Institute for Research in Fundamental Sciences

Is there New Physics in semileptonic $b \to s$ transitions, if so, what type?

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Based on arXiv:1603.00865, arXiv:1702.02234 & arXiv:1705.06274 and work in progress

In collaboration with T. Hurth, N. Mahmoudi, D. Martinez Santos and V. Chobanova

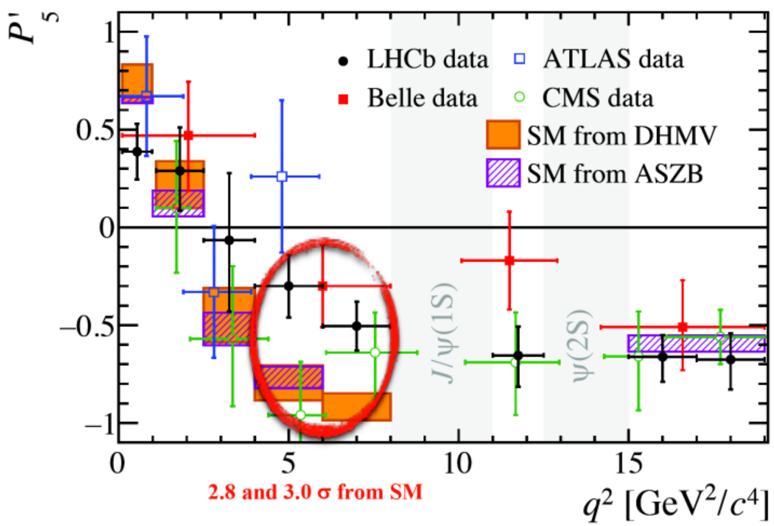
LIO International Conference on Flavour Physics:

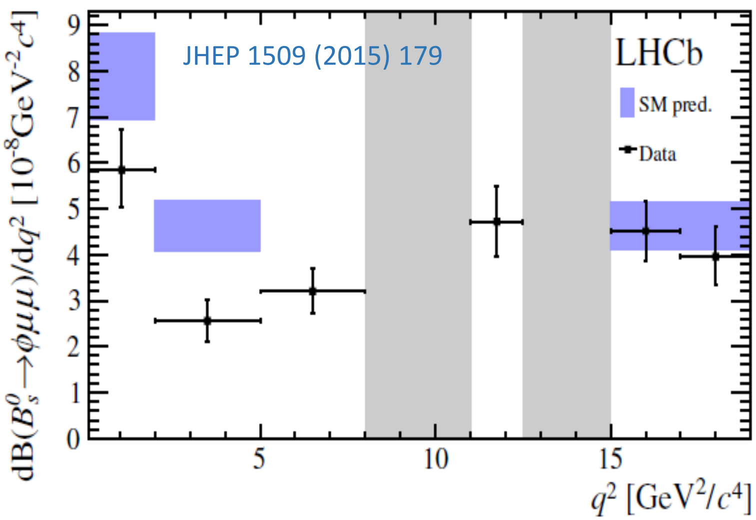
"From Flavour to New Physics"

April 18-20, 2018

- $B \to K^*\mu^+\mu^-$ angular observable P_5' (or S_5): 2.8 and 3.0σ in [4.0-6.0] and [6.0-8.0] GeV^2 bins with 3 fb^{-1} at LHCb
- BR($B_s \to \phi\mu^+\mu^-$): 3.2σ tension in the [1-6] GeV^2 bin with 3 fb^{-1} at LHCb (2015)

Similar theory description: difference in form factor choice ($B \to K^*$ or $B_s \to \phi$) and $B_s - \bar{B}_s$ mixing should be considered for $B_s \to \phi\mu^+\mu^-$; both suffer from hadronic uncertainties





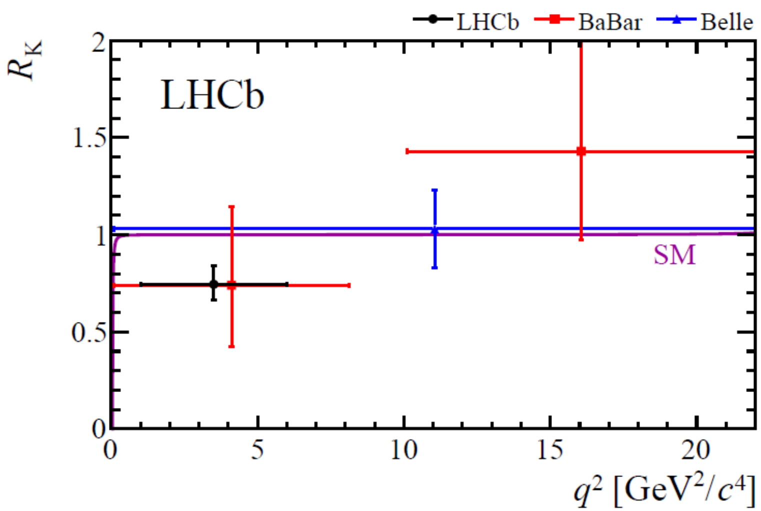
Possible explanations for the tensions

- Statistical fluctuations ← $P_5'(B \to K^*\mu^+\mu^-)$ also measured by Belle and ATLAS and CMS
- Theoretical issues ← underestimated hadronic contributions
- New Physics

LHCb, JHEP 02 (2016) 104; Belle, PRL 118 (2017);
ATLAS, ATLAS-CONF-2017-023; CMS, CMS-PAS-BPH-15-008

Lepton flavour universality observables:

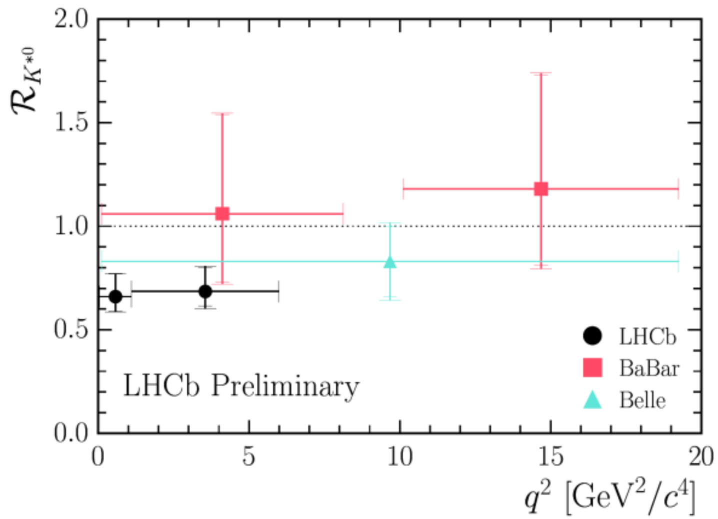
- $R_K = \text{BR}(B^+ \to K^+\mu^+\mu^-)/\text{BR}(B^+ \to K^+e^+e^-)$: 2.6$\sigma$ tension in [1-6] GeV^2 bin
- $R_{K^*} = \text{BR}(B^0 \to K^{*0}\mu^+\mu^-)/\text{BR}(B^0 \to K^{*0}e^+e^-)$: 2.3$\sigma$ and 2.5σ tension in [0.045-1.1] and [1.1-6.0] GeV^2 bins



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

$R_K^{SM} = 1.0006 \pm 0.0004$

Bordone, Isidori, Pattori, arXiv:1605.07633



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

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

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

$R_{K}^{\text{SM, bin2}} = 0.906 \pm 0.010_{\text{QED}}$

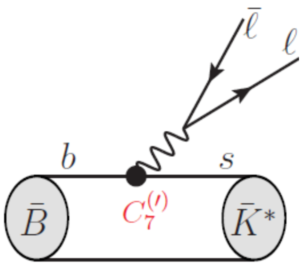
Possible explanations for the tensions

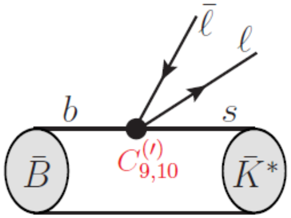
- Statistical fluctuations
- Theoretical issues ← SM prediction very accurate (cancellation of hadronic uncertainties)
- New Physics

Underestimated hadronic corrections: a closer look at the calculations for $B \to K^* \ell^+ \ell^-$

$$\mathcal{A}(B \to K^* \ell^+ \ell^-) = \langle K^* \ell^+ \ell^- | (\mathcal{H}_{\rm eff}^{\rm sl} + \mathcal{H}_{\rm eff}^{\rm had}) | B \rangle$$

$$\mathcal{H}_{\rm eff}^{\rm sl} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \Big[\sum_{i=7,9,10} C_i^{(\prime)}(\mu) O_i^{(\prime)}(\mu) \Big]$$



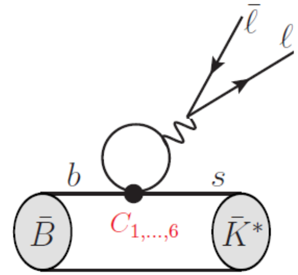


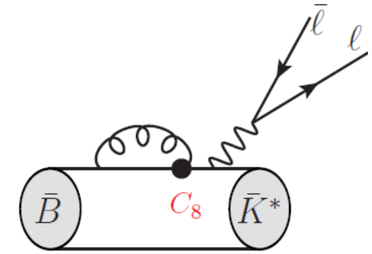
Factorisation of leptonic and hadronic parts

- $\langle K_\lambda^* | O_7 | B \rangle \longrightarrow \tilde{T}_\lambda$
- $\langle K_\lambda^* | O_{9,10} | B \rangle \longrightarrow \tilde{V}_\lambda$ ⟹ 7 independent FFs
- $\langle K_\lambda^* | O_{S,P} | B \rangle \longrightarrow \tilde{S}$

$(\lambda = -1, 0, +1)$

$$\mathcal{H}_{\rm eff}^{\rm had} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \Big[\sum_{i=1\dots6} C_i(\mu) O_i(\mu) + C_8(\mu) O_8(\mu) \Big]$$





$\mathcal{H}_{\rm eff}^{\rm had}$ contributes to $b \to s\bar\ell\ell$ through virtual photon exchange
⇒ affect only $H_V(\lambda)$

Helicity amplitudes:

$$H_V(\lambda) \approx -i\, N' \Big\{ (C_9 - C_9') \tilde{V}_\lambda(q^2) + \frac{m_B^2}{q^2} \Big[\frac{2\,\hat{m}_b}{m_B} (C_7^{\rm eff} - C_7') \tilde{T}_\lambda(q^2) \Big] \Big\}$$

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

$$H_P = i\, N' \Big\{ \frac{2\, m_\ell \hat{m}_b}{q^2} (C_{10} - C_{10}') \Big(1 + \frac{m_s}{m_b} \Big) \tilde{S}(q^2) \Big\}$$

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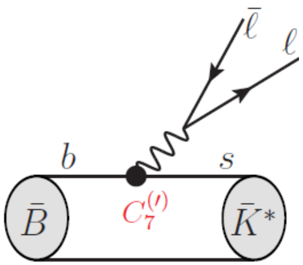
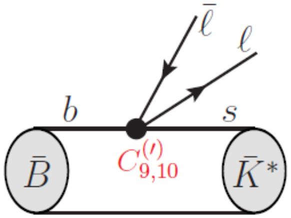
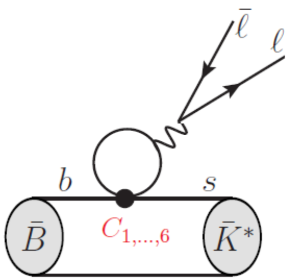
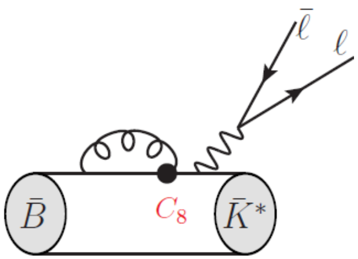




$$\mathcal{H}_{\rm eff}^{\rm had} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \Big[\sum_{i=1\ldots6} C_i(\mu) O_i(\mu) + C_8(\mu) O_8(\mu) \Big]$$





