Recent anomalies in flavour physics

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Outline

- **Introduction**
  - → Theoretical framework
- **Observables**
  - → Recent anomalies
- **Implications**
  - → Model independent global fits
  - → Implications for Wilson coefficients
  - → Assessment of the theoretical uncertainties
  - → Identifying the origin of the anomalies
  - → Model dependent interpretations
- **Conclusions**

Indirect search for New Physics

- In the past, the objective of flavour physics experiments was focused on the tests of the Standard Model and the CKM paradigm
  $\rightarrow$ This is now well established!
- Focus is now towards the new physics!
  And search for the **indirect signs of new physics**
- **LHCb** has a very rich program to search for indirect signs of new physics!
  Main probes: Rare decays

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Why rare decays are interesting?

- Rare B decays 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!

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

- Very promising experimental situation

  $\rightarrow$ Branching ratios and distributions can be measured precisely

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Theoretical framework

A multi-scale problem

- new physics: $1/\Lambda_{\rm NP}$
- electroweak interactions: $1/M_W$
- hadronic effects: $1/m_b$
- QCD interactions: $1/\Lambda_{\rm QCD}$

$\Rightarrow$ Effective field theory approach:

separation between low and high energies using Operator Product Expansion

- short distance: Wilson coefficients, computed perturbatively
- long distance: local operators

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

New physics:

- Corrections to the Wilson coefficients: $C_i \to C_i + \Delta C_i^{NP}$
- Additional operators: $\sum_j C_j^{NP} \mathcal{O}_j^{NP}$

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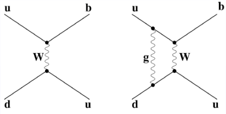
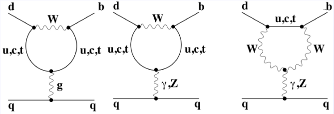
$\mathcal{O}$perators

$$\mathcal{O}_1 = (\bar{s}\gamma_\mu T^a P_L c)(\bar{c}\gamma^\mu T^a P_L b)$$
$$\mathcal{O}_2 = (\bar{s}\gamma_\mu P_L c)(\bar{c}\gamma^\mu P_L b)$$



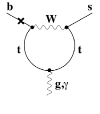
Current

$$\mathcal{O}_3 = (\bar{s}\gamma_\mu P_L b)\textstyle\sum_q(\bar{q}\gamma^\mu q)$$
$$\mathcal{O}_4 = (\bar{s}\gamma_\mu T^a P_L b)\textstyle\sum_q(\bar{q}\gamma^\mu T^a q)$$
$$\mathcal{O}_5 = (\bar{s}\gamma_{\mu_1}\gamma_{\mu_2}\gamma_{\mu_3} P_L b)\textstyle\sum_q(\bar{q}\gamma^{\mu_1}\gamma^{\mu_2}\gamma^{\mu_3} q)$$
$$\mathcal{O}_6 = (\bar{s}\gamma_{\mu_1}\gamma_{\mu_2}\gamma_{\mu_3} T^a P_L b)\textstyle\sum_q(\bar{q}\gamma^{\mu_1}\gamma^{\mu_2}\gamma^{\mu_3} T^a q)$$



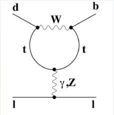
QCD penguins Electroweak penguins

$$\mathcal{O}_7 = \frac{e}{16\pi^2}\left[\bar{s}\sigma^{\mu\nu}(m_s P_L + m_b P_R)b\right]F_{\mu\nu}$$
$$\mathcal{O}_8 = \frac{g}{16\pi^2}\left[\bar{s}\sigma^{\mu\nu}(m_s P_L + m_b P_R)T^a b\right]G^a_{\mu\nu}$$



Magnetic operators

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



Semileptonic operators

Wilson coefficients

Two main steps:

- Calculating $C_i^{eff}(\mu)$ at scale $\mu \sim M_W$ by requiring matching between the effective and full theories

