New physics fits to the latest bsll data

Nazila Mahmoudi

Lyon University & CERN

Based on arXiv:1603.00865, arXiv:1702.02234 & arXiv:1705.06274 and arXiv:1804.xxxxx

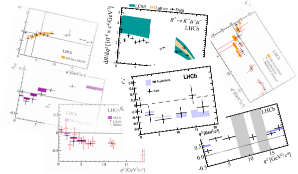
Thanks to T. Hurth, S. Neshatpour, D. Martinez Santos and V. Chobanova

CrossTalk Workshop: Flavour anomalies – Brussels, 29 March 2018

Introduction

Several tensions with the SM predictions observed in the $bs\ell\ell$ 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?**

Outline

- **Introduction**
  - → Theoretical framework
- **Observables**
  - → Definitions
  - → Recent anomalies
- **Theoretical uncertainties**
  - → Hadronic effects
  - → Statistical comparison of NP vs hadronic effects
- **NP global fits**
  - → Model independent implications
- **Specific NP models**
- **Future prospects to understand the source of anomalies**
- **Conclusions**

Theoretical framework

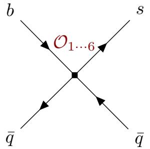
Effective field theory

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \Big(\sum_{i=1\cdots10,S,P} \big(C_i(\mu)\mathcal{O}_i(\mu) + C'_i(\mu)\mathcal{O}'_i(\mu)\big)\Big)$$

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

Operator set for $b \to s$ transitions:

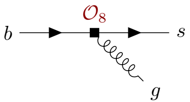
4-quark operators



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

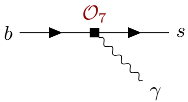
$\mathcal{O}_{3,4} \propto (\bar{s}\Gamma_\mu b)\sum_q(\bar{q}\Gamma^\mu q)$

chromomagnetic dipole operator



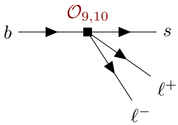
$\mathcal{O}_8 \propto (\bar{s}\sigma^{\mu\nu} T^a P_R) G^a_{\mu\nu}$

electromagnetic dipole operator



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

semileptonic operators



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

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

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

Wilson coefficients

The Wilson coefficients are calculated perturbatively up to NNLO

Two main steps:

- matching between the effective and full theories → extraction of the $C_i^{eff}(\mu)$ at scale $\mu \sim M_W$

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

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

The Wilson coefficients are process independent.

In the SM:

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

Wilson coefficients

The Wilson coefficients are calculated perturbatively up to NNLO

Two main steps:

- matching between the effective and full theories → extraction of the $C_i^{eff}(\mu)$ at scale $\mu \sim M_W$

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

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

The Wilson coefficients are process independent.

In the SM:

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

Hadronic quantities

To compute the amplitudes:

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

$\langle B|\mathcal{O}_i|A\rangle$: hadronic matrix element

How to compute matrix elements?

$\to$ Model building, Lattice simulations, Light flavour symmetries, Heavy flavour symmetries, ...

$\to$ Describe hadronic matrix elements in terms of **hadronic quantities**

Two types of hadronic quantities:

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

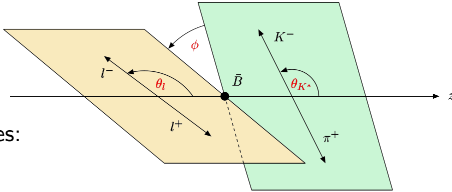
Once the Wilson coefficients and hadronic quantities calculated, the physical observables (branching fractions,...) can be calculated.

Observables and Anomalies

$B \to K^* \mu^+ \mu^-$ – Angular distributions

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

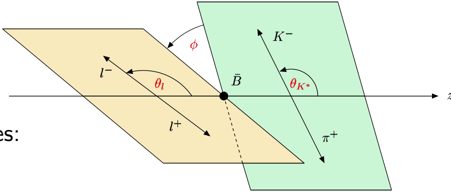
Main operators:

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

$$\mathcal{O}_S = \frac{e^2}{16\pi^2}(\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\,\ell), \quad \mathcal{O}_P = \frac{e^2}{16\pi^2}(\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\gamma_5 \ell)$$

$B \to K^* \mu^+ \mu^-$ – Angular distributions

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}

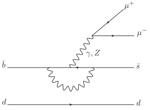
↘ functions of the spin amplitudes A_0, $A_\parallel$, $A_\perp$, A_t, and A_S

