8 \quad -0.29\,\delta C_9 \quad -0.03\,\delta C_{10}$$

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

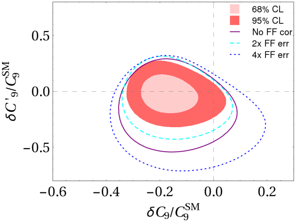
New Physics contributions to C_i' are suppressed by a factor m_s/m_b and $m_s m_b/m_t^2$

The rest of the observables are less sensitive to real NP contributions in $C_{7,8,9,10}$

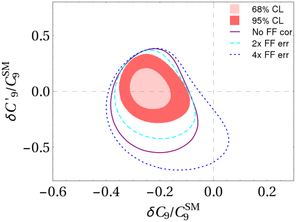
Fits with $B \to K^* \mu\mu$ angular observables only:

$(C_9 - C_{10})$ $(C_9 - C_9')$

Method of moments



Likelihood

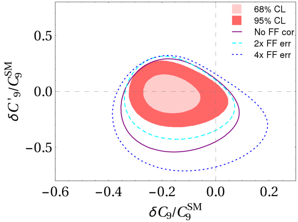


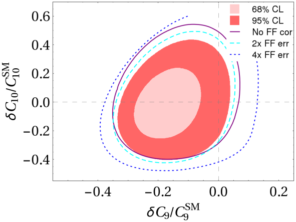
Form factor dependence

Fits with $B \to K^* \mu\mu$ angular observables only:

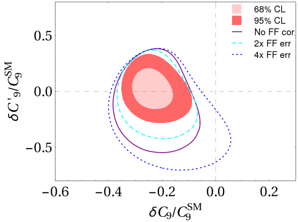
$(C_9 - C_{10})$ $(C_9 - C_9')$

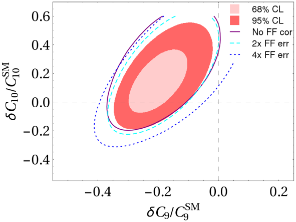
Method of moments





Likelihood



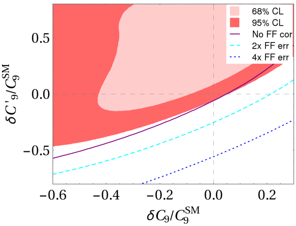


Form factor dependence

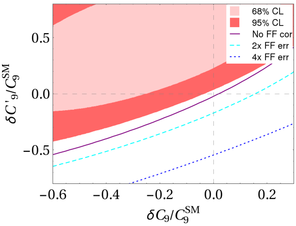
Fits with $B_s \to \phi\mu\mu$ branching fractions only:

$(C_9 - C_{10})$ $(C_9 - C_9')$

Low and high-q^2 bins



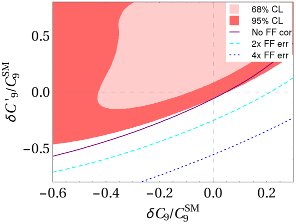
Low-q^2 bins

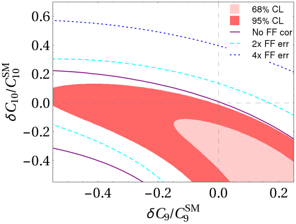


Fits with $B_s \to \phi\mu\mu$ branching fractions only:

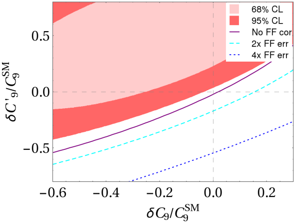
$(C_9 - C_{10})$ $(C_9 - C_9')$

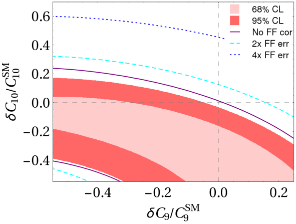
Low and high-q^2 bins





Low-q^2 bins

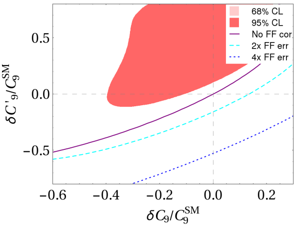




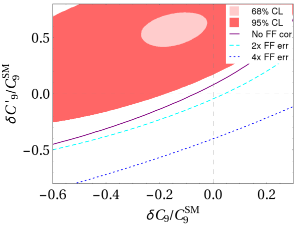
Fits with $B_s \to \phi\mu\mu$ branching fractions only, using absolute χ^2 (goodness of fit):