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

- Evolving the $C_i^{eff}(\mu)$ to scale $\mu \sim m_b$ using the RGE:

$$\mu \frac{d}{d\mu} C_i^{eff}(\mu) = C_j^{eff}(\mu) \gamma_{ji}^{eff}(\mu)$$

driven by the anomalous dimension matrix $\hat{\gamma}^{eff}(\mu)$:

$$\hat{\gamma}^{eff}(\mu) = \frac{\alpha_s(\mu)}{4\pi} \hat{\gamma}^{(0)eff} + \frac{\alpha_s^2(\mu)}{(4\pi)^2} \hat{\gamma}^{(1)eff} + \cdots$$

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**

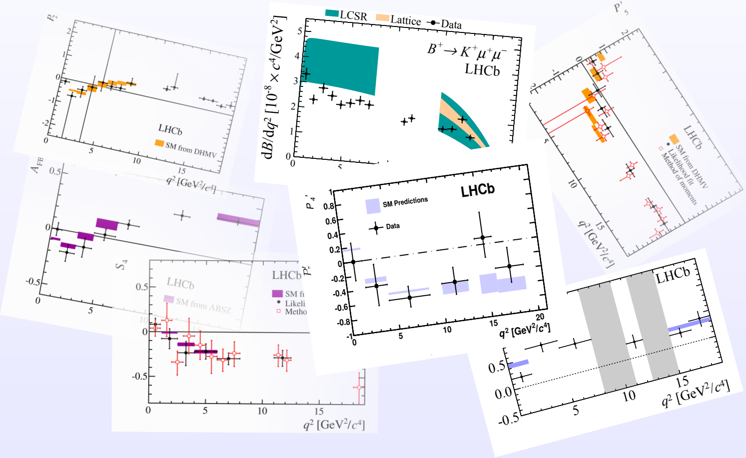
Two types of hadronic quantities:

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

LHCb measurements

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

$B \to K\mu^+\mu^-$, $B \to K^+e^+e^-$, $B \to K^*\mu^+\mu^-$ (F_L, A_{FB}, S_i, P_i), $B_s \to \phi\mu^+\mu^-$, ...

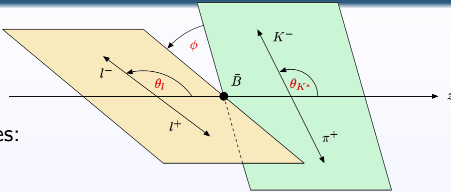


Deviations from the SM predictions in $B \to K^*\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$ and R_K : "anomalies"

$B \to K^* \mu^+ \mu^-$ – 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:

$$\mathcal{O}_9 = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell), \quad \mathcal{O}_{10} = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\gamma_5 \ell)$$
$$\mathcal{O}_S = \frac{e^2}{16\pi^2}(\bar{s}^\alpha_L b^\alpha_R)(\bar{\ell}\,\ell), \quad \mathcal{O}_P = \frac{e^2}{16\pi^2}(\bar{s}^\alpha_L b^\alpha_R)(\bar{\ell}\gamma_5 \ell)$$

F. Kruger et al., Phys. Rev. D 61 (2000) 114028;
W. Altmannshofer et al., JHEP 0901 (2009) 019; U. Egede et al., JHEP 1010 (2010) 056

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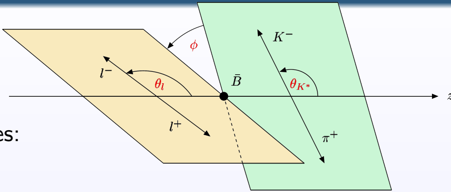

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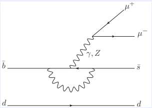

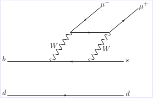

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$B \to K^* \mu^+ \mu^-$ observables

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

- 2013 (1 fb^{-1}): disagreement with the SM for P_2 and P_5' (PRL 111, 191801 (2013))
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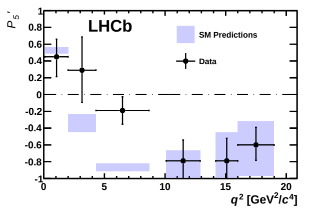