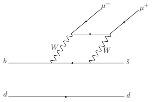
Spin amplitudes: functions of Wilson coefficients and form factors

Main operators:

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

$$\mathcal{O}_S = \frac{e^2}{16\pi^2}(\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\,\ell), \quad \mathcal{O}_P = \frac{e^2}{16\pi^2}(\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\gamma_5 \ell)$$





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

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:

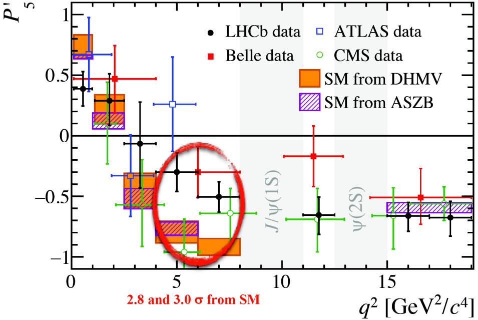
$$S_i = \frac{J_{i(s,c)}+\bar{J}_{i(s,c)}}{\frac{d\Gamma}{dq^2}+\frac{d\bar{\Gamma}}{dq^2}}\,, \qquad P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_L(1-F_L)}}$$

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

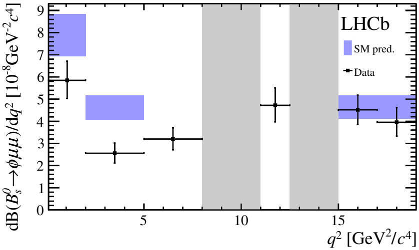
- Also measured by ATLAS, CMS and Belle

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

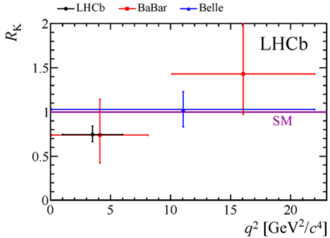


The LHCb anomalies (3)

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)): **2.6**σ 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!

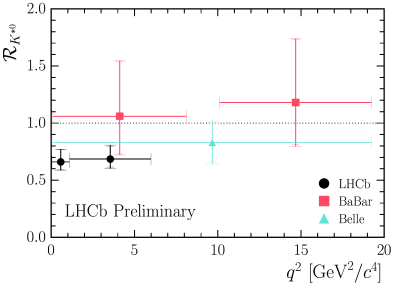
The LHCb anomalies (4)

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



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

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

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

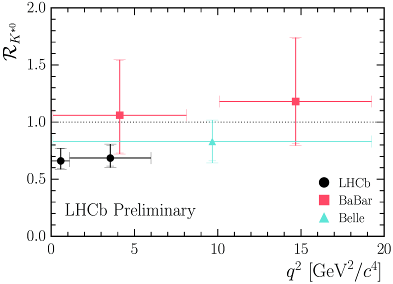
The LHCb anomalies (4)

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



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

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

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

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

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

Bordone, Isidori, Pattori, arXiv:1605.07633

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

Transversity amplitudes

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:

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

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

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

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

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

Transversity amplitudes

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

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

$$\mathcal{H}_{\rm eff}^{\rm had} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[\sum_{i=1\ldots 6} C_i O_i + C_8 O_8 \right]$$

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

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

Beneke et al.:
106067; 0412400

Transversity amplitudes

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

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

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

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

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

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

Non-Fact., QCDf — Beneke et al.: 106067; 0412400

power corrections → **unknown**
partial calculation: Khodjamirian et al., 1006.4945

Transversity amplitudes

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

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

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

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

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

Non-Fact., QCDf — Beneke et al.: 106067; 0412400

power corrections $\to$ **unknown** — partial calculation: Khodjamirian et al., 1006.4945

Anomalies can be explained with 20-50% non-factorisable power corrections at the observable level in the critical bins (Ciuchini et al., 1512.07157)

This corresponds to more than 150% error at the amplitude level for the critical bins!

