Global fits to the latest LHCb data on bsll

Nazila Mahmoudi

Lyon University & CERN

In collaboration with T. Hurth and S. Neshatpour

Rare B Decays: Theory and Experiment 2016

18-20 April 2016
Barcelona
Europe/Madrid timezone

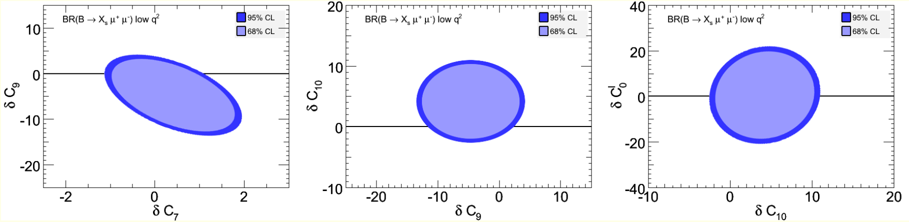
Inclusive decays $B \to X_s \ell^+ \ell^-$

- Precise theory calculations (see e.g. T. Huber, T. Hurth, E. Lunghi, JHEP 1506 (2015) 176)
  Theoretical description of power corrections available $\to$ they can be calculated or estimated within the theoretical approach
- Final results from Belle and Babar still not available!
- Promising situation with Belle II!

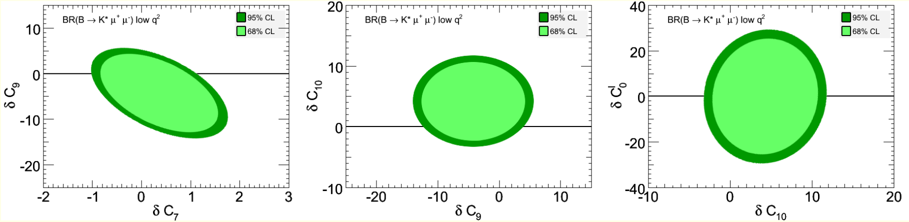
Exclusive decays

- Angular distributions of $B \to K^* \mu^+ \mu^-$
  $\to$ many experimentally accessible observables
- Also: $B \to K \mu^+ \mu^-$ and $B_s \to \phi \mu^+ \mu^-$
- Issue of hadronic uncertainties in exclusive modes
  no theoretical description of power corrections existing within the theoretical framework of QCD factorisation and SCET

Inclusive:



Exclusive (2012):



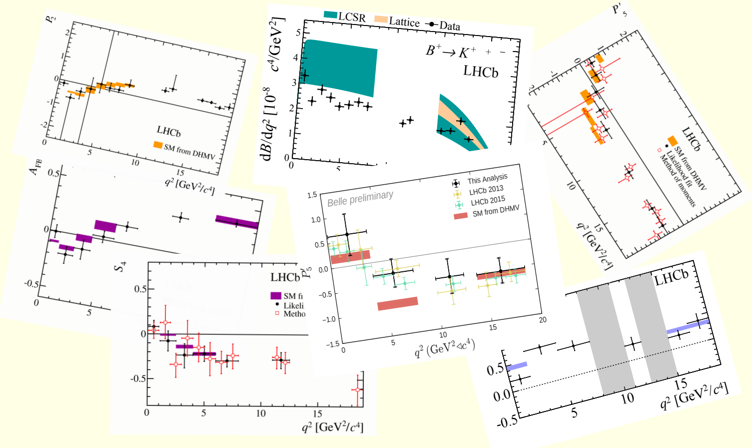
T. Hurth, FM, Nucl. Phys. B865 (2012) 461

$b \to s\ell\ell$ transitions

Exclusive (2016):

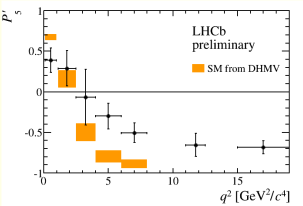
The situation has changed drastically with the measurements of many angular observables!