$(C_9 - C_{10})$ $(C_9 - C_9')$

Low and high-q^2 bins



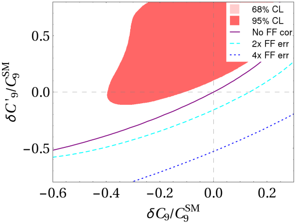
Low-q^2 bins

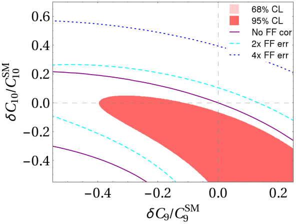


Fits with $B_s \to \phi\mu\mu$ branching fractions only, using absolute χ^2 (goodness of fit):

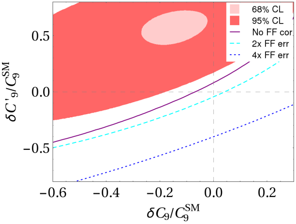
$(C_9 - C_{10})$ $(C_9 - C_9')$

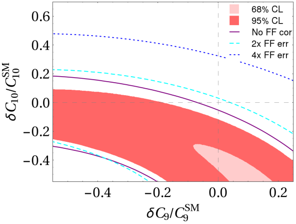
Low and high-q^2 bins





Low-q^2 bins





Fit results with more than two operators: All observables except $R_{K^{(*)}}$

Preliminary!

104 observables

Set of WC	Nb parameters	χ^2_{min}	Pull$_{SM}$	Improv.
SM	0	89.84	-	-
$C_9^{(e,\mu)}$ real	2	71.05	3.93σ	3.93σ
$C_7, C_8, C_9^{(e,\mu)}, C_{10}^{(e,\mu)}$ real	6	70.04	2.97σ	0.13σ
All non-primed WC real	10	69.25	2.25σ	0.07σ
All WC real (incl. primed)	20	67.15	1.03σ	0.01σ
All WC complex (incl. primed)	40	58.24	0.22σ	0.02σ

- Similar results to the case with $R_{K^{(*)}}$
- The value of δC_9^e is shifted

Fit results with more than two operators: All observables except $R_{K^{(*)}}$

All observables except $R_{K^{(*)}}$ $(\chi^2_{\rm SM} = 89.8,\ \chi^2_{\rm min} = 58.2)$

	δC_7	δC_8
Re(δC_i)	0.02 ± 0.01	0.03 ± 0.35
Im(δC_i)	0.02 ± 0.16	-0.96 ± 0.76
	$\delta C'_7$	$\delta C'_8$
Re(δC_i)	0.02 ± 0.03	-0.28 ± 0.93
Im(δC_i)	-0.07 ± 0.02	-0.55 ± 1.41

	δC_9^μ	δC_9^e	δC_{10}^μ	δC_{10}^e
Re(δC_i)	-1.26 ± 0.17	0.45 ± 0.51	-0.18 ± 0.23	4.48 ± 3.78
Im(δC_i)	0.29 ± 4.38	-1.51 ± 0.58	0.00 ± 0.98	-0.16 ± 3.35
	$\delta C_9'^\mu$	$\delta C_9'^e$	$\delta C_{10}'^\mu$	$\delta C_{10}'^e$
Re(δC_i)	0.09 ± 0.36	0.00 ± 1.41	-0.10 ± 0.19	0.00 ± 1.41
Im(δC_i)	0.42 ± 0.59	0.93 ± 3.98	-0.14 ± 0.23	0.03 ± 9.20

	$\delta C_{Q_1}^\mu$	$\delta C_{Q_1}^e$	$\delta C_{Q_2}^\mu$	$\delta C_{Q_2}^e$
Re(δC_i)	-0.06 ± 0.02	-2.90 ± 4.51	0.06 ± 0.04	-2.82 ± 4.00
Im(δC_i)	0.00 ± 0.19	-2.89 ± 2.33	0.05 ± 0.04	-2.88 ± 2.09
	$\delta C_{Q_1}'^\mu$	$\delta C_{Q_1}'^e$	$\delta C_{Q_2}'^\mu$	$\delta C_{Q_2}'^e$
Re(δC_i)	0.06 ± 0.02	0.00 ± 1.41	-0.04 ± 0.04	0.00 ± 1.41
Im(δC_i)	0.00 ± 0.19	-2.85 ± 4.16	-0.01 ± 0.04	-2.81 ± 4.09

Preliminary!