Hadronic effects

Description also possible in terms of helicity amplitudes:

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

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

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

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

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

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

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

S. Jäger and J. Camalich, Phys.Rev. D93 (2016) 014028

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

It seems

$$h_\lambda^{(0)} \longrightarrow C_7^{NP}, \qquad h_\lambda^{(1)} \longrightarrow C_9^{NP}$$

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

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

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

Hadronic effects

Description also possible in terms of helicity amplitudes:

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

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

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

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

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

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) 014028

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

It seems

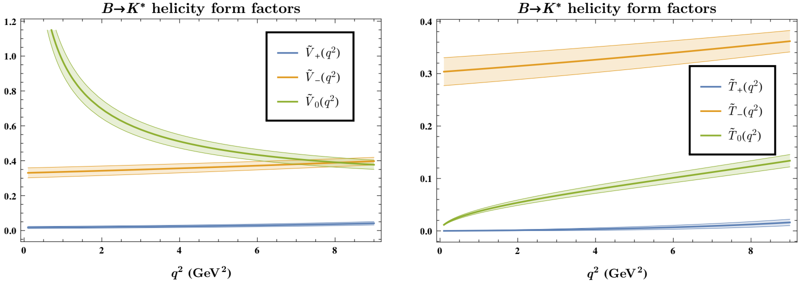
$$h_\lambda^{(0)} \longrightarrow C_7^{NP}, \qquad h_\lambda^{(1)} \longrightarrow C_9^{NP}$$

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

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

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

Hadronic effects



$\Longrightarrow$ q^4 terms can rise due to terms which multiply Wilson coefficients

$\Longrightarrow$ $C_7^{\rm NP}$ and $C_9^{\rm NP}$ can each cause effects similar to $h_\lambda^{(0,1,2)}$

Hadronic effects

Hadronic power correction effect:

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

New Physics effect:

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

and similarly for C_7

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

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

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

Hadronic effects

Hadronic power correction effect:

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

New Physics effect:

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

and similarly for C_7

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

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

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

Wilk's test

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

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

	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

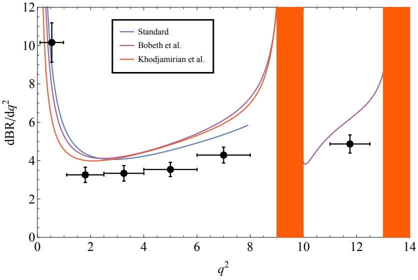
The situation is still inconclusive

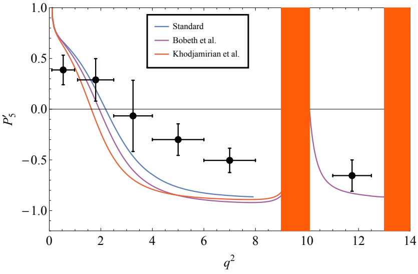
Estimates of hadronic effects

Various methods for hadronic effects

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

	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





Global fits

New Physics interpretation?

Many observables → **Global fits** of the latest LHCb data

Relevant $\mathcal{O}$perators:

$$\mathcal{O}_7,\ \mathcal{O}_8,\ \mathcal{O}_{9\mu,e}^{(\prime)}\ ,\ \mathcal{O}_{10\mu,e}^{(\prime)} \quad \text{and} \quad \mathcal{O}_{S-P} \propto (\bar{s}P_R b)(\bar{\mu}P_L\mu) \equiv \mathcal{O}_0^\prime$$

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

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

→ Scans over the values of δC_i

→ Calculation of flavour observables

→ Comparison with experimental results

→ Constraints on the Wilson coefficients C_i

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:

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

$|a_k|$ 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

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

$(\Sigma_{\rm th} + \Sigma_{\rm exp})^{-1}$ 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
- $B \to K^{*0} \mu^+ \mu^-$: 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

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)

	b.f. value	$\chi^2_{\rm min}$	$\mathrm{Pull}_{\rm SM}$
ΔC_9	-0.24	70.5	4.1σ
$\Delta C_9'$	-0.02	87.4	0.3σ
ΔC_{10}	-0.02	87.3	0.4σ
$\Delta C_{10}'$	$+0.03$	87.0	0.7σ
ΔC_9^μ	-0.25	68.2	4.4σ
ΔC_9^e	$+0.18$	86.2	1.2σ
ΔC_{10}^μ	-0.05	86.8	0.8σ
ΔC_{10}^e	-2.14 $+0.14$	86.3	1.1σ

$\rightarrow$ C_9 and C_9^μ solutions are favoured with SM pulls of 4.1 and 4.4σ
$\rightarrow$ Primed operators have a very small SM pull
$\rightarrow$ 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)

	b.f. value	$\chi^2_{\rm min}$	Pull$_{\rm SM}$
ΔC_9	-0.24	70.5	4.1σ
$\Delta C_9'$	-0.02	87.4	0.3σ
ΔC_{10}	-0.02	87.3	0.4σ
$\Delta C_{10}'$	$+0.03$	87.0	0.7σ
ΔC_9^μ	-0.25	68.2	4.4σ
ΔC_9^e	$+0.18$	86.2	1.2σ
ΔC_{10}^μ	-0.05	86.8	0.8σ
ΔC_{10}^e	-2.14 $+0.14$	86.3	1.1σ