3.7σ deviation in the 3rd bin

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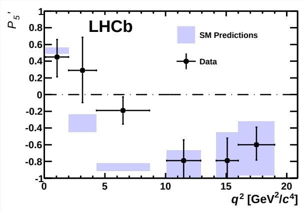

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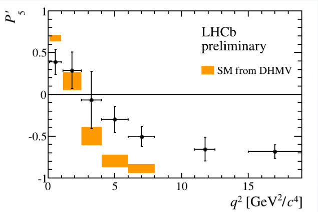

2.9σ in the 4th and 5th bins (3.7σ combined)

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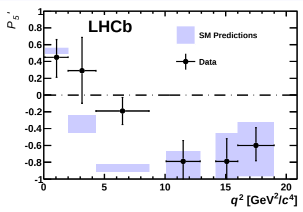

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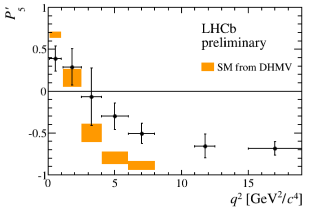

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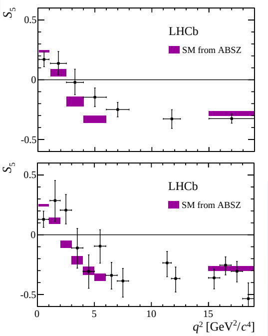

3.4σ combined fit (likelihood)

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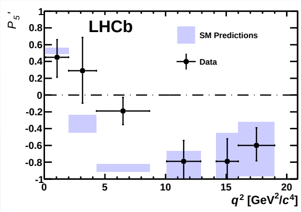

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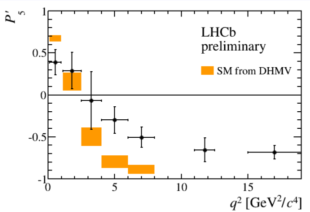

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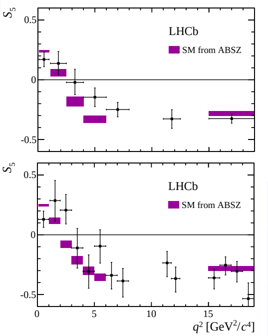

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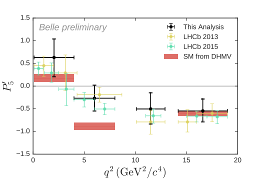
Belle supports LHCb (arXiv:1604.04042) tension at 2.1σ

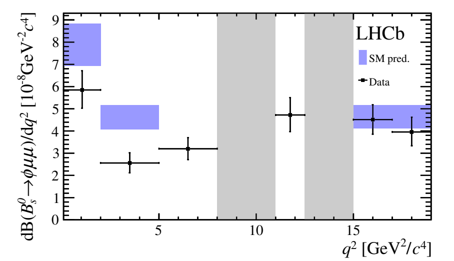


The LHCb anomalies (2)

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

- Same theoretical description as $B \to K^*\mu^+\mu^-$
- 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)

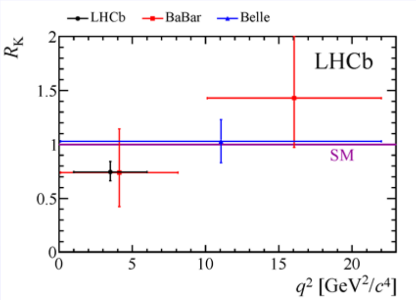
Lepton universality in $B^+ \to K^+\ell^+\ell^-$

- June 2015 (3 fb^{-1}): measurement of R_K in the [1-6] GeV^2 bin
  2.6σ tension in [1-6] GeV^2 bin

PRL 113, 151601 (2014)

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

$$R_K^{\rm SM} \approx 1$$



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

New Physics interpretation?

