Implications of flavour anomalies for new physics

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Moriond QCD, March 30, 2017

Indirect search for New Physics

I will focus on **indirect hints for new physics** from Flavour sector

Flavour physics is sensitive to new physics at $\Lambda_{\rm NP} \gg E_{\rm experiments}$
$\rightarrow$ can discover new physics or probe it before it is directly observed in experiments

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- They occur at loop level

  $\rightarrow$ The SM contributions are very small and the NP contributions can have a comparable magnitude.

- The theory ingredients are known at a very good accuracy!

  $\rightarrow$ In particular: QCD corrections are known with a good precision!

- The experimental situation is very promising

  $\rightarrow$ Branching ratios can be measured precisely

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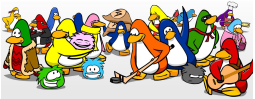

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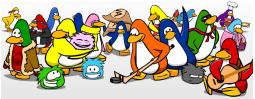
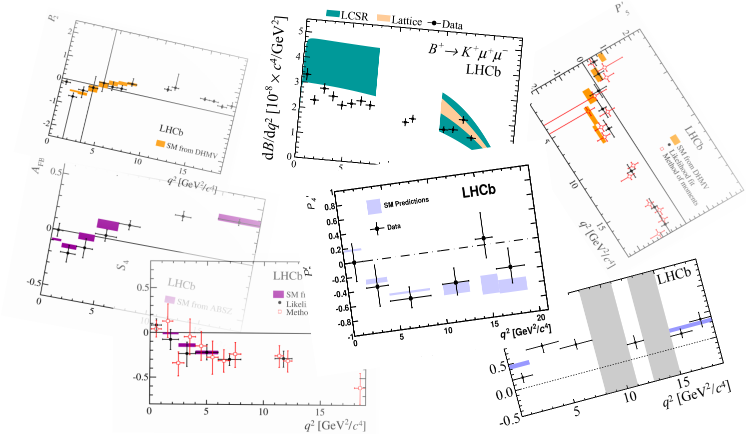


There are currently some tensions (anomalies)
Confirmations are needed, but they are still among our best bets!

(LHCb) Observables and Anomalies

Impressive effort in studying **exclusive** $b \to s\ell\ell$ transitions at LHCb with the measurements of a large number of independent angular observables!



Deviations from the SM predictions in $B \to K^*\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$ and $R_{K^{(*)}}$: "anomalies"

Theoretical framework

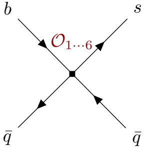
Effective field theory

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

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

Operator set for $b \to s$ transitions:

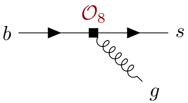
4-quark operators



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

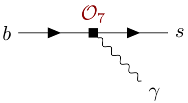
$\mathcal{O}_{3,4} \propto (\bar{s}\Gamma_\mu b)\sum_q(\bar{q}\Gamma^\mu q)$

chromomagnetic dipole operator



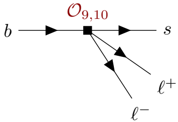
$\mathcal{O}_8 \propto (\bar{s}\sigma^{\mu\nu}T^a P_R)G^a_{\mu\nu}$

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, $\mathcal{O}'_i$

Wilson coefficients

The Wilson coefficients are calculated perturbatively

Two main steps:

- matching between the effective and full theories $\rightarrow$ 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.

SM contributions to the Wilson coefficients known to NNLL:
(Bobeth, Misiak, Urban '99; Misiak, Steinhauser '04, Gorbahn, Haisch '04; Gorbahn, Haisch, Misiak '05; Czakon, Haisch, Misiak '06,...)

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

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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?

→ 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 (e.g. ratios,...)

Prime example: $B \to K^* \mu^+ \mu^-$
gives access to a variety of observables!