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- $\langle K_\lambda^* | O_{9,10} | B \rangle \longrightarrow \tilde{V}_\lambda$ ⟹ 7 independent FFs $(\lambda = -1, 0, +1)$
- $\langle K_\lambda^* | O_{S,P} | B \rangle \longrightarrow \tilde{S}$

In general, "naïve" factorization not applicable

$$\frac{e^2}{q^2} \epsilon_\mu L_V^\mu \Big[\underbrace{Y(q^2) \tilde{V}_\lambda}_{\text{fact., perturbative}} + \underbrace{\text{LO in } \mathcal{O}\big(\frac{\Lambda}{m_b}, \frac{\Lambda}{E_{K^*}}\big)}_{\text{non-fact., QCDf}} + \underbrace{h_\lambda(q^2)}_{\text{power corrections, unknown}} \Big]$$

Usually "guesstimated" to 10% of LO non-fact

$$\left(C_9^{\rm eff} \equiv C_9 + Y(q^2) \right)$$

Helicity amplitudes:

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

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

$$H_P = i\, N' \Big\{ \frac{2\, m_\ell \hat{m}_b}{q^2} (C_{10} - C_{10}') \Big(1 + \frac{m_s}{m_b} \Big) \tilde{S}(q^2) \Big\}$$

Model independent global fits

Many $b \to s\ell^+\ell^-$ observables ⇒ Global fits

- $\mathrm{BR}^{\mathrm{low}}(B \to X_s\,\mu^+\mu^-)$
- $\mathrm{BR}^{\mathrm{high}}(B \to X_s\,\mu^+\mu^-)$
- $\mathrm{BR}^{\mathrm{low}}(B \to X_s\,e^+e^-)$
- $\mathrm{BR}^{\mathrm{high}}(B \to X_s\,e^+e^-)$

- $\mathrm{BR}(B \to K^* e^+e^-)$
- $\mathrm{BR}(B \to K^{*+}\mu^+\mu^-)$
- $\mathrm{BR}(B_s \to \phi\,\mu^+\mu^-)$
- $B \to K^{*0}\mu^+\mu^-$: angular observables
- $B_s \to \phi\,\mu^+\mu^-$: angular observables

- $\mathrm{BR}(B_s \to \mu^+\mu^-)$
- $\mathrm{BR}(B_d \to \mu^+\mu^-)$
- $\mathrm{BR}(B \to K^0\mu^+\mu^-)$
- $\mathrm{BR}(B^+ \to K^+\mu^+\mu^-)$
- R_K, R_{K^*}

NP manifests itself in terms of shifts to the SM Wilson coefficients: $C_i(\mu) = C_i^{\mathrm{SM}}(\mu) + \delta C_i$

- Scanning over the values of δC_i
- Minimizing $\chi^2 = \left(\vec{O}^{th} - \vec{O}^{exp}\right) \cdot \left(\Sigma_{\mathrm{th}} + \Sigma_{\mathrm{exp}}\right)^{-1} \cdot \left(\vec{O}^{th} - \vec{O}^{exp}\right)$

$\left(\Sigma_{\mathrm{th}} + \Sigma_{\mathrm{exp}}\right)^{-1}$: the inverse covariance matrix

Theoretical uncertainties and correlations

- Monte Carlo analysis
- Variation of the "standard" input parameters: masses, scales, CKM, …
- Decay constants taken from latest lattice results
- $B \to K^*$ and $B_s \to \phi$ form factors obtained from the lattice+LCSR combinations (W. Altmannshofer, D. Straub, Eur.Phys.J. C75 (2015) no.8, 382 and A. Bharucha, D. Straub, R. Zwicky, JHEP 1608 (2016) 098) incl. all correlations
- Parameterisation of uncertainties from power corrections:

Leading Order QCDf of non-factorisable piece $\times \left(1 + a_k \exp(i\phi_k) + b_k \frac{q^2}{6\ \mathrm{GeV}^2} \exp(i\theta_k)\right)$

With a_k varied between 10 to 60%, $b_k \sim 2.5 a_k$

Computations performed using SuperIso public program

Fit results: single operator

Global fit of Wilson coefficients $C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$

	b.f. value	$\chi^2_{\rm min}$	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	$[+0.11,+0.36]$	$[+0.03,+0.46]$

Best fit when assuming NP in $\delta C_9^{(\mu)} \sim -1$

Several groups doing fits (with similar results)

based on latest LHCb data:

B. Capdevila, A. Crivellin, S. Descotes-Genon, J. Matias and J. Virto, JHEP 1801 (2018) 093

W. Altmannshofer, P. Stangl and D. M. Straub, Phys. Rev. D 96 (2017) no.5, 055008

G. D'Amico, M. Nardecchia, P. Panci, F. Sannino, A. Strumia, R. Torre and Urbano, JHEP 1709 (2017) 010

G. Hiller and I. Nisandzic, Phys. Rev. D 96 (2017) no.3, 035003

L. S. Geng, B. Grinstein, S. Jger, J. Martin Camalich, X. L. Ren and R. X. Shi, Phys. Rev. D 96 (2017) no.9, 093006

M. Ciuchini, A. M. Coutinho, M. Fedele, E. Franco, A. Paul, L. Silvestrini and M. Valli, Eur. Phys. J. C 77 (2017) no.10, 688

T. Hurth, F. Mahmoudi, D. Martinez Santos and SN, Phys. Rev. D 96 (2017) no.9, 095034

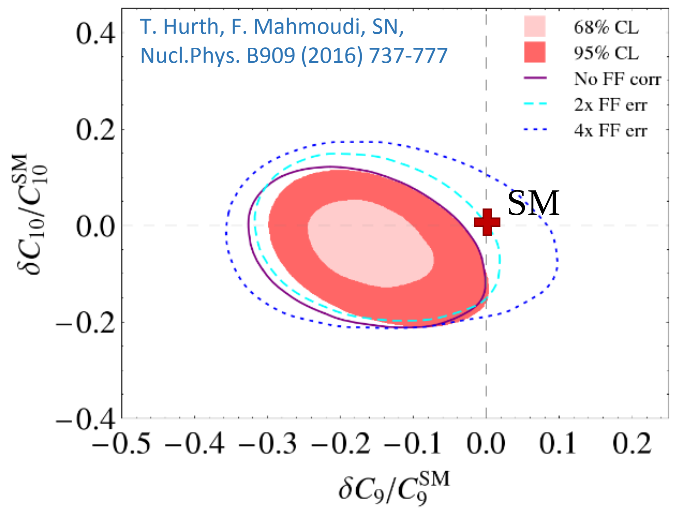
…

Fit results for two operators: hadronic uncertainty dependence

Stability of the fit with respect to hadronic uncertainties:

1. Different assumptions on the form factor uncertainties

Filled area: global fit with normal form factor error
Bharucha, Straub, Zwicky: 1503.05534
Solid contour: removing form factor error correlations
Dashed contour: 2 x form factor errors
Dotted contour: 4 x form factor errors



- Only when assuming 4 × form factor errors tensions goes below 2σ

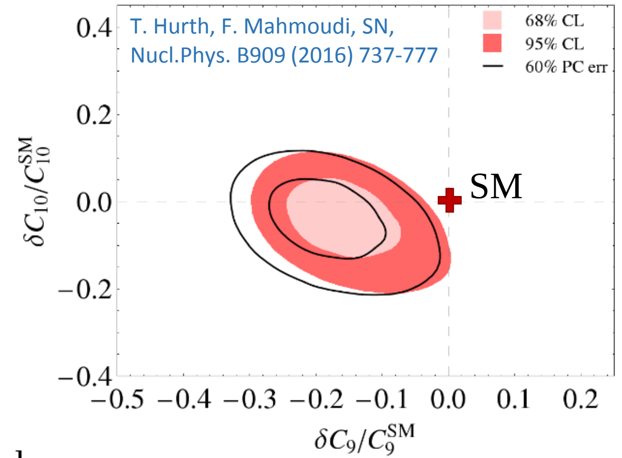
2. Different assumptions on the size of the non-factorisable power corrections

Filled area: 10% power correction
Solid contour: 60% power correction

"Guesstimate" of unknown power corrections:

Leading Order QCDf of non-factorisable piece $\times \left(1 + a_k \exp(i\phi_k) + b_k \frac{q^2}{6\ \text{GeV}^2} \exp(i\theta_k)\right)$

with $a_k(b_k)$ varied between $-X\%(\times 2.5)$ and $+X\%(\times 2.5)$



- Tension not significantly reduced with 60% power correction
- 60% power corrections at amplitude level $\Longrightarrow$ 17-20% on the observable level
- Large enough hadronic power corrections required to remove tension amount to more than 150% at the amplitude level in the critical bins (20-50% on the observable level) M. Ciuchini et al., JHEP 1606 (2016) 116
- Significance of the tension depends on the assumption on the size of the power corrections

Estimates of hadronic effects

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

	factorisable	non-factorisable	power corrections (soft gluon)	region of calculation	physical region of interest
Standard	✓	✓	×	$q^2 \lesssim 7\ \text{GeV}^2$	directly
Khodjamirian et al. [1006.4945]	✓	×	✓	$q^2 < 1\ \text{GeV}^2$	extrapolation by dispersion relation
Bobeth et al. [1707.07305]	✓	✓	✓	$q^2 < 0\ \text{GeV}^2$	extrapolation by analyticity

Uncertainties of the different implementations

- **Standard**: assuming 10% ansatz for non fact. power corrections (rel. to the leading non. fact. amplitude)
- **Khodjamirian et al.**: uncertainties of the given parameters describing the ansatz (correlations not calculated)
- **Bobeth et al.**: uncertainties of the given parameters describing the ansatz (correlations calculated but not available publically)

Estimates of hadronic effects

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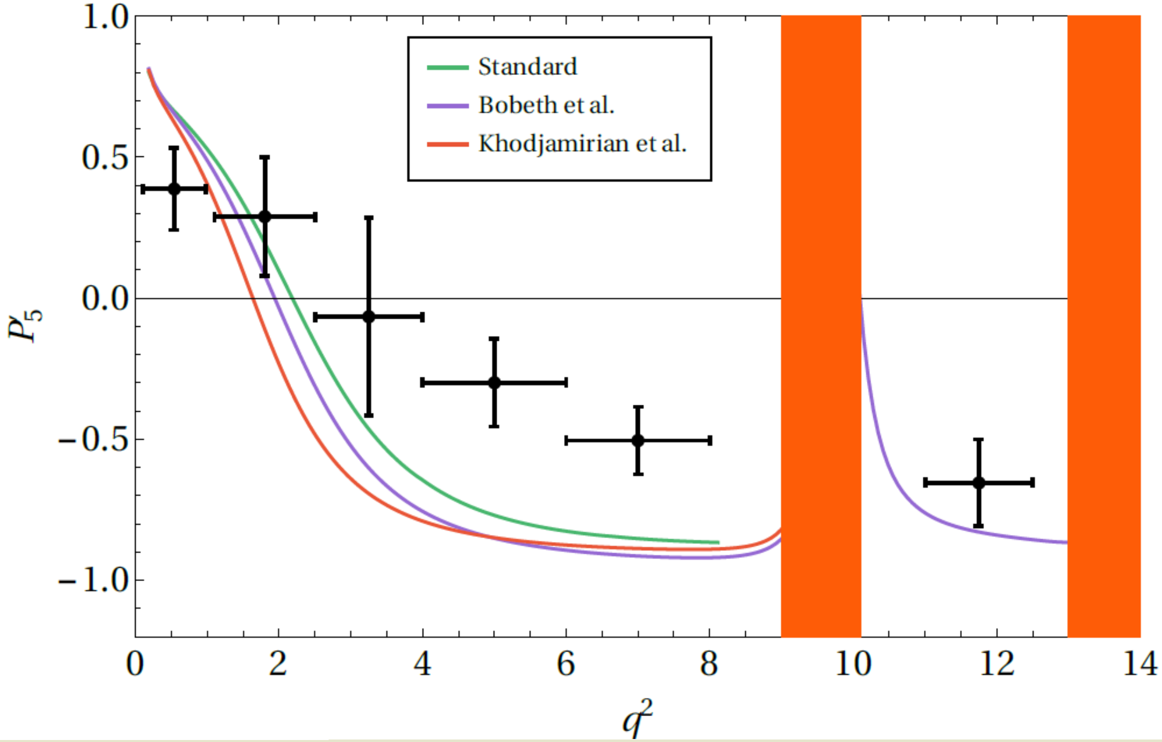

