Recent LHCb anomalies in $b \to s\ell\ell$ transitions

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In collaboration with T. Hurth and S. Neshatpour

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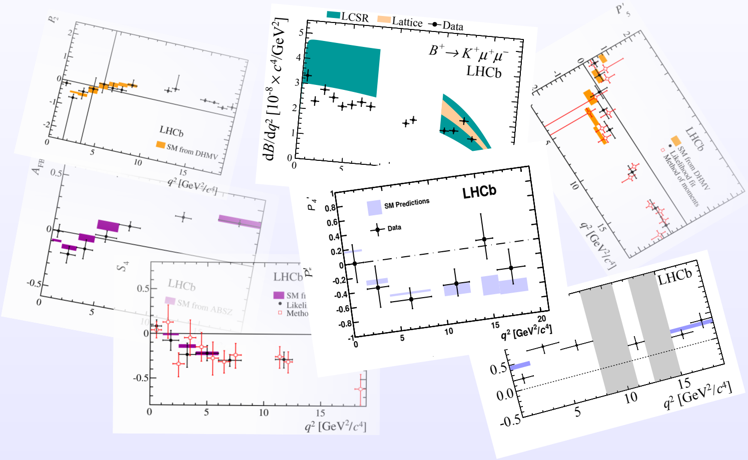
Impressive effort in studying **exclusive** $b \to s\ell\ell$ transitions at LHCb with the measurements of a large number of independent angular observables!

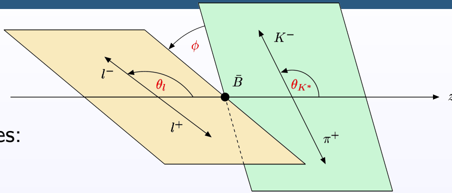
$B \to K\mu^+\mu^-$, $B \to K^+e^+e^-$, $B \to K^*\mu^+\mu^-$ (F_L, A_{FB}, S_i, P_i), $B_s \to \phi\mu^+\mu^-$, ...



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

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

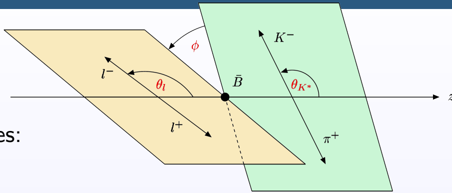
Main operators:

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

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

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

Angular distributions



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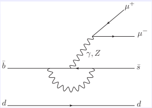

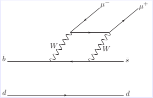

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$B \to K^* \mu^+ \mu^-$ observables

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

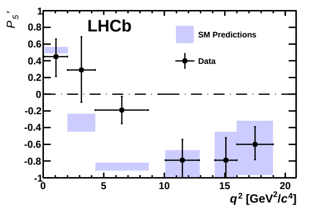
Or alternatively:

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

W. Altmannshofer, P. Ball, A. Bharucha, A.J. Buras, D.M. Straub, M. Wick, JHEP 0901 (2009) 019

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



3.7σ deviation in the 3rd bin

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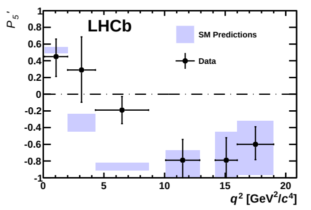

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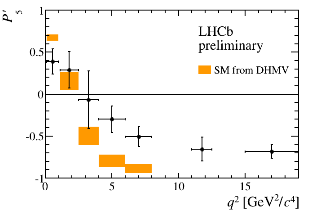

2.9σ in the 4th and 5th bins (3.7σ combined)