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

Relevant $\mathcal{O}$perators:

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

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

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

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

Global fits using the latest LHCb results:

M. Ciuchini, M. Fedele, E. Franco, S. Mishima, A. Paul, L. Silvestrini, M. Valli, 1512.07157
T. Hurth, FM, S. Neshatpour, 1603.00865
B. Capdevila, S. Descotes-Genon, J. Matias, J. Virto, 1605.03156

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:

T. Hurth, FM, S. Neshatpour, 1603.00865

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

Computations performed using SuperIso public program

Theoretical uncertainties and correlations (1)

- 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 (Cholesky decomposition method)
- use for the $B \to K$ form factors of the lattice+LCSR combinations from 1411.3161, including correlations
- for $B_s \to \phi\mu^+\mu^-$, mixing effects taken into account

Global fits

Theoretical uncertainties and correlations (2)

- Two approaches for calculation of the exclusive decays: full form factors (7 independent FFs), soft form factors (2 independent FFs)
- full FF approach = soft FF approach + $(1/m_b, \alpha_s)$ "factorisable corrections"
- Both approaches receive contributions from non-local 4 quark operators: "non-factorisable corrections"
- However, non-factorisable corrections only known at LO in $(\Lambda/m_b, E_{K^*}/m_b)$
- Higher powers of $(\Lambda/m_b, E_{K^*}/m_b)$ unknown = "non-factorisation power corrections"
- Evaluation of uncertainties from factorisable and non-factorisable power corrections:

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

Soft: parametrisation of both factorisable and non-factorisable power corrections
Full: parametrisation of only non-factorisable power corrections

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

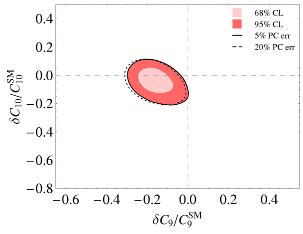
$\Rightarrow$ Computation of a (theory + exp) correlation matrix

Fit results for two operators

Fit results using full form factor approach:

- filled areas: 10% power correction errors
- solid line: 5% power correction errors
- dashed line: 20% power correction errors

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



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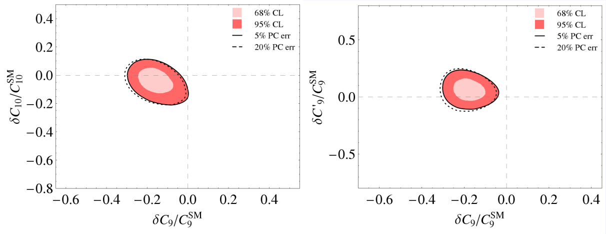

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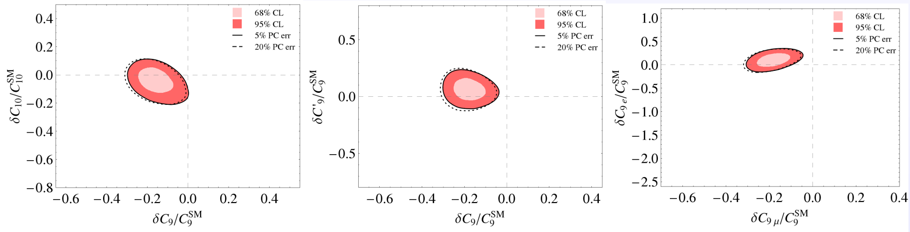


About 3σ deviations with the SM in all cases

Power correction uncertainty between 5 and 20% does not change the picture.

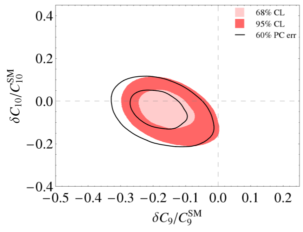
Results using soft form factors are very similar

Fit results for two operators: effect of power corrections

Fits assuming different power correction uncertainties:

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

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



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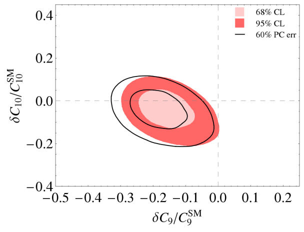
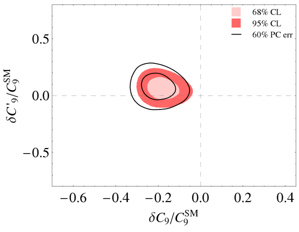