→ C_9 and C_9^μ solutions are favoured with SM pulls of 4.1 and 4.4σ
→ Primed operators have a very small SM pull
→ C_{10}-like solutions do not play a role

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

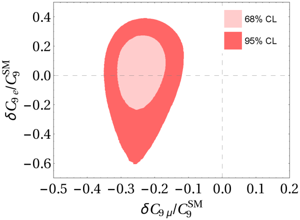
	b.f. value	$\chi^2_{\rm min}$	Pull$_{\rm SM}$
ΔC_9	-0.48	18.3	0.3σ
$\Delta C_9'$	$+0.78$	18.1	0.6σ
ΔC_{10}	-1.02	18.2	0.5σ
$\Delta C_{10}'$	$+1.18$	17.9	0.7σ
ΔC_9^μ	-0.35	5.1	3.6σ
ΔC_9^e	$+0.37$	3.5	3.9σ
ΔC_{10}^μ	-1.66 -0.34	2.7	4.0σ
ΔC_{10}^e	-2.36 $+0.35$	2.2	4.0σ

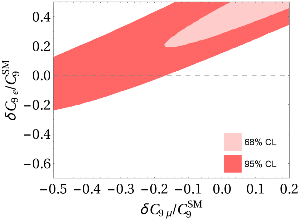
→ NP in C_9^e, C_9^μ, C_{10}^e, or C_{10}^μ are favoured by the $R_{K^{(*)}}$ ratios (significance: $3.6-4.0\sigma$)
→ NP contributions in primed operators do not play a role.

Fit results for two operators

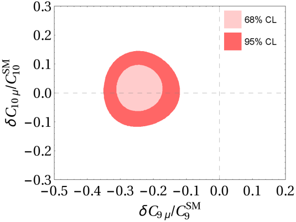
using all but R_K and R_{K^*} — using only R_K and R_{K^*}

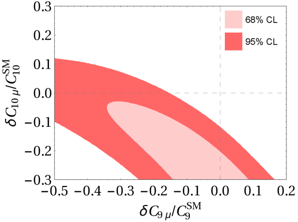
$(C_9^\mu - C_9^e)$





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





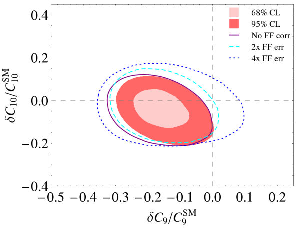
The two sets are compatible at least at the 2σ level.

Fit results for two operators: form factor dependence

Fits with different assumptions for the form factor uncertainties:

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

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

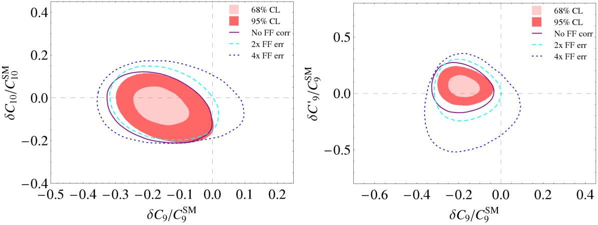


Fit results for two operators: form factor dependence

Fits with different assumptions for the form factor uncertainties:

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

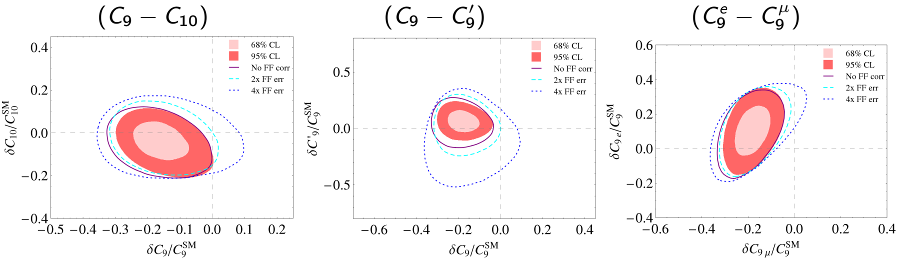
$(C_9 - C_{10})$ $(C_9 - C_9')$ $(C_9^e - C_9^\mu)$



Fit results for two operators: form factor dependence

Fits with different assumptions for the form factor uncertainties:

- correlations ignored (solid line)
- normal form factor errors (filled areas)
- 2 × 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 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
	$\delta C_9'^\mu$	$\delta C_9'^e$	$\delta C_{10}'^\mu$	$\delta C_{10}'^e$
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
	$\delta C_{Q_1}'^\mu$	$\delta C_{Q_1}'^e$	$\delta C_{Q_2}'^\mu$	$\delta C_{Q_2}'^e$
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

NP scenarios

New physics scenarios

Global fits: New physics is likely to appear in C_9:

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

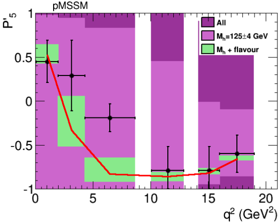
It can also affect C_9' and C_{10} in a much lesser extent.

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

Very difficult in the MSSM!

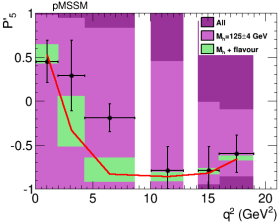
MSSM

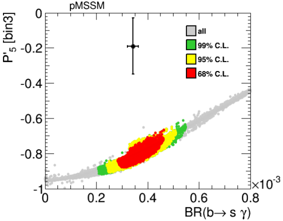
Fit results in the pMSSM



MSSM

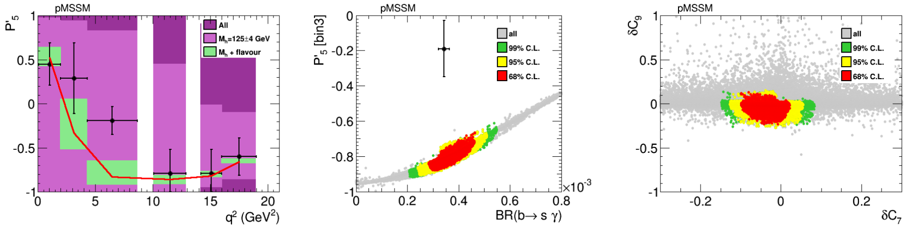
Fit results in the pMSSM





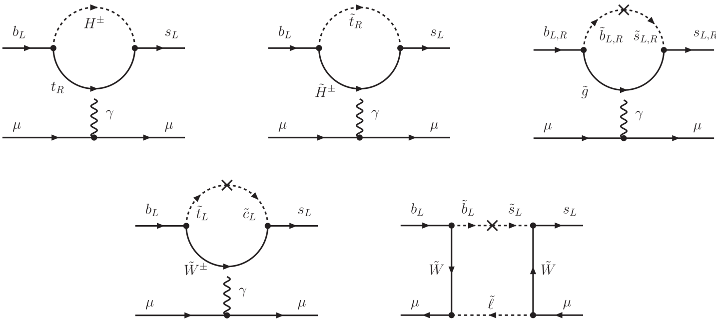
MSSM

Fit results in the pMSSM



MSSM and C_9

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



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

New physics scenarios

Global fits: New physics is likely to appear in C_9:

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

It can also affect C_9' and C_{10} in a much lesser extent.

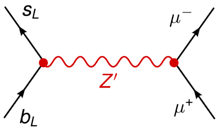
However, difficult to generate $\delta C_9 \sim -1$ at loop level...

$\rightarrow$ Need for tree level diagrams...

Mainstream scenarios:

- Z' bosons
- leptoquarks
- composite models

Z' bosons



Z' obvious candidate to generate the O_9 operator

Needs:

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

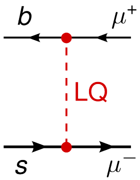
Strong constraints from $B_s - \bar{B}_s$ mixing and LEP contact interactions.

Anomalies consistent with a Z' of 1 to 10 TeV

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

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

Leptoquarks



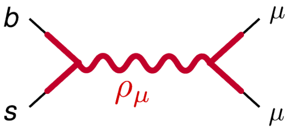
- t-channel diagrams
- Different possible representations, can be scalar (spin 0) or vector (spin 1)
- Cannot alter only C_9, but both C_9 and C_{10} $(= -C_9)$
- Cannot be lepton flavour non-universal and conserve lepton number simultaneously

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

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

See e.g. Hiller et al. 1408.1627, Biswas et al. 1409.0882, Buras et al. 1409.4557, Sahoo et al. 1501.05193, Hiller et al. 1411.4773, Becirevic et al. 1503.09024, Alonso et al. 1505.05164, ...