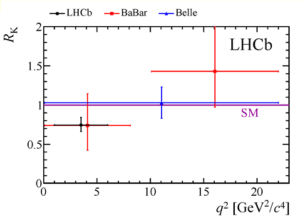
$B \to K^+\mu^+\mu^-$, $B \to K^0\mu^+\mu^-$, $B \to K^{*+}\mu^+\mu^-$, $B \to K^{*0}\mu^+\mu^-$ (F_L, A_{FB}, S_i, P_i),
$B_s \to \phi\mu^+\mu^-$, ...

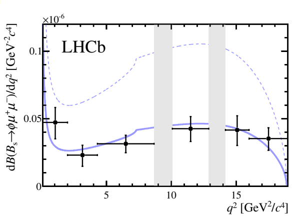


3 main LHCb anomalies:

- $B \to K^* \mu^+\mu^-$ angular observables (P_5' / S_5,...): 3.4σ tension $\leftarrow$ supported by Belle
- $R_K = BR(B^+ \to K^+\mu^+\mu^-)/BR(B^+ \to K^+e^+e^-)$: 2.6σ tension in [1-6] GeV^2 bin
- $\mathrm{BR}(B_s \to \phi\mu^+\mu^-)$: 3.2σ tension in [1-6] GeV^2 bin







New Physics or theoretical issues?

New Physics interpretation?

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

Relevant $\mathcal{O}$perators:

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

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

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

- $\rightarrow$ 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
S. Descotes-Genon, L. Hofer, J. Matias, J. Virto, 1510.04239v2

Global fits

Experimental errors and correlations

3 fb^{-1} LHCb data for $B \to K^{*0}\mu^+\mu^-$: JHEP 1602 (2016) 104
And for $B_s \to \phi\mu^+\mu^-$: JHEP 1509 (2015) 179
And for $B \to K\mu^+\mu^-$, R_K: Phys. Rev. Lett. 113 (2014) 151601

More than 100 observables relevant for leptonic and semileptonic decays:

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

calculations done using SuperIso program

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 (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
- two approaches for the exclusive decays: soft form factors, full form factors
- 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
Low recoil: $b_k = 0$
$|a_k|$ between 10 to 60%, $b_k \sim 2.5 a_k$

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

Global fits of the observables by minimization 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.

Statistical approaches:

- $\Delta\chi^2 = \chi^2 - \chi^2_{\rm min}$ method
  1. Determination of the minimum of χ^2 in a given scenario $\rightarrow$ best fit point
  2. Computation for each point of the scan of the difference of χ^2 with the best fit point
  3. Find the $1-2\sigma$ regions corresponding to the number of d.o.f.

  Interpretation: considering the best fit point gives the "real" description, which variations of the parameters are allowed in a given scenario $\rightarrow$ *relative* global fit

- Absolute χ^2 method
  1. Computation of the χ^2 for each point
  2. Find the $1-2\sigma$ regions corresponding to N d.o.f. where $N = (N_o$ observables - n_v variables)
  3. If an observable is relatively insensitive to the variation of the Wilson coefficients, remove it from the fit

  Interpretation: global fit assessing if each point is *globally* in agreement with all the measurements

We need both methods to make sure we have a reasonable fit and maximal information

Fit results for two operators

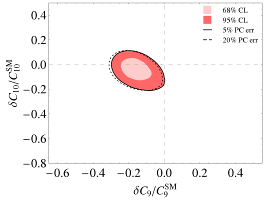
Using full FFs, assuming 10% power correction errors