- The various prediction are similar in the critical bins

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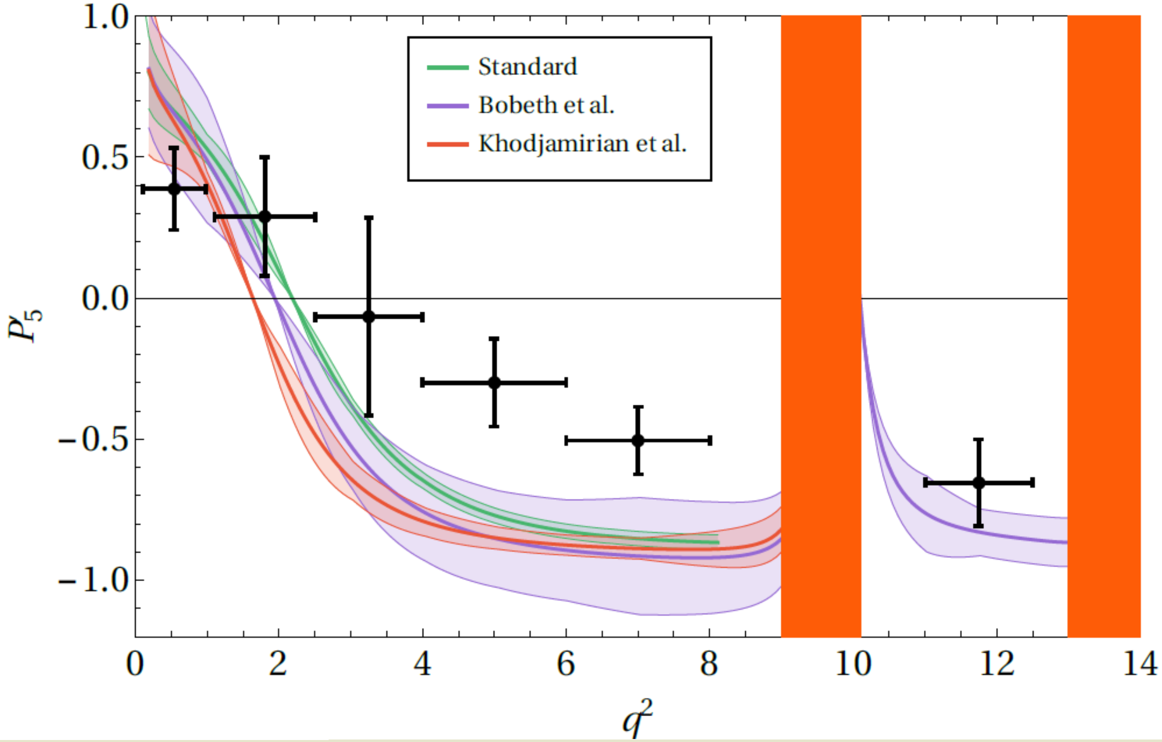

- The various prediction are similar in the critical bins
- There is agreement within 1σ
- Large errors of Bobeth et al. method mostly due to not including the correlations

Estimates of hadronic effects

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

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Fit to $B \to K^*\mu^+\mu^-$ observables only (63 observables):

		SM	C_9	C_{10}	C'_9	C'_{10}
Standard	χ^2	60.7	45.6(3.9σ)	60.7 (0.0σ)	54.2(2.6σ)	53.8(2.6σ)
Khodjamirian et al.	χ^2	79.6	52.9(5.2σ)	74.1(2.3σ)	73.0(2.6σ)	76.8(1.7σ)
Bobeth et al.	χ^2	53.7	45.4(2.9σ)	52.5(1.1σ)	53.1(0.8σ)	52.9(0.9σ)

- Significance of the NP scenario from 2.9 to 5.2σ depending how hadronic effects are estimated
- The significance of the Bobeth et al. method would be higher with correlations included

Hadronic effects vs. New Physics

Non-factorisable contributions appear in: $H_V(\lambda) = -i\,N'\Big\{(C_9^{\rm eff} - C_9')\tilde{V}_\lambda(q^2) + \frac{m_B^2}{q^2}\Big[\frac{2\,\hat{m}_b}{m_B}(C_7^{\rm eff} - C_7')\tilde{T}_\lambda(q^2) - 16\pi^2\mathcal{N}_\lambda(q^2)\Big]\Big\}$

$\mathcal{N}_\lambda(q^2) =$ Leading Order QCDf of non-factorisable piece $+\, h_\lambda(q^2)$

Instead of making assumptions on the size of the unknown hadronic contributions ($h_\lambda(q^2)$), the power corrections can be parameterised by some general ansatz M. Ciuchini et al., JHEP 1606 (2016) 116

Separate fits for NP and the power corrections using only $B \to K^*\mu^+\mu^-$ observables

The power correction ansatz (e.g. with 18 free parameters) can be such that the NP effect is embedded

$\Longrightarrow$ direct comparison of the separate fits (NP vs. hadronic) with the Wilks' test

(p-value indicates the significance of the parameters added)

up to 8 GeV^2 observables			
	δC_9	$\delta C_7, \delta C_9$	Hadronic fit
Plain SM	3.7×10^{-5} (4.1σ)	6.3×10^{-5} (4.0σ)	6.1×10^{-3} (2.7σ)
δC_9	--	0.13 (1.5σ)	0.45 (0.76σ)
δC_7 & δC_9	--	--	0.61 (0.52σ)