Composite models



- Neutral resonance ρ_μ coupling to the muons via composite elementary mixing
- requires some compositeness for the muons
- can allow for lepton flavour violating couplings
- constrained by the LEP Z-width measurements and $B_s - \bar{B}_s$ mixing

See e.g. Gripaios et al. 1412.1791, Niehoff, et al. 1503.03865, Niehoff et al. 1508.00569, Carmona et al. 1510.07658, ...

Future prospects

How to resolve the issue?

1) Unknown power corrections

- Significance of the anomalies depends on the assumptions on the power corrections
- Anomalies can be explained with 20-50% non-factorisable power corrections at the observable level in the critical bins (Ciuchini et al. 1512.07157)
- This corresponds to more than 100% error at the amplitude level (for S_3, S_4 and S_5)!

- Towards a calculation...
- Problem: they are not calculable in QCD factorisation
- Alternative approaches exist based on light cone sum rule techniques (Khodjamirian et al. 1006.4945)
  $\rightarrow$ the available partial calculation increases the tension in P_5'

How to resolve the issue?

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

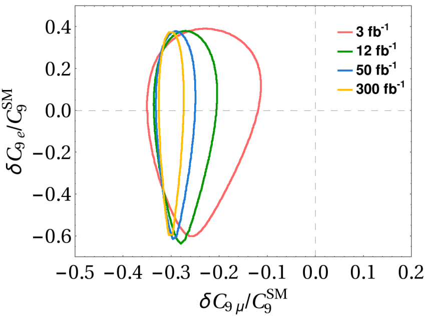
A confirmation of the deviations in the ratios would indirectly confirm the NP interpretation of the anomalies in the angular observables!

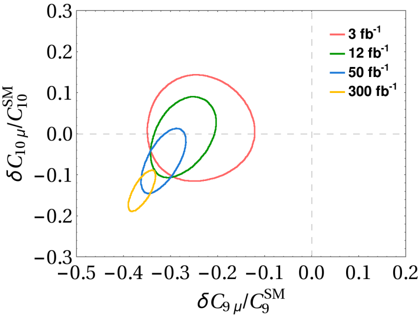
How to resolve the issue?

3) Future LHCb prospects

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

Considering several luminosities, assuming the current central values





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

How to resolve the issue?

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

Assuming current central values remain.

ΔC_9^μ	Syst. Pull_{SM}	Syst./2 Pull_{SM}	Syst./3 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.

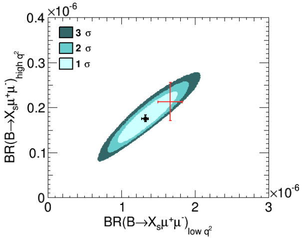
This is independent of the hadronic uncertainties!

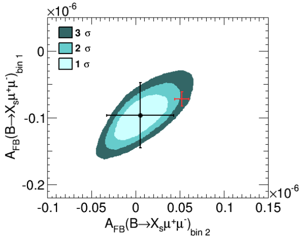
How to resolve the issue?

4) Cross-check with inclusive modes

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

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





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

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

SuperIso

All the results shown in this talk are obtained using the SuperIso program

- public C program
- dedicated to the **flavour physics** observable calculations
- based on the most precise calculations publicly available
- various models implemented
- interfaced to several spectrum calculators
- modular program with a well-defined structure
- reference manual available ($\sim$ 160 pages)
- Latest version: SuperIso v3.6

http://superiso.in2p3.fr

FM, Comput. Phys. Commun. 178 (2008) 745
FM, Comput. Phys. Commun. 180 (2009) 1579
FM, Comput. Phys. Commun. 180 (2009) 1718

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
- We compared the fits for NP and hadronic parameters through the Wilk's test
- 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
- If the issue remains, Belle-II will be able to resolve it
- The recent measurement of R_K^* supports the NP hypothesis, but the exp. errors are still large and the update of R_K (or other ratio measurements) is eagerly awaited!