$(C_9 - C_{10})$

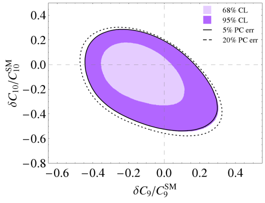
$(C_9 - C_9')$

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

$\Delta\chi^2$ method



Absolute χ^2 method



Fit results for two operators

Using full FFs, assuming 10% power correction errors

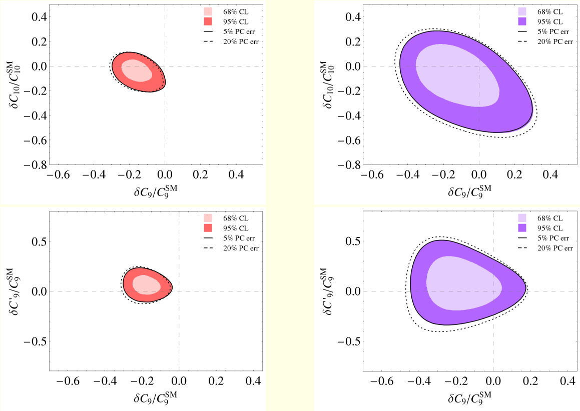
$(C_9 - C_{10})$

$(C_9 - C'_9)$

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

$\Delta\chi^2$ method

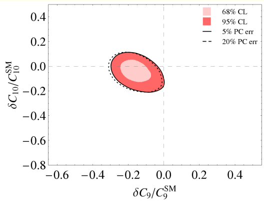
Absolute χ^2 method

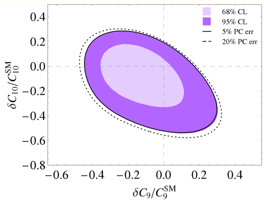


$\Delta\chi^2$ method / Absolute χ^2 method

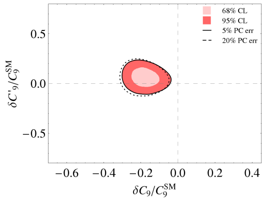
Using full FFs, assuming 10% power correction errors

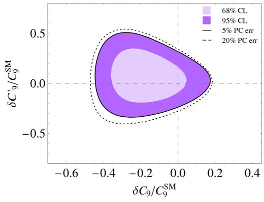
$(C_9 - C_{10})$



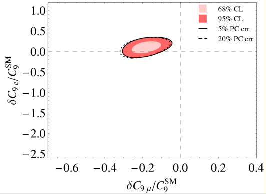


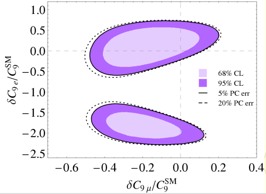
$(C_9 - C_9')$





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

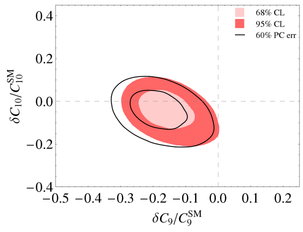




Fits assuming different power correction uncertainties:

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

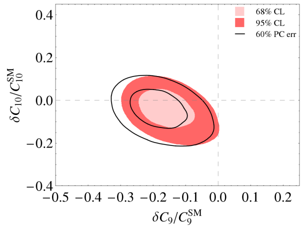
$(C_9 - C_{10})$ $(C_9 - C_9')$ $(C_9^e - C_9^\mu)$



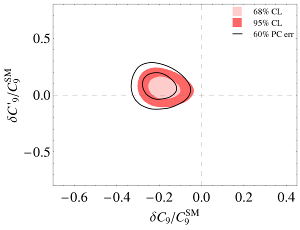
Fits assuming different power correction uncertainties:

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

$(C_9 - C_{10})$



$(C_9 - C_9')$

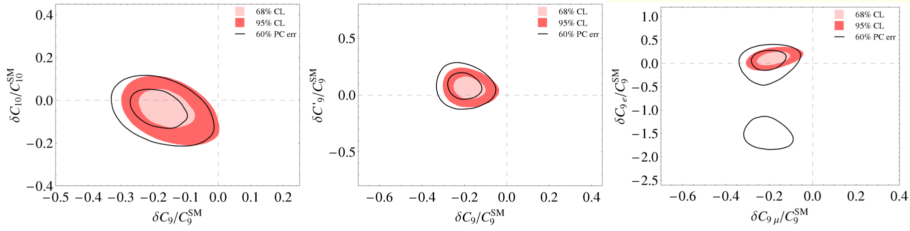


$(C_9^e - C_9^\mu)$

Fits assuming different power correction uncertainties:

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

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



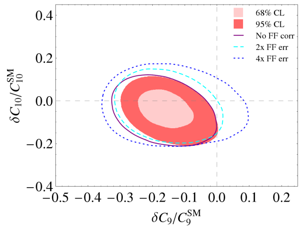
Not a huge impact!