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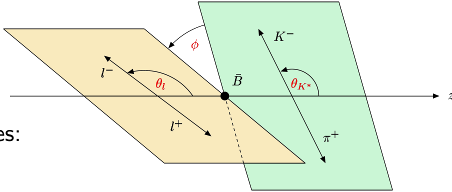
$B \to K^* \mu^+ \mu^-$

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 transversity amplitudes A_0, $A_\|$, $A_\perp$, A_t, and A_S

↘ or alternatively, helicity amplitudes H_V, H_A and H_S

Transversity/helicity amplitudes: functions of Wilson coefficients and form factors

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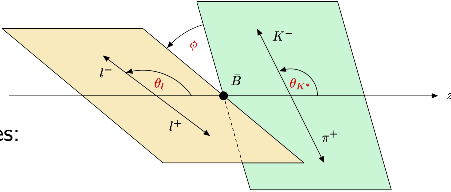

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Transversity/helicity amplitudes: functions of Wilson coefficients and form factors

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

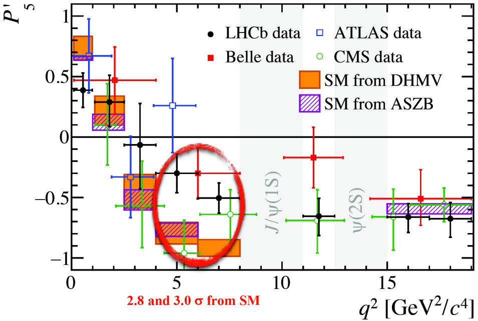
$$S_i = \frac{J_{i(s,c)} + \bar{J}_{i(s,c)}}{\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}} \, , \qquad P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_L(1-F_L)}}$$

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

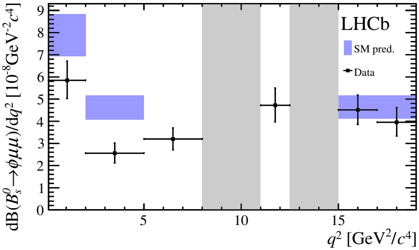
- Also measured by ATLAS, CMS and Belle

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

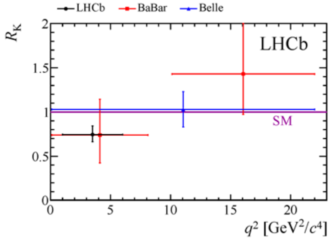


The LHCb anomalies (3)

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

- Theoretical description similar to $B \to K^* \mu^+ \mu^-$, but different since K 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!

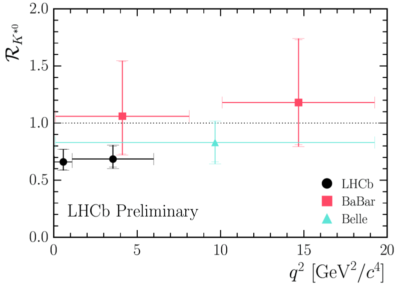
The LHCb anomalies (4)

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



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

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

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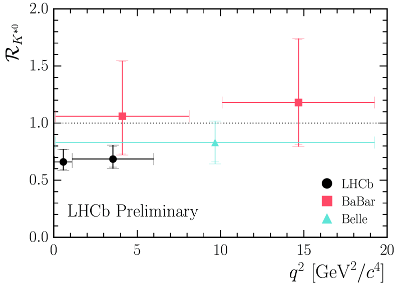

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$$R_{K^*}^{\rm SM,bin1} = 0.906 \pm 0.020_{\rm QED} \pm 0.020_{\rm FF}$$

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

Bordone, Isidori, Pattori, arXiv:1605.07633

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

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

A closer look at the calculations...

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:

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

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

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

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

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

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$$\mathcal{A}_\lambda^{\rm (had)} = -\, i \frac{e^2}{q^2} \int d^4x e^{-iq\cdot x} \langle \ell^+ \ell^- | j_\mu^{\rm em,lept}(x)|0\rangle$$
$$\times \int d^4y\, e^{iq\cdot y} \langle \bar{K}_\lambda^* | T\{ j^{\rm em,had,\mu}(y) \mathcal{H}_{\rm eff}^{\rm had}(0)\} | \bar{B}\rangle$$
$$\equiv \frac{e^2}{q^2} \epsilon_\mu L_V^\mu \Big[\underbrace{\text{LO in } \mathcal{O}(\frac{\Lambda}{m_b}, \frac{\Lambda}{E_{K^*}})}_{\text{Non-Fact., QCDf}} + \underbrace{h_\lambda(q^2)}_{\text{power corrections}} \Big]$$

Beneke et al.:
106067; 0412400

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

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

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

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

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!