$(C_9 - C_9')$



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

Fit results for two operators: effect of power corrections

Fits assuming different power correction uncertainties:

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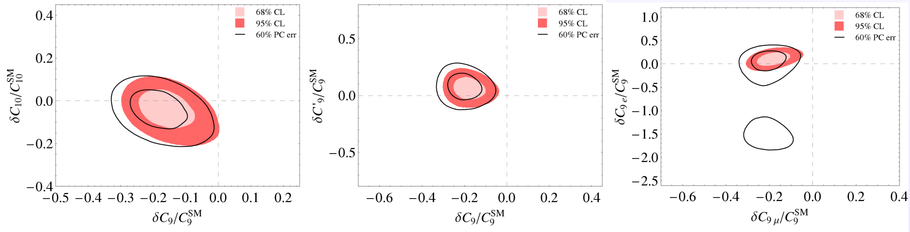
- 60% uncertainty (solid line)

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



Not a huge impact!

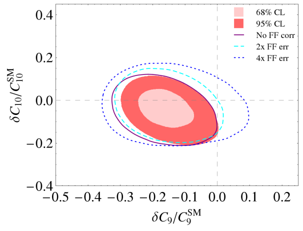
60% power correction uncertainty leads to only 17-20% error at the observable level.

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 $\times$ form factor errors (dashed line)
- 4 $\times$ form factor errors (dotted line)

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



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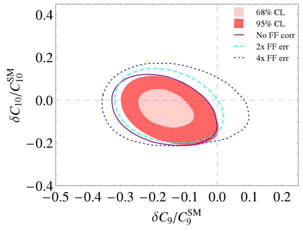
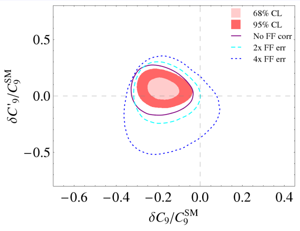
$(C_9 - C_{10})$



$(C_9 - C_9')$



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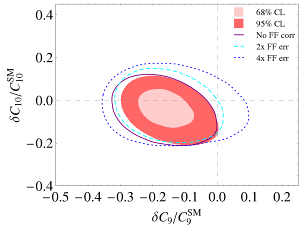
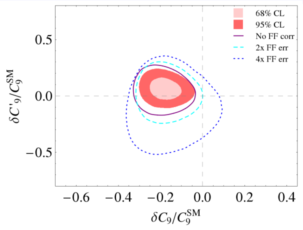
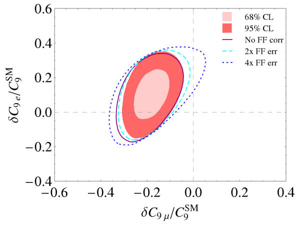


$(C_9 - C_9')$



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



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

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

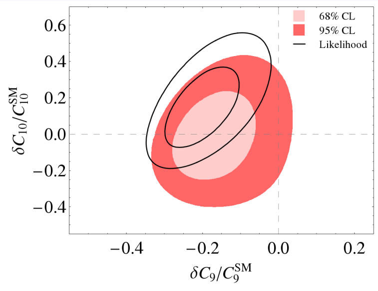
LHCb presented the $B \to K^* \mu^+ \mu^-$ angular analysis with two different methods:

- 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

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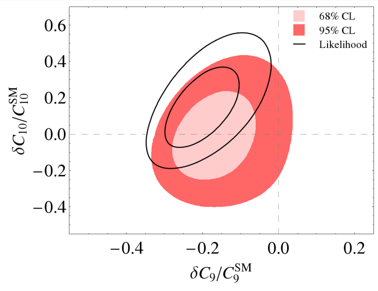
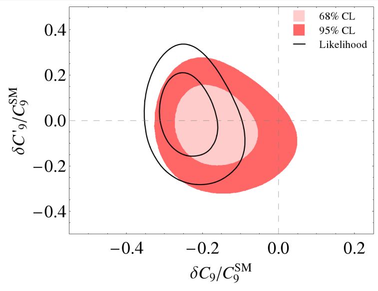