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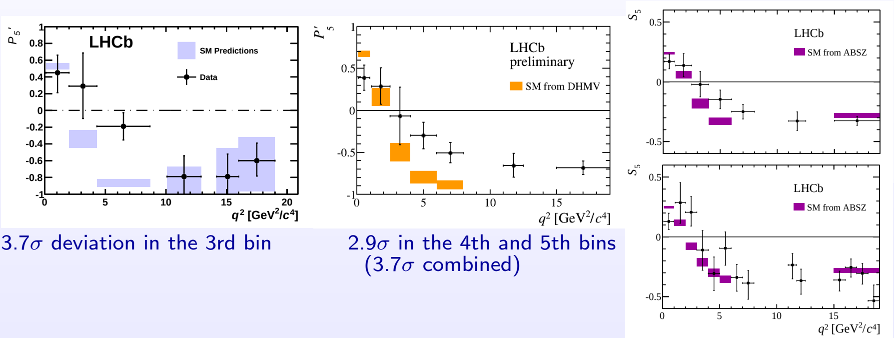

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3.4σ combined fit (likelihood)

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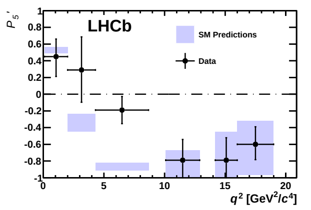

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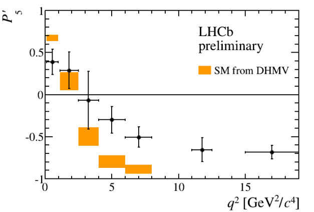

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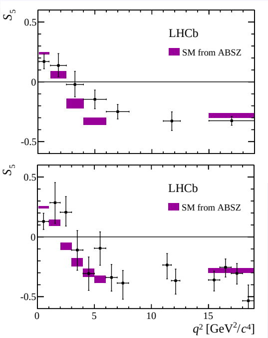
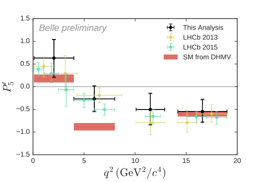


3.4σ combined fit (likelihood)

Belle supports LHCb

(arXiv:1604.04042)

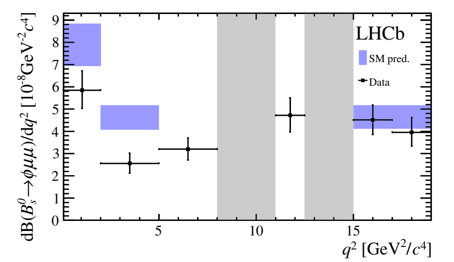
tension at 2.1σ



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

- 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

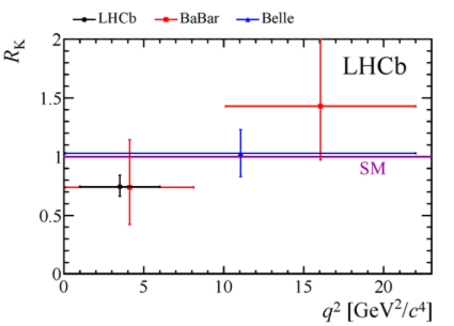


Lepton universality in $B^+ \to K^+\ell^+\ell^-$

- 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)

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



New Physics interpretation?

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

Relevant $\mathcal{O}$perators:

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

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 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.

More than 100 observables relevant for leptonic and semileptonic decays:

T. Hurth, FM, S. Neshatpour, 1603.00865

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

Computations performed using SuperIso public program (latest release: v3.5 April 2016)

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:

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

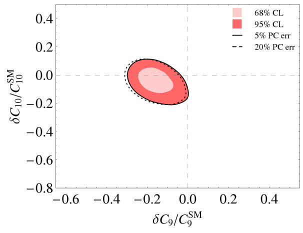
Soft: parametrisation of both factorisable and non-factorisable power corrections
Full: parametrisation of only non-factorisable power corrections
Low recoil: $b_k = 0$
$|a_k|$ between 10 to 60%, $b_k \sim 2.5 a_k$

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

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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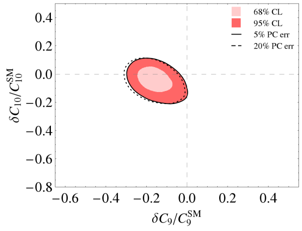
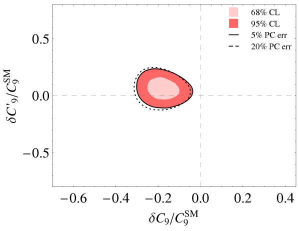