V. Chobanova, T. Hurth, F. Mahmoudi, D. Martinez Santos, SN, JHEP 1707 (2017) 025

- Adding the hadronic parameters (16 more parameters) does not really improve the fits
- Strong indication that the NP interpretation is a valid option, even if the situation remains inconclusive

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$\mathcal{N}_\lambda(q^2) =$ Leading Order QCDf of non-factorisable piece $+ h_\lambda(q^2)$

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δC_9	--	0.13 (1.5σ)	0.45 (0.76σ)
δC_7 & δC_9	--	--	0.61 (0.52σ)

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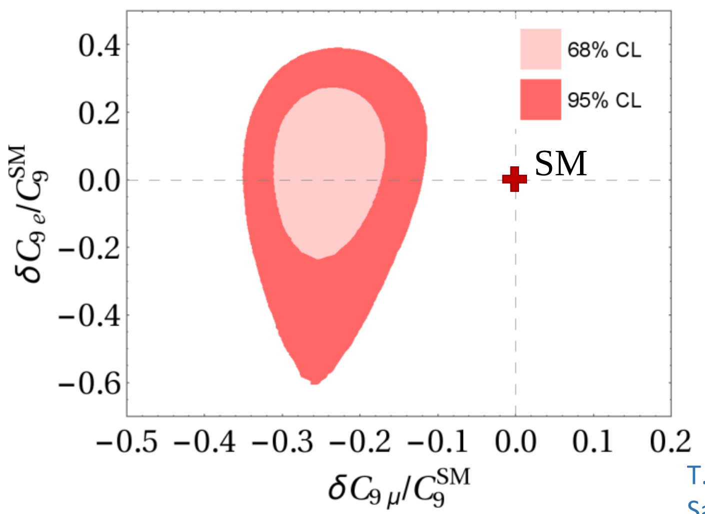
- Adding the hadronic parameters (16 more parameters) does not really improve the fits
- Strong indication that the NP interpretation is a valid option, even if the situation remains inconclusive
- Hadronic contributions cannot explain the R_K and R_{K^*} anomalies

NP fits separating the clean R_K and R_{K^*} observables from the rest

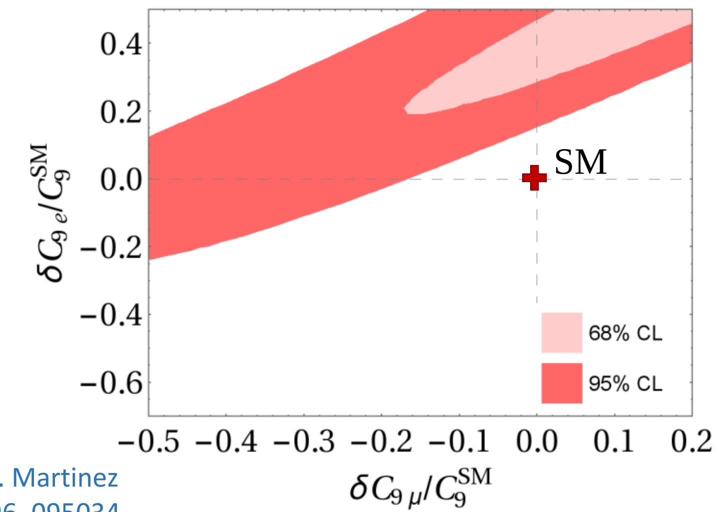
Comparison of NP fit results: clean vs. not so clean (two operator fit)

all observables except R_K and R_{K^*}

only R_K and R_{K^*} ratios



$C_9^e - C_9^\mu$



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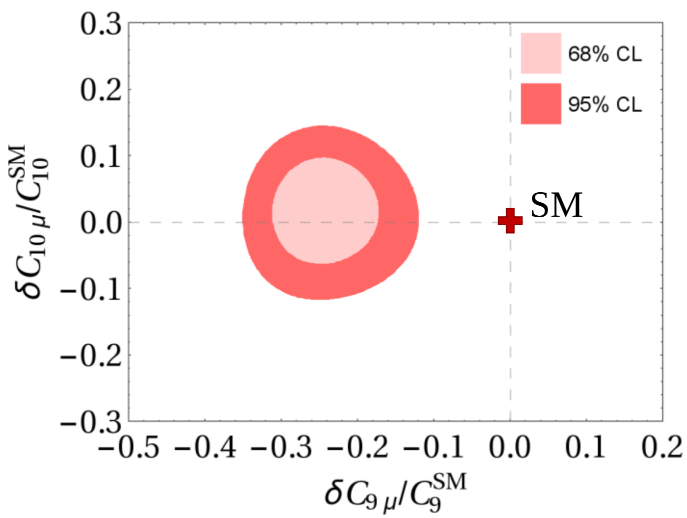
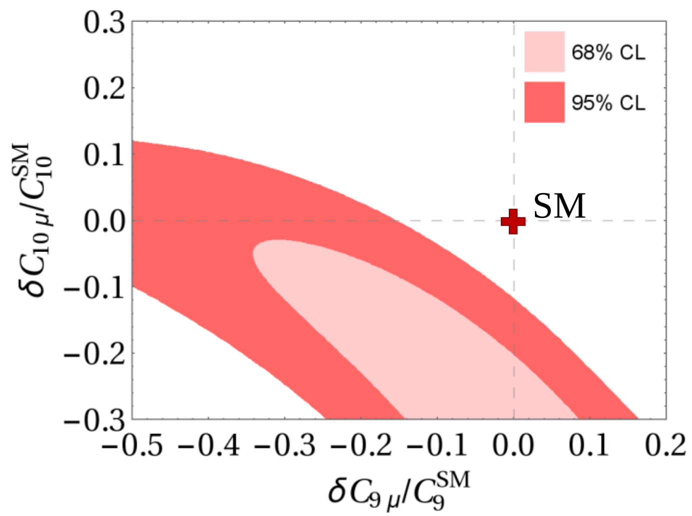


$C_{10}^\mu - C_9^\mu$



The two sets are compatible (at 2σ level)

Comparison of NP fit results: clean vs. not so clean (one operator fit)