$(C_9 - C_9')$

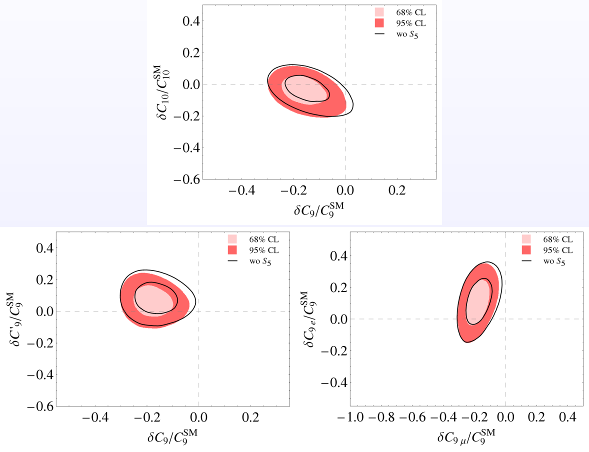


likelihood fits: solid lines
method of moments: filled areas

Tension decreases using the method of moments results!

Role of S_5

Removing S_5 from the fit:

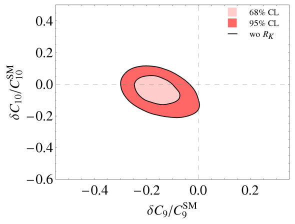


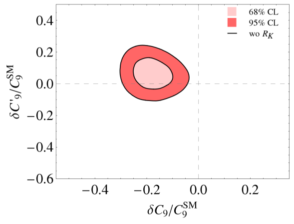
While the tension of $C_9^{\rm SM}$ and best fit point value of C_9 is slightly reduced in the various two operator fits, still the tension exists at more than 2σ

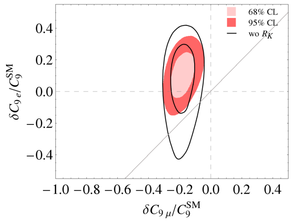
$\rightarrow$ **S_5 is not the only observable which drives C_9 to negative values!**

Role of R_K

Removing R_K from the fit:



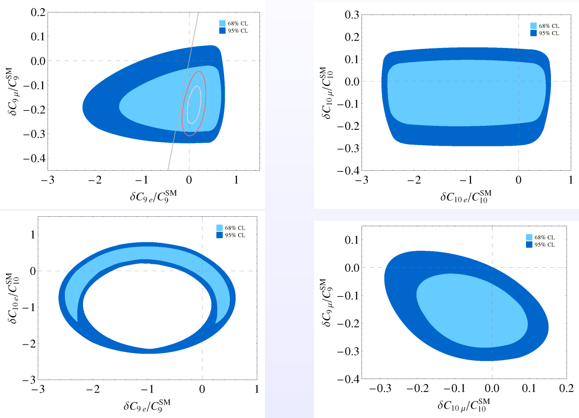




R_K is the main measurement resulting in the best fit values for C_9^μ and C_9^e which are in more than 2σ tension with lepton-universality

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.

Strategies to identify the origin of the observed anomalies (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 calculations...

  "Any reasonable calculation is better than a fit!" – T. Hurth

- 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'

Strategies to identify the origin of the observed anomalies (2)

Cross-check with other $R_{\mu/e}$ ratios

- R_K is theoretically very clean compared to the angular observables
- Its tension cannot be explained by power corrections
- Both tensions could be explained by new physics in C_9^μ

Cross-checks needed with other ratios. Our predictions (within the $\{C_9^\mu, C_9^e\}$ set):