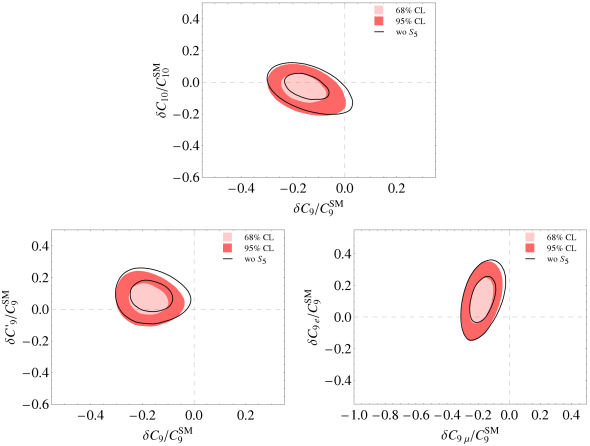
Backup

$$
\begin{aligned}
\delta\langle P_2\rangle_{[0.1,2]} &\simeq +0.37\,\delta C_7 \quad +0.02\,\delta C_8 \quad -0.03\,\delta C_{10}\\
\delta\langle P_2\rangle_{[2,4.3]} &\simeq -2.48\,\delta C_7 \quad -0.10\,\delta C_8 \quad -0.17\,\delta C_9 \quad +0.03\,\delta C_{10}\\
\delta\langle P_2\rangle_{[4.3,8.68]} &\simeq -0.71\,\delta C_7 \quad -0.04\,\delta C_8 \quad -0.09\,\delta C_9 \quad -0.04\,\delta C_{10}\\
\delta\langle P'_4\rangle_{[0.1,2]} &\simeq +0.59\,\delta C_7 \quad -0.08\,\delta C_9 \quad -0.13\,\delta C_{10}\\
\delta\langle P'_4\rangle_{[2,4.3]} &\simeq +2.45\,\delta C_7 \quad +0.11\,\delta C_8 \quad +0.06\,\delta C_9 \quad -0.14\,\delta C_{10}\\
\delta\langle P'_4\rangle_{[4.3,8.68]} &\simeq +0.33\,\delta C_7 \quad +0.01\,\delta C_8 \quad +0.01\,\delta C_9\\
\delta\langle P'_5\rangle_{[0.1,2]} &\simeq -0.91\,\delta C_7 \quad -0.04\,\delta C_8 \quad -0.12\,\delta C_9 \quad -0.03\,\delta C_{10}\\
\delta\langle P'_5\rangle_{[2,4.3]} &\simeq -3.04\,\delta C_7 \quad -0.14\,\delta C_8 \quad -0.29\,\delta C_9 \quad -0.03\,\delta C_{10}\\
\delta\langle P'_5\rangle_{[4.3,8.68]} &\simeq -0.52\,\delta C_7 \quad -0.03\,\delta C_8 \quad -0.08\,\delta C_9 \quad -0.03\,\delta C_{10}
\end{aligned}
$$

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 $C_{7,8,9,10}$

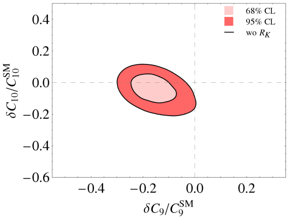
Removing S_5 from the fit:

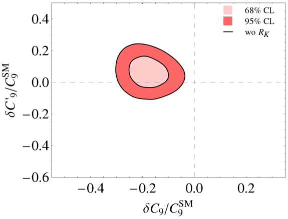


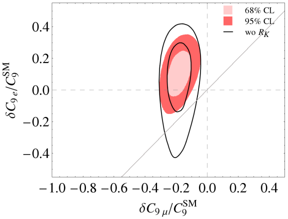
While the tension of $C_9^{\rm SM}$ and best fit point value of C_9 is slightly reduced in the various two operator fits, still the tension exists at more than 2σ

$\rightarrow$ **S_5 is not the only observable which drives C_9 to negative values!**

Removing R_K from the fit:



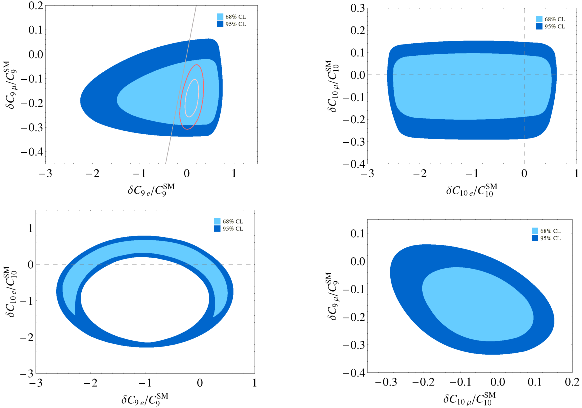




R_K is the main measurement resulting in the best fit values for C_9^μ and C_9^e which are in more than 2σ tension with lepton-universality

Fit results for four operators: $\{C_9^{\mu}, C_9^{e}, C_{10}^{\mu}, C_{10}^{e}\}$