- Similar results to the case with $R_{K^{(*)}}$
- The value of δC_9^e is shifted

Fit results with more than two operators: Only R_K and R_{K^*} ($+ B_{s,d} \to \ell\ell + B \to X_s\ell\ell$)

Preliminary!

8 observables

Set of WC	Nb parameters	χ^2_{min}	Pull$_{SM}$	Improv.
SM	0	16.74	-	-
$C_9^{(e,\mu)}$ real	2	9.78	2.16σ	2.16σ
$C_7, C_8, C_9^{(e,\mu)}, C_{10}^{(e,\mu)}$ real	6	8.89	1.16σ	0.09σ
All non-primed WC real	10	8.87	0.47σ	0.00σ
All WC real (incl. primed)	20	7.75	0.02σ	0.00σ
All WC complex (incl. primed)	40	7.35	0.00σ	0.00σ

- R_K and R_{K^*} points to a best fit point different from the previous fits
- The values of δC_{10}^{μ} and $\delta C_{10}^{\prime\mu}$ are more constrained than δC_9

Fit results with more than two operators: Only R_K and R_{K^*} ($+ B_{s,d} \to \ell\ell + B \to X_s\ell\ell$)

Preliminary!

Only R_K and R_{K^*} ($\chi^2_{\rm SM} = 16.74$, $\chi^2_{\rm min} = 7.35$)				
	δC_7		δC_8	
Re(δC_i)	0.18 ± 0.03		0.80 ± 0.49	
Im(δC_i)	0.02 ± 0.25		0.03 ± 11.93	
	$\delta C'_7$		$\delta C'_8$	
Re(δC_i)	-0.17 ± 0.03		-2.04 ± 0.18	
Im(δC_i)	-0.01 ± 0.17		-0.41 ± 2.78	
	δC_9^μ	δC_9^e	δC_{10}^μ	δC_{10}^e
Re(δC_i)	6.59 ± 1.70	3.38 ± 5.48	-3.02 ± 0.44	-3.29 ± 5.65
Im(δC_i)	0.00 ± 1.41	3.38 ± 5.48	0.00 ± 1.41	-3.29 ± 5.65
	$\delta C_9^{\prime\mu}$	$\delta C_9^{\prime e}$	$\delta C_{10}^{\prime\mu}$	$\delta C_{10}^{\prime e}$
Re(δC_i)	11.18 ± 1.70	0.00 ± 1.41	-7.11 ± 0.44	0.00 ± 1.41
Im(δC_i)	0.35 ± 3.11	-10.26 ± 5.83	0.00 ± 3.43	-24.01 ± 2.49
	$\delta C_{Q_1}^\mu$	$\delta C_{Q_1}^e$	$\delta C_{Q_2}^\mu$	$\delta C_{Q_2}^e$
Re(δC_i)	0.00 ± 1.41	-0.56 ± 8.03	-0.07 ± 0.02	-0.31 ± 8.43
Im(δC_i)	0.00 ± 1.58	-0.60 ± 6.18	0.00 ± 1.41	-0.29 ± 6.45
	$\delta C_{Q_1}^{\prime\mu}$	$\delta C_{Q_1}^{\prime e}$	$\delta C_{Q_2}^{\prime\mu}$	$\delta C_{Q_2}^{\prime e}$
Re(δC_i)	0.00 ± 1.41	0.00 ± 1.41	0.07 ± 0.02	0.00 ± 1.41
Im(δC_i)	0.00 ± 1.58	-0.66 ± 6.09	0.00 ± 1.41	-0.25 ± 8.40

- R_K and R_{K^*} points to a best fit point different from the previous fits
- The values of δC_{10}^μ and $\delta C_{10}^{\prime\mu}$ are more constrained than δC_9