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

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)

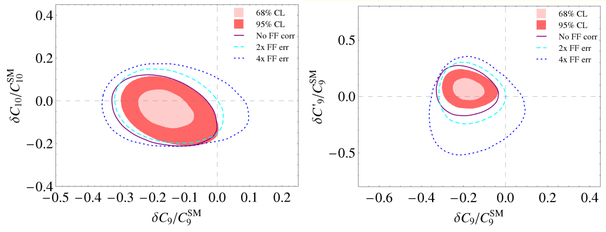
$(C_9 - C_{10})$ $(C_9 - C_9')$ $(C_9^e - C_9^\mu)$



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)

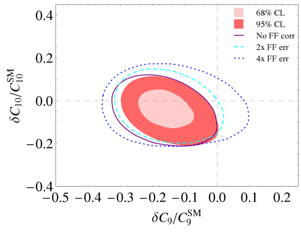
$(C_9 - C_{10})$ $(C_9 - C_9')$ $(C_9^e - C_9^\mu)$



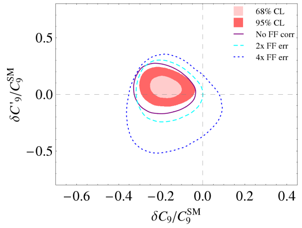
Fits with different assumptions for the form factor uncertainties:

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

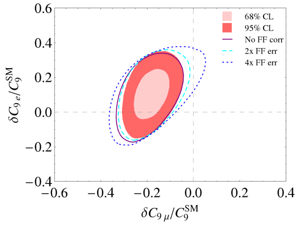
$(C_9 - C_{10})$



$(C_9 - C_9')$



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



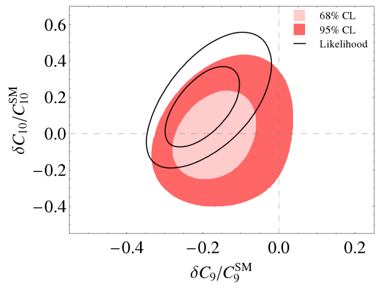
The size of the form factor errors has a crucial role in constraining the allowed region!

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

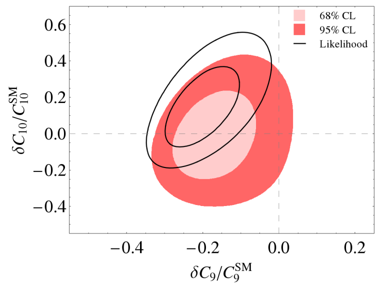
Fit results for two operators: likelihood vs. method of moments

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

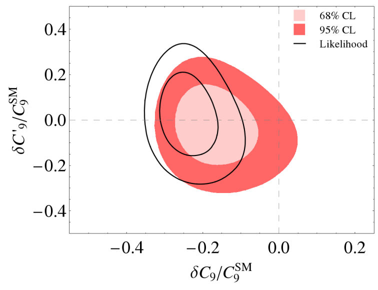
- likelihood fits: smaller uncertainties, but involves model-dependent assumptions
- method of moments: more robust (?), but larger uncertainties

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

$(C_9 - C_{10})$



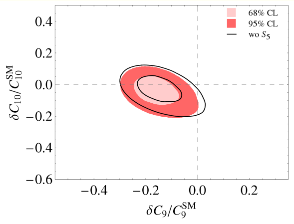
$(C_9 - C_9')$

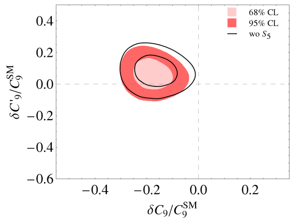


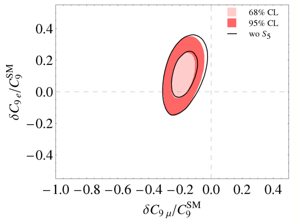
likelihood fits: solid lines
method of moments: filled areas

Tension decreases using the method of moments results!