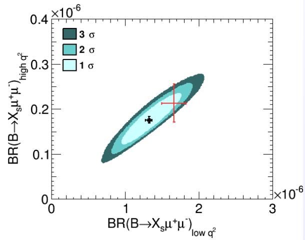
Observable	95% C.L. prediction
$\mathrm{BR}(B \to X_s\mu^+\mu^-)/\mathrm{BR}(B \to X_s e^+e^-)_{q^2\in[1,6](\mathrm{GeV})^2}$	$[0.61, 0.93]$
$\mathrm{BR}(B \to X_s\mu^+\mu^-)/\mathrm{BR}(B \to X_s e^+e^-)_{q^2>14.2(\mathrm{GeV})^2}$	$[0.68, 1.13]$
$\mathrm{BR}(B^0 \to K^{*0}\mu^+\mu^-)/\ \mathrm{BR}(B^0 \to K^{*0}e^+e^-)_{q^2\in[1,6](\mathrm{GeV})^2}$	$[0.65, 0.96]$
$\langle F_L(B^0 \to K^{*0}\mu^+\mu^-)\rangle/\langle F_L(B^0 \to K^{*0}e^+e^-)\rangle_{q^2\in[1,6](\mathrm{GeV})^2}$	$[0.85, 0.96]$
$\langle A_{FB}(B^0 \to K^{*0}\mu^+\mu^-)\rangle/\langle A_{FB}(B^0 \to K^{*0}e^+e^-)\rangle_{q^2\in[4,6](\mathrm{GeV})^2}$	$[-0.21, 0.71]$
$\langle S_5(B^0 \to K^{*0}\mu^+\mu^-)\rangle/\langle S_5(B^0 \to K^{*0}e^+e^-)\rangle_{q^2\in[4,6](\mathrm{GeV})^2}$	$[0.53, 0.92]$
$\mathrm{BR}(B^0 \to K^{*0}\mu^+\mu^-)/\ \mathrm{BR}(B^0 \to K^{*0}e^+e^-)_{q^2\in[15,19](\mathrm{GeV})^2}$	$[0.58, 0.95]$
$\langle F_L(B^0 \to K^{*0}\mu^+\mu^-)\rangle/\langle F_L(B^0 \to K^{*0}e^+e^-)\rangle_{q^2\in[15,19](\mathrm{GeV})^2}$	$[0.998, 0.999]$
$\langle A_{FB}(B^0 \to K^{*0}\mu^+\mu^-)\rangle/\langle A_{FB}(B^0 \to K^{*0}e^+e^-)\rangle_{q^2\in[15,19](\mathrm{GeV})^2}$	$[0.87, 1.01]$
$\langle S_5(B^0 \to K^{*0}\mu^+\mu^-)\rangle/\langle S_5(B^0 \to K^{*0}e^+e^-)\rangle_{q^2\in[15,19](\mathrm{GeV})^2}$	$[0.87, 1.01]$
$\mathrm{BR}(B^+ \to K^+\mu^+\mu^-)/\ \mathrm{BR}(B^+ \to K^+e^+e^-)_{q^2\in[1,6](\mathrm{GeV})^2}$	$[0.58, 0.95]$
$\mathrm{BR}(B^+ \to K^+\mu^+\mu^-)/\ \mathrm{BR}(B^+ \to K^+e^+e^-)_{q^2\in[15,22](\mathrm{GeV})^2}$	$[0.58, 0.95]$

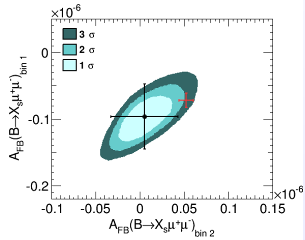
Strategies to identify the origin of the observed anomalies (3)

Cross-check with inclusive modes

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

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





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

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

Predictions based on our model-independent analysis

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

red cross: SM predictions

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

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...

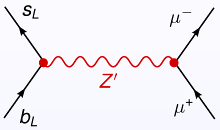
Need for tree level diagrams...

$\rightarrow$ difficult in MSSM with MFV

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

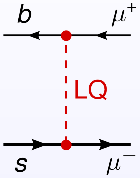
Strong constraints from $B_s - \bar{B}_s$ mixing and LEP contact interactions.