$(C_9 - C_9')$



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

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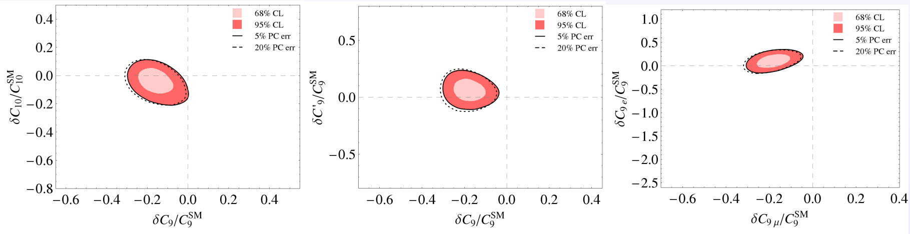


About 3σ deviations with the SM in all cases

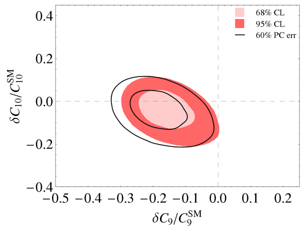
Power correction uncertainty between 5 and 20% does not change the picture.

Results using soft form factors are very similar

Fits assuming different power correction uncertainties:

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

$(C_9 - C_{10})$



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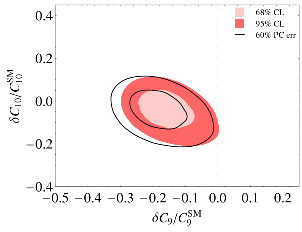

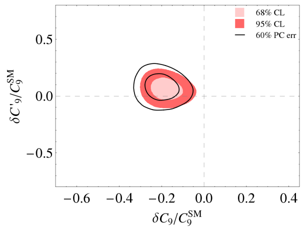

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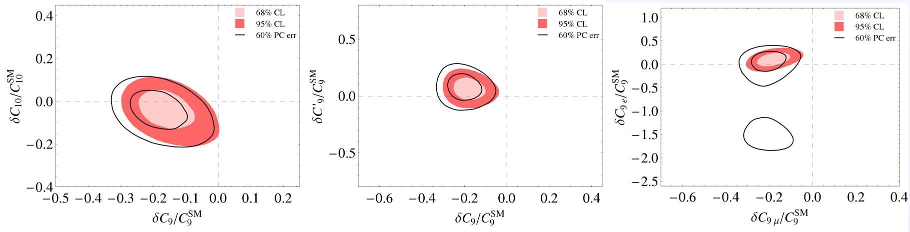


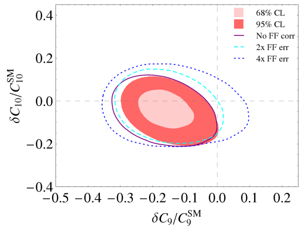
Not a huge impact!

60% power correction uncertainty leads to only 17-20% 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 × 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:

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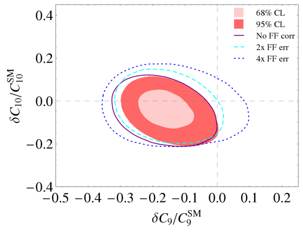
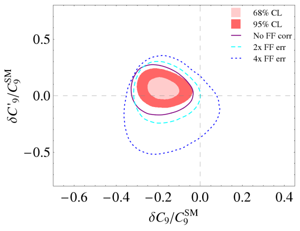
- normal form factor errors (filled areas)
- $2 \times$ form factor errors (dashed line)
- $4 \times$ form factor errors (dotted line)