No reason that only 2 Wilson coefficients receive contributions from new physics

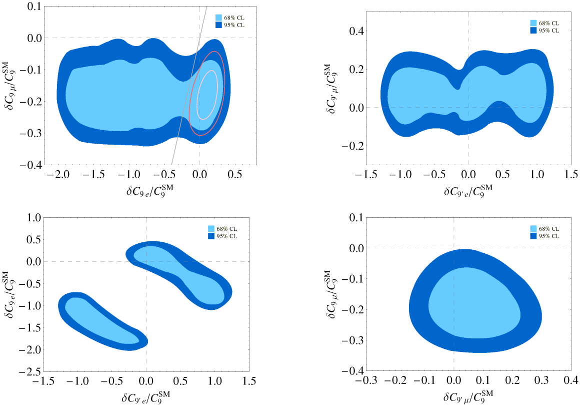


Larger ranges are allowed for the Wilson coefficients

Considering 4 operator fits considerably relaxes the constraints on the Wilson coefficients leaving room for more diverse new physics contributions which are otherwise overlooked.

Fit results for four operators: $\{C_9^\mu, C_9'^\mu, C_9^e, C_9'^e\}$

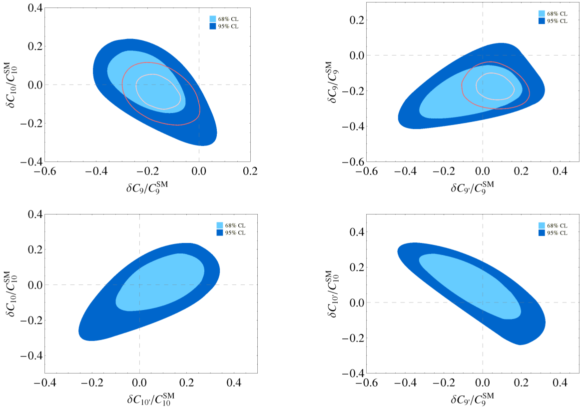
No reason that only 2 Wilson coefficients receive contributions from new physics



Larger ranges are allowed for the Wilson coefficients

Fit results for four operators: $\{C_9, C_9', C_{10}, C_{10}'\}$

No reason that only 2 Wilson coefficients receive contributions from new physics



Larger ranges are allowed for the Wilson coefficients

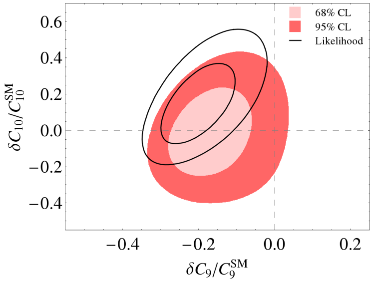
Fit results for two operators: likelihood vs. method of moments

LHCb presented the $B \to K^* \mu^+ \mu^-$ angular analysis with two different methods:

- likelihood fits: smaller uncertainties, but involves model-dependent assumptions
- method of moments: more robust, but larger uncertainties

How does the choice of method affect fits? Let's consider only $B \to K^* \mu^+ \mu^-$ measurements.

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



likelihood fits: solid lines
method of moments: filled areas

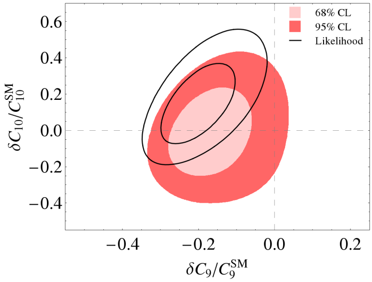
Fit results for two operators: likelihood vs. method of moments

LHCb presented the $B \to K^* \mu^+ \mu^-$ angular analysis with two different methods:

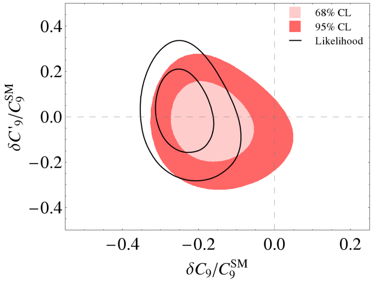
- likelihood fits: smaller uncertainties, but involves model-dependent assumptions
- method of moments: more robust, but larger uncertainties

How does the choice of method affect fits? Let's consider only $B \to K^* \mu^+ \mu^-$ measurements.

$(C_9 - C_{10})$



$(C_9 - C'_9)$



likelihood fits: solid lines
method of moments: filled areas

Tension decreases using the method of moments results!