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

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

$(\Sigma_{\rm th} + \Sigma_{\rm exp})^{-1}$ 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, 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

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

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

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!

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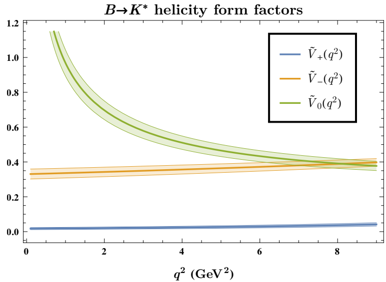

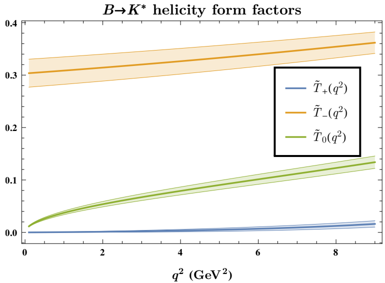

$\Longrightarrow$ q^4 terms can rise due to terms which multiply Wilson coefficients

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

New physics or 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

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

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

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	$\chi^2_{\rm min}$	$\mathrm{Pull_{SM}}$
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

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→ 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	$\chi^2_{\rm min}$	$\rm Pull_{SM}$
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: $3.6-4.0\sigma$)

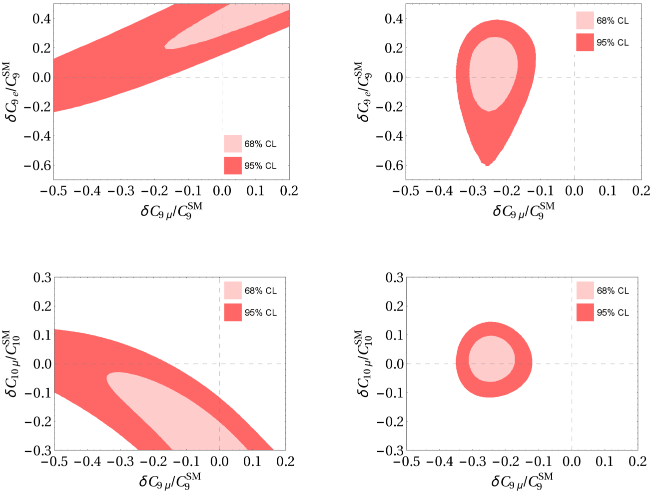
→ NP contributions in primed operators do not play a role.

Fit results for two operators

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

How to resolve the issue?

1) Unknown power corrections

- Significance of the anomalies depends on the assumptions on the power corrections
- Towards a calculation...
- Problem: they are not calculable in QCD factorisation
- Alternative approaches exist based on light cone sum rule techniques

Khodjamirian et al. JHEP 1009 (2010) 089
Dimou, Lyon, Zwicky PRD 87, 074008 (2012), PRD 88, 094004 (2013)
A more recent approach based on the analyticity structure: Bobeth et al. arXiv:1707.07305

2) Cross-check with inclusive modes

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

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

T. Hurth, FM, JHEP 1404 (2014) 097
T. Hurth, FM, S. Neshatpour, JHEP 1412 (2014) 053

How to resolve the issue?

3) 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
$R_{F_L}^{[1.1,6.0]}$	$[0.785, 0.913]$	$[0.909, 0.933]$	$[1.005, 1.042]$	$[1.001, 1.018]$
$R_{A_{FB}}^{[1.1,6.0]}$	$[6.048, 14.819]$	$[-0.288, -0.153]$	$[0.816, 0.928]$	$[0.974, 1.061]$
$R_{S_5}^{[1.1,6.0]}$	$[-0.787, 0.394]$	$[0.603, 0.697]$	$[0.881, 1.002]$	$[1.053, 1.146]$
$R_{F_L}^{[15,19]}$	$[0.999, 0.999]$	$[0.998, 0.998]$	$[0.997, 0.998]$	$[0.998, 0.998]$
$R_{A_{FB}}^{[15,19]}$	$[0.616, 0.927]$	$[1.002, 1.061]$	$[0.860, 0.994]$	$[1.046, 1.131]$
$R_{S_5}^{[15,19]}$	$[0.615, 0.927]$	$[1.002, 1.061]$	$[0.860, 0.994]$	$[1.046, 1.131]$
$R_{K^*}^{[15,19]}$	$[0.621, 0.803]$	$[0.577, 0.771]$	$[0.589, 0.778]$	$[0.586, 0.770]$
$R_K^{[15,19]}$	$[0.597, 0.802]$	$[0.590, 0.778]$	$[0.659, 0.818]$	$[0.632, 0.805]$
$R_\phi^{[1.1,6.0]}$	$[0.748, 0.852]$	$[0.620, 0.805]$	$[0.578, 0.770]$	$[0.578, 0.764]$
$R_\phi^{[15,19]}$	$[0.623, 0.803]$	$[0.577, 0.771]$	$[0.586, 0.776]$	$[0.583, 0.769]$