Removing S_5 from the fit:





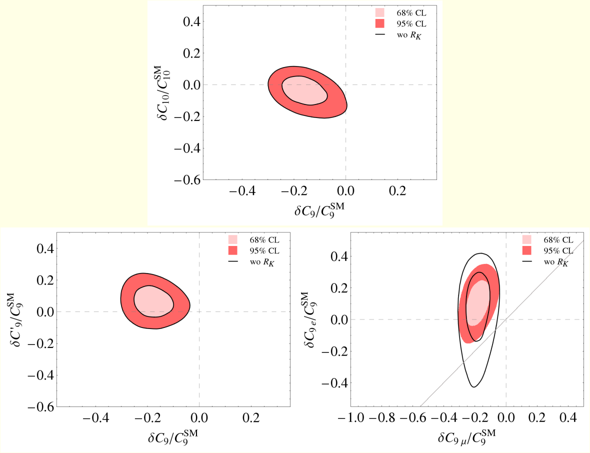


While the tension of $C_9^{\rm SM}$ and best fit point value of C_9 is slightly reduced in the various two operator fits, still the tension exists at more than 2σ

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

Role of R_K

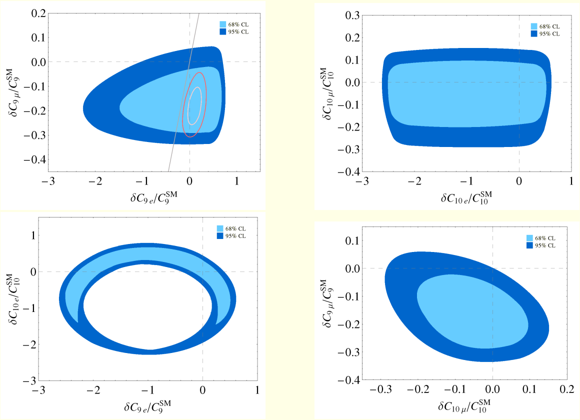
Removing R_K from the fit:



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: $\{C_9^\mu, C_9^e, C_{10}^\mu, C_{10}^e\}$

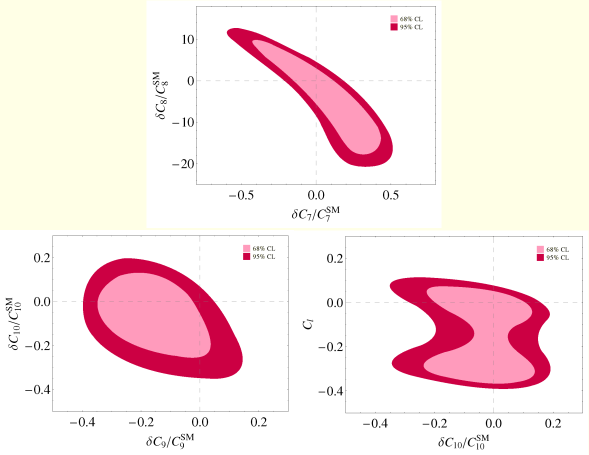
No reason that only 2 Wilson coefficients receive contributions from new physics



Larger ranges are allowed for the Wilson coefficients

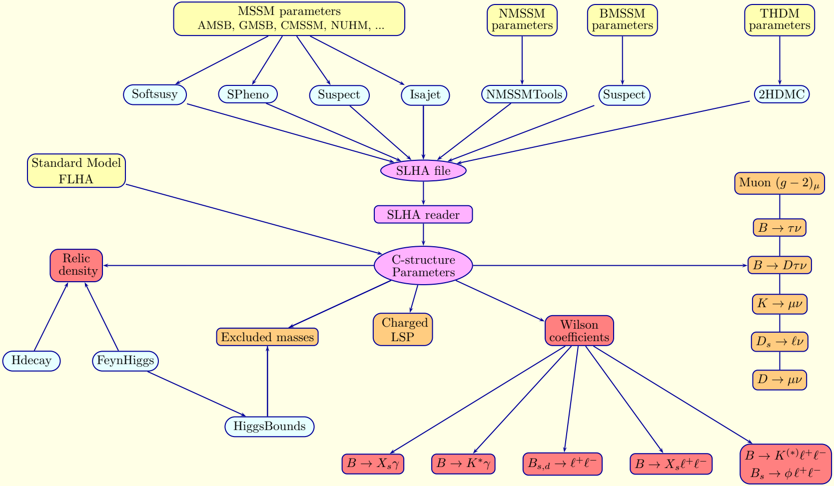
Considering 4 operator fits considerably relaxes the constraints on the Wilson coefficients leaving room for more diverse new physics contributions which are otherwise overlooked.