$(C_9 - C_{10})$



$(C_9 - C'_9)$



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

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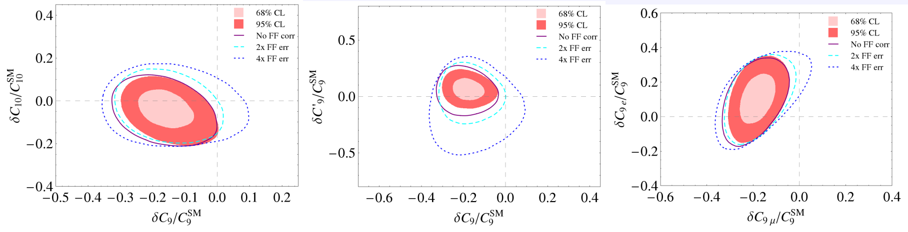
$(C_9 - C_{10})$ $(C_9 - C_9')$ $(C_9^e - C_9^\mu)$



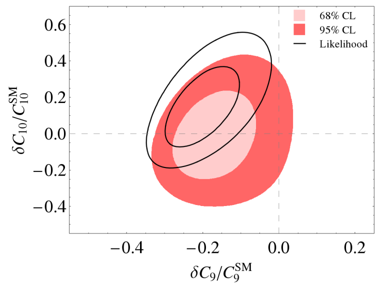
The size of the form factor errors has a crucial role in constraining the allowed region!

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

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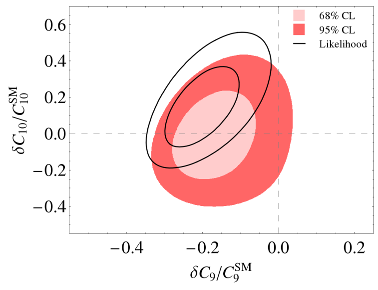
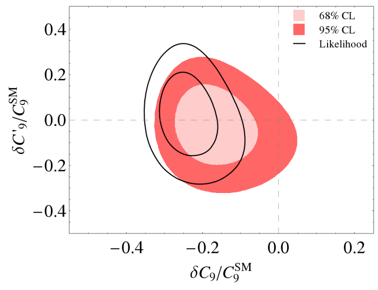
$(C_9 - C_{10})$



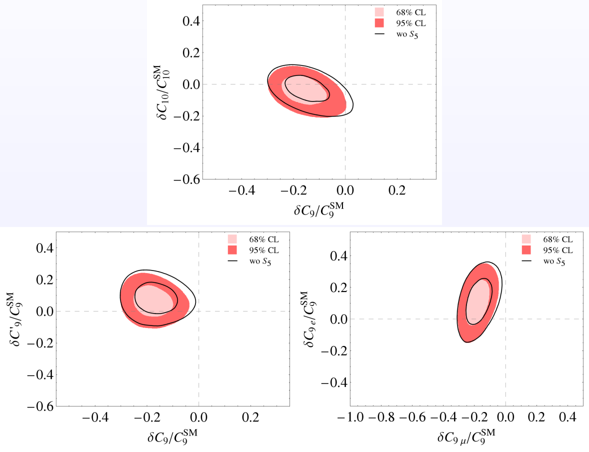
$(C_9 - C_9')$



likelihood fits: solid lines
method of moments: filled areas

Tension decreases using the method of moments results!

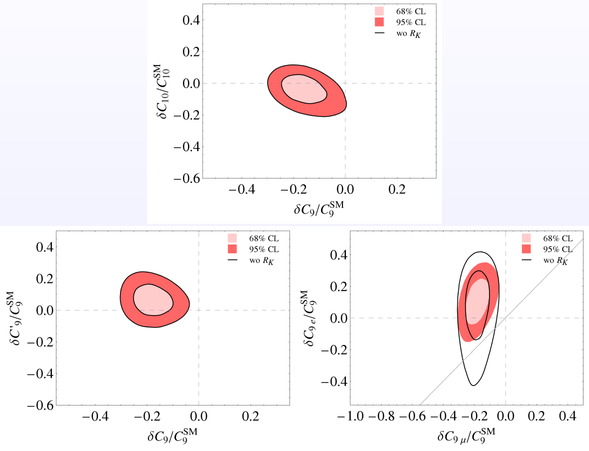
Removing S_5 from the fit:



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!**

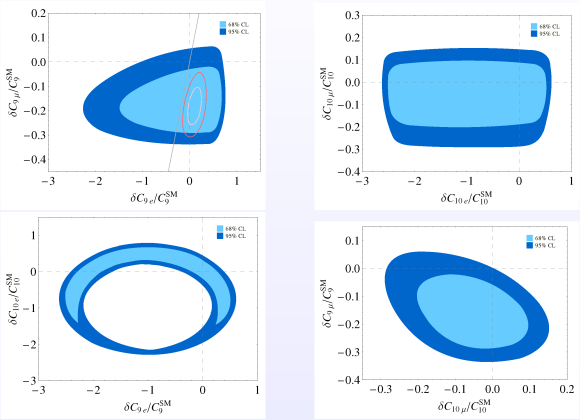
Removing R_K from the fit:



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.

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 factorization
- 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'

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

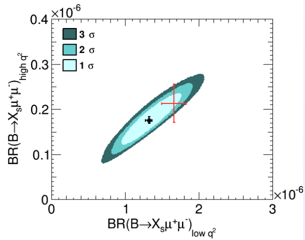
Cross-checks needed with other ratios. Our predictions (within the $\{C_9^\mu, C_9^e\}$ set):

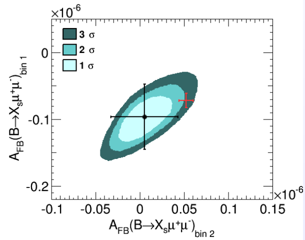
Observable	95% C.L. prediction
$\mathrm{BR}(B \to X_s \mu^+\mu^-)/\mathrm{BR}(B \to X_s e^+e^-)_{q^2 \in [1,6](\mathrm{GeV})^2}$	$[0.61, 0.93]$
$\mathrm{BR}(B \to X_s \mu^+\mu^-)/\mathrm{BR}(B \to X_s e^+e^-)_{q^2 > 14.2(\mathrm{GeV})^2}$	$[0.68, 1.13]$
$\mathrm{BR}(B^0 \to K^{*0}\mu^+\mu^-)/\ \mathrm{BR}(B^0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

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

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 $\delta C_9^e = \delta C_9^{\mu}$
- 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

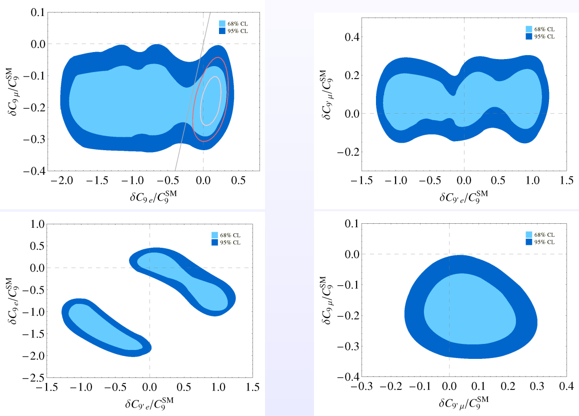
Backup

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

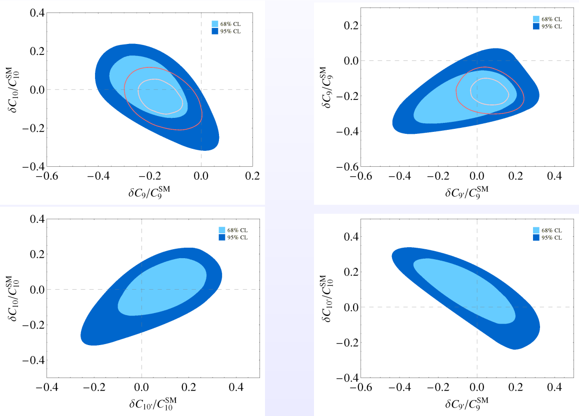
No reason that only 2 Wilson coefficients receive contributions from new physics



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