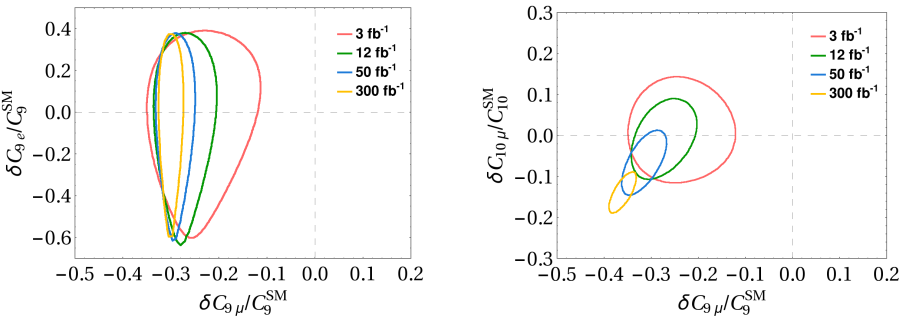
A confirmation of the deviations in the ratios would indirectly confirm the NP interpretation of the anomalies in the angular observables!

How to resolve the issue?

4) Future LHCb upgrade

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?

$\mathrm{Pull}_{\mathrm{SM}}$ 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. $\mathrm{Pull}_{\mathrm{SM}}$	Syst./2 $\mathrm{Pull}_{\mathrm{SM}}$	Syst./3 $\mathrm{Pull}_{\mathrm{SM}}$
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

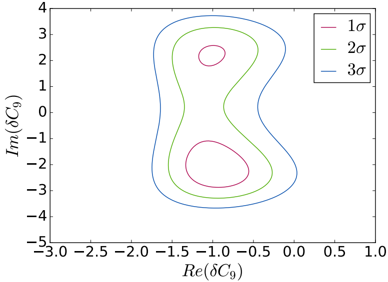
- The full LHCb Run 1 results still show some tensions with the SM predictions
- Significance of the anomalies depends on the assumptions on the power corrections
- Model independent fits point to about 25% reduction in C_9, and new physics in muonic C_9^μ is preferred
- Comparing the fits for NP and 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 recent measurement of R_{K^*} supports the NP hypothesis, but the experimental errors are still large and the update of R_K is eagerly awaited!
- The LHCb upgrade will have enough precision to distinguish between NP and hadronic effects

Backup

Global fit results

Fit with 2 parameters (complex C_9)

low q^2 bins (up to 8 GeV^2)



About 3σ tension for $Re(\delta C_9)$

Global fit results

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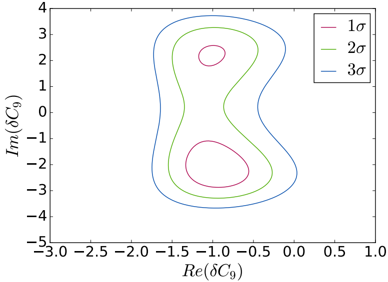
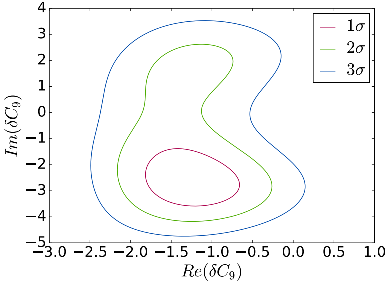


Fit with 4 parameters (complex C_7 and C_9)

low q^2 bins (up to 8 GeV^2)