Fit results for C_7, C_8, C_9, C_{10}, C_0^l with MFV hypothesis



The five operator fit within the MFV framework shows compatibility with the MFV hypothesis.

Latest version: SuperIso v3.5

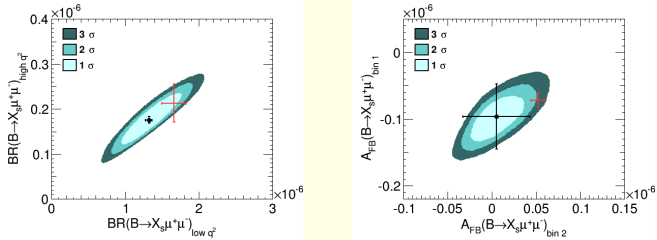


Available from **http://superiso.in2p3.fr**

- Latest LHCb results, based on the 3 fb^{-1} data set and on two different experimental analysis methods, 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 a 2σ tension for $\delta C_9^e = \delta C_9^\mu$
- In four operator fits, possible to have $\delta C_9^e = \delta C_9^\mu$ but lepton flavour non-universality would take place in C_9' or $C_{10}^{(\prime)}$
- 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

Backup

At Belle-II, for inclusive $b \to s\ell\ell$:
expected uncertainty of 2.9% (4.1%) for the branching fraction in the low- (high-)q^2 region, absolute uncertainty of 0.050 in the low-q^2 bin 1 ($1 < q^2 < 3.5$ GeV^2), 0.054 in the low-q^2 bin 2 ($3.5 < q^2 < 6$ GeV^2) for the *normalised* A_{FB}



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

→ inclusive mode will lead to very strong constraints

Global fit results assuming new physics in one operator only

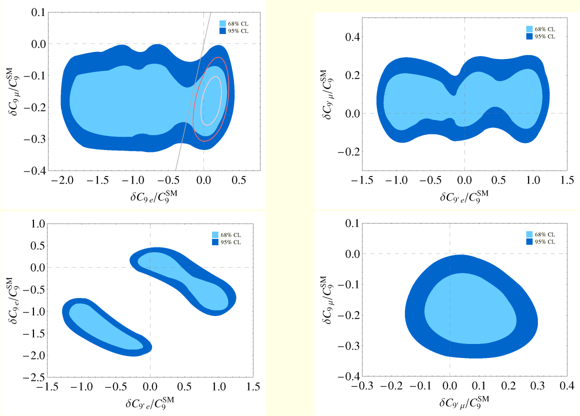
	b.f. value	$\chi^2_{\rm min}$	$\mathrm{Pull}_{\rm SM}$	68% C.L.	95% C.L.
$\delta C_9/C_9^{\rm SM}$	-0.18	123.8	3.0σ	$[-0.25, -0.09]$	$[-0.30, -0.03]$
$\delta C_9'/C_9^{\rm SM}$	$+0.03$	131.9	1.0σ	$[-0.05, +0.12]$	$[-0.11, +0.18]$
$\delta C_{10}/C_{10}^{\rm SM}$	-0.12	129.2	1.9σ	$[-0.23, -0.02]$	$[-0.31,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

Predictions for other ratios

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

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

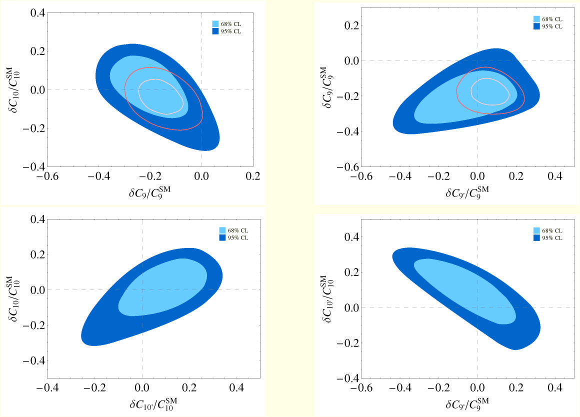
No reason that only 2 Wilson coefficients receive contributions from new physics



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