Best fit values considering
all observables except R_K and R_{K^*}

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

$$\Delta C_i^{(\prime)} \equiv \delta C_i^{(\prime)} / C_i^{\rm SM}$$

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Best fit values considering
only R_K and R_{K^*} ratios

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

- For both sets primed operators have very small SM pull

- NP favoured in C_9 and C_9^μ
- C_{10}-like solutions DO NOT play a role

- NP favoured in C_9^e, C_9^μ, C_{10}^e or C_{10}^μ
- C_{10}-like solutions ARE favoured

- The two sets don't show a completely coherent picture
- Considering only the clean observables it is not possible to differentiate NP scenarios $C_9^{e/\mu}$ or $C_{10}^{e/\mu}$

Prospect of establishing NP:

- fits using only the clean observables R_K, R_{K^*} [and BR$(B_s \to \mu^+\mu^-)$]
- with future LHCb upgraded luminosities of 12, 50 and 300 fb^{-1} where the statistical errors get reduced by a factor of 2, 4 and 10, assuming the current central values remain

	Pull$_{\rm SM}$ with R_K and R_K^* and BR$(B_s \to \mu^+\mu^-)$ prospects		
LHCb lum.	12 fb^{-1}	50 fb^{-1}	300 fb^{-1}
C_9^μ	7.4σ [7.4σ]	12.9σ [12.9σ]	19.5σ [19.5σ]
C_{10}^μ	8.1σ [7.6σ]	13.9σ [13.5σ]	20.8σ [20.6σ]

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- New Physics can be established with a significance of more than 7σ already with 12 fb^{-1} data
- Preferred scenario cannot be differentiated [even when considering BR$(B_s \to \mu^+\mu^-)$]

Prospect of differentiating between (lepton flavour violating) NP scenarios

Crosscheck with other $R_{\mu/e}$ ratios within future LHCb results

- Hadronic uncertainties cancel out (theoretically clean) → in the SM all predicted to be ~1
- Assuming the current central values of R_K and R_{K^*} remain, with LHCb upgraded luminosity of 12 fb^{-1}

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	Predictions assuming 12 fb^{-1} luminosity			
Obs.	C_9^μ	C_9^e	C_{10}^μ	C_{10}^e
$R_{F_L}^{[1.1,6.0]}$	$[0.785, 0.913]$	$[0.909, 0.933]$	$[1.005, 1.042]$	$[1.001, 1.018]$
$R_{A_{FB}}^{[1.1,6.0]}$	$[6.048, 14.819]$	$[-0.288, -0.153]$	$[0.816, 0.928]$	$[0.974, 1.061]$
$R_{S_3}^{[1.1,6.0]}$	$[0.890, 0.932]$	$[0.768, 0.919]$	$[0.230, 0.838]$	$[0.714, 0.873]$
$R_{S_4}^{[1.1,6.0]}$	$[0.971, 1.152]$	$[0.822, 0.950]$	$[0.161, 0.822]$	$[0.695, 0.862]$
$R_{S_5}^{[1.1,6.0]}$	$[-0.787, 0.394]$	$[0.603, 0.697]$	$[0.881, 1.002]$	$[1.053, 1.146]$
$R_{F_L}^{[15,19]}$	$[0.999, 0.999]$	$[0.998, 0.998]$	$[0.997, 0.998]$	$[0.998, 0.998]$
$R_{A_{FB}}^{[15,19]}$	$[0.616, 0.927]$	$[1.002, 1.061]$	$[0.860, 0.994]$	$[1.046, 1.131]$
$R_{S_5}^{[15,19]}$	$[0.615, 0.927]$	$[1.002, 1.061]$	$[0.860, 0.994]$	$[1.046, 1.131]$
$R_{\phi}^{[1.1,6.0]}$	$[0.748, 0.852]$	$[0.620, 0.805]$	$[0.578, 0.770]$	$[0.578, 0.764]$
$R_{\phi}^{[15,19]}$	$[0.623, 0.803]$	$[0.577, 0.771]$	$[0.586, 0.776]$	$[0.583, 0.769]$

- ➢ The NP scenarios could be differentiated for example with $R_{S_5}^{[1.1,6.0]}$
- ➢ These tensions, if observed cannot be explained by hadronic uncertainties
  $\Longrightarrow$ would indirectly confirm the NP interpretation of the anomalies in the angular observables!

Prospects of establishing NP within the angular observables

Non-flavour violating NP can also be established via

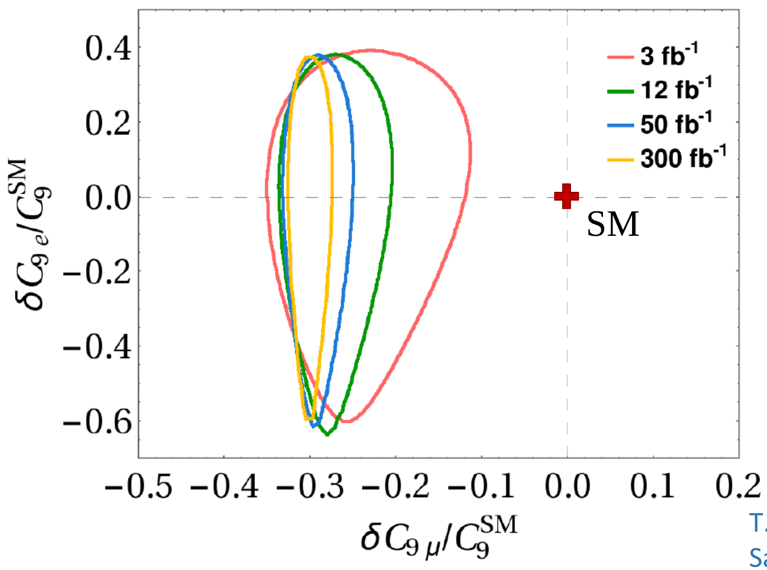
1. More precise estimation of the unknown power corrections
   - Alternative theoretical approaches based on light-cone sum rules and the analyticity approach