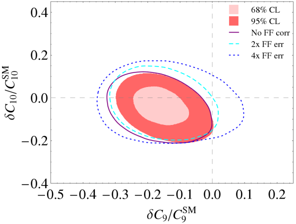
About 3σ tension for $Re(\delta C_9)$

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)

$(C_9 - C_{10})$



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

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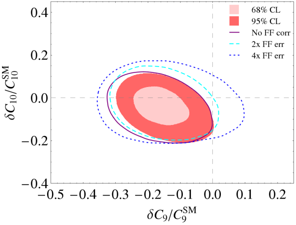
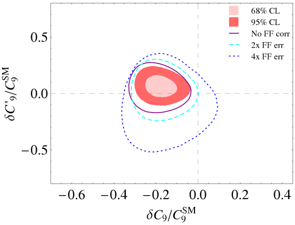


$(C_9 - C_9')$



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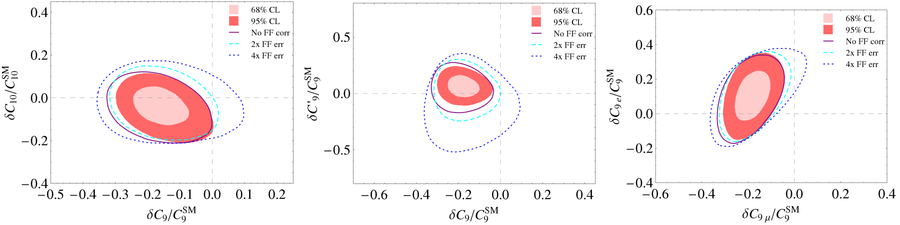
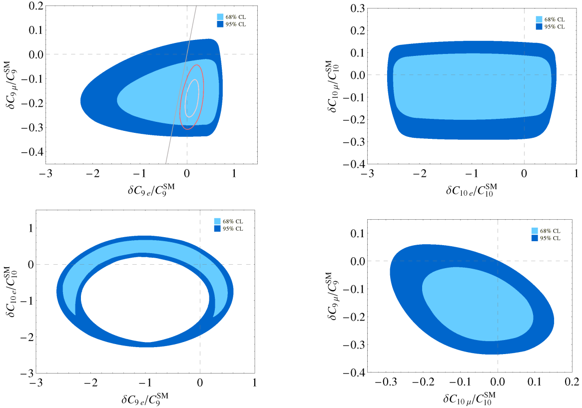


The size of the form factor errors has a crucial role in constraining the allowed region!

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: $\{C_9^\mu, C_9^{'\mu}, C_9^e, C_9^{'e}\}$

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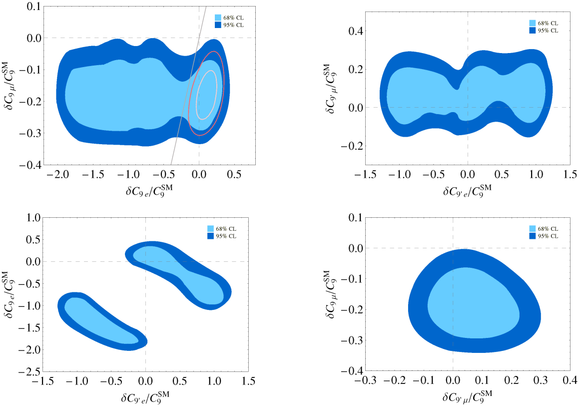

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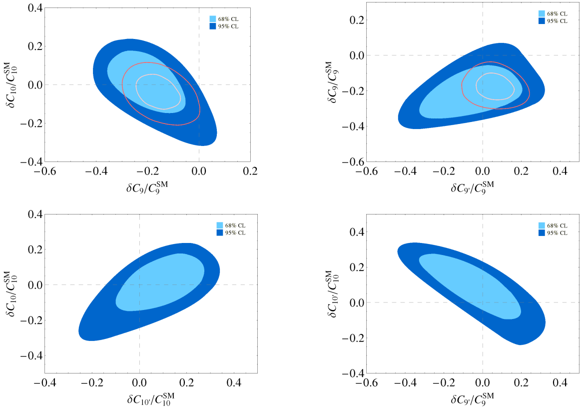
Fit results for four operators: $\{C_9, C_9', C_{10}, C_{10}'\}$

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



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