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



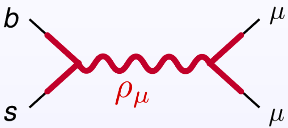
- t-channel diagrams
- Different possible representations, can be scalar (spin 0) or vector (spin 1)
- Cannot alter only C_9, but both C_9 and C_{10} $(= -C_9)$
- Cannot be lepton flavour universal and conserve lepton number simultaneously

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

In addition, such models may explain the excesses observed in WW, WZ, Wh and $\ell^+\ell^-$ resonance searches by ATLAS and CMS

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

Conclusion

- Latest LHCb results, based on the 3 fb^{-1} data set still show some tensions with the SM predictions
- Model independent fits point to $C_9^{NP} \sim -1$, and new physics in muonic C_9^{μ} is preferred
- In two operator fits there is more than 2σ tension for $\delta C_9^{e} = \delta C_9^{\mu}$
- The fit results do not depend very much on whether one uses soft or full form factor approach
- Factorisable power corrections have small effects at observable level
- The cross check with other not-yet-measured ratios (e.g. R_{K^*}) and the inclusive measurements would be of importance to identify the origin of the anomalies

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With the 750 GeV being gone, these are at the moment the only significant tensions with the SM at the LHC, so stay tuned!

Backup

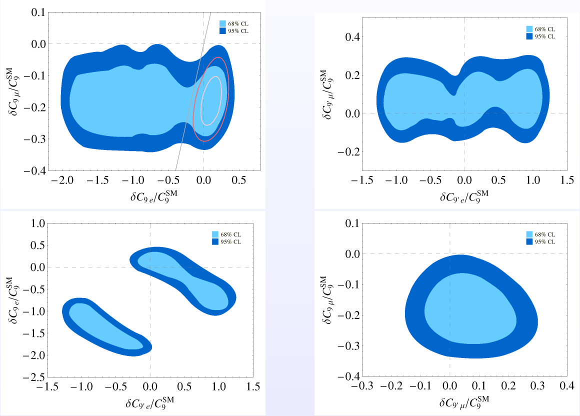
Backup

Global fit results assuming new physics in one operator only

	b.f. value	$\chi^2_{\rm min}$	$\mathrm{Pull}_{\rm SM}$	68% C.L.	95% C.L.
$\delta C_9/C_9^{\rm SM}$	-0.18	123.8	3.0σ	$[-0.25,-0.09]$	$[-0.30,-0.03]$
$\delta C_9'/C_9^{\rm SM}$	$+0.03$	131.9	1.0σ	$[-0.05,+0.12]$	$[-0.11,+0.18]$
$\delta C_{10}/C_{10}^{\rm SM}$	-0.12	129.2	1.9σ	$[-0.23,-0.02]$	$[-0.31,+0.04]$
$\delta C_9^{\mu}/C_9^{\rm SM}$	-0.21	115.5	4.2σ	$[-0.27,-0.13]$	$[-0.32,-0.08]$
$\delta C_9^{e}/C_9^{\rm SM}$	$+0.25$	124.3	2.9σ	$[+0.11,+0.36]$	$[+0.03,+0.46]$

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

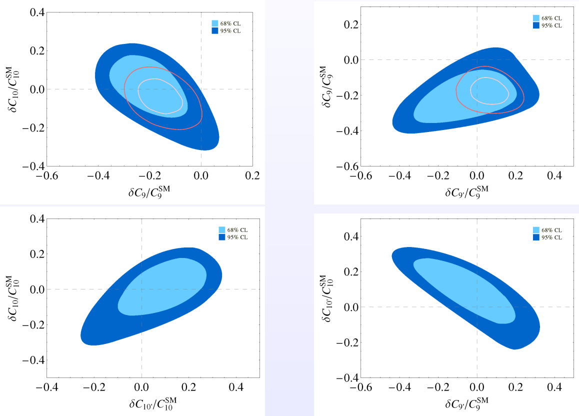
No reason that only 2 Wilson coefficients receive contributions from new physics



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