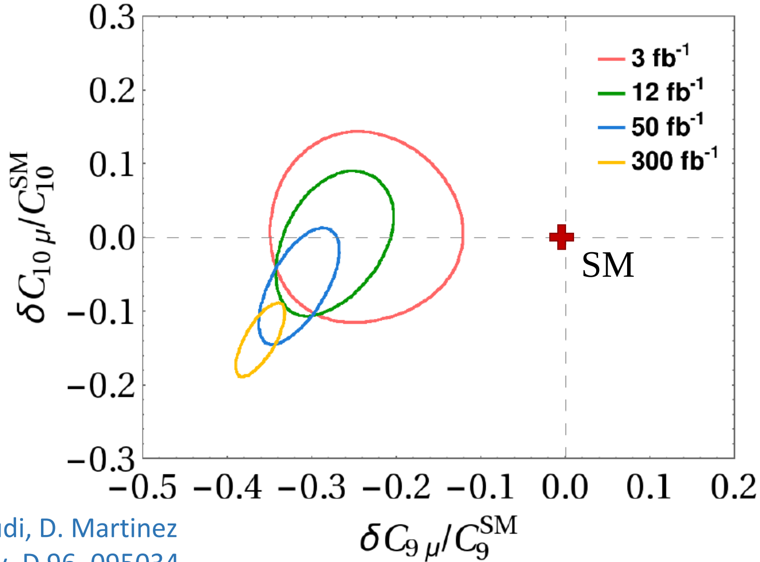
     Khodjamirian et al. JHEP 1009 (2010) 089
     Dimou, Lyon, Zwicky PRD 87, 074008 (2012), PRD 88, 094004 (2013)
     Bobeth et al. arXiv:1707.07305

   - Empirical model (determining hadronic resonant contributions modelled as relativistic Breit-Wigner functions)

     Blake, Egede, Owen, Petridis, Pomery 1709.03921

   - If the 10% assumption of power corrections confirmed
   - Assuming the current central values, the 2σ regions of future LHCb luminosities





T. Hurth, F. Mahmoudi, D. Martinez Santos, SN, Phys. Rev. D 96, 095034

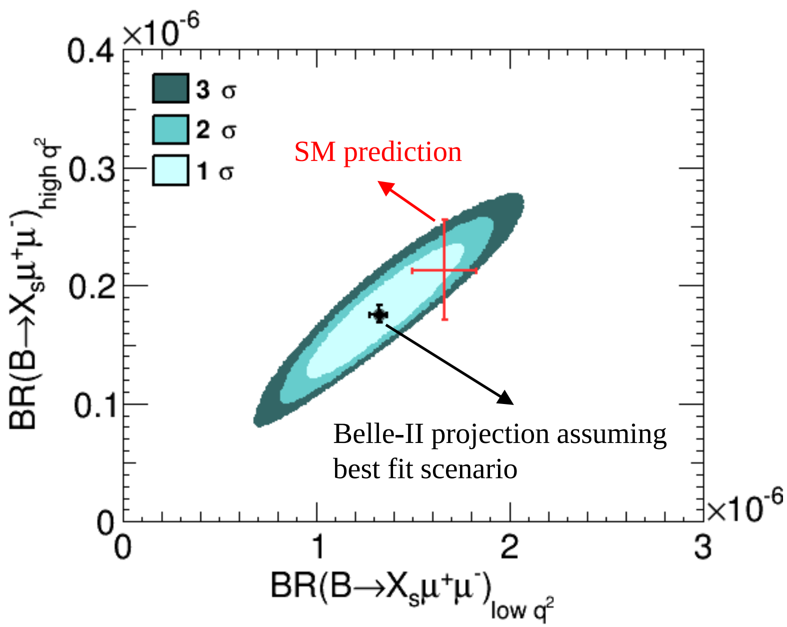
➢ Global fits using only the angular observables can confirm NP

Non-flavour violating NP can also be established via

2. Crosschecking with the inclusive mode $B \to X_s\, \mu^+\mu^-$; theoretically better known than the exclusive decays

(see e.g. T. Huber, T. Hurth, E. Lunghi, JHEP 1506 (2015) 176)

- Using the best fit point of $C_{7,9,10}$ we predict the branching ratio at low- and high-q^2 at 1,2 and 3σ ranges
- The black cross corresponds to the future Belle-II measurement assuming the best fit scenario



T. Hurth, F. Mahmoudi, JHEP 1404 (2014) 097
T. Hurth, F. Mahmoudi, SN, JHEP 1412 (2014) 053

➢ NP effect is large enough to be checked by the theoretically cleaner inclusive modes at Belle-II

NP in more than two Wilson coefficients

Fit results with more than two operators

Preliminary!

Wilson coefficients affecting $b \to s\ell^+\ell^-$ observables

$$C_7, C_8, C_9^\ell, C_{10}^\ell, C_S^\ell, C_P^\ell$$

$\to$ 10 independent Wilson coefficients (considering $\ell = e, \mu$)

$+$ 10 primed Wilson coefficients

In the general case, Wilson coefficients can be complex

$\to$ 40 independent real parameters!

Fit results with more than two operators: All observables

Preliminary!

107 observables

Set of WC	Nb parameters	χ^2_{min}	Pull_{SM}	Improv.
SM	0	105.56	-	-
$C_9^{(e,\mu)}$ real	2	79.84	4.70σ	4.70σ
C_7, C_8, $C_9^{(e,\mu)}$, $C_{10}^{(e,\mu)}$ real	6	79.03	3.75σ	0.08σ
All non-primed WC real	10	78.20	3.05σ	0.07σ
All WC real (incl. primed)	20	75.90	1.78σ	0.01σ
All WC complex (incl. primed)	40	67.20	0.61σ	0.01σ

- In the last column the significance of the improvement of the fit compared to the scenario of the previous line is given

➢ No real improvement in the fits when going beyond the $C_9^{(e,\mu)}$ case

➢ Pull with respect to the SM below 1σ when all Wilson coefficients are varied

Fit results with more than two operators: All observables

Best fit points for when all Wilson coefficients (40 parameters) are varied

Preliminary!

All observables $(\chi^2_{\rm SM} = 105.6,\ \chi^2_{\rm min} = 67.2)$		
	δC_7	δC_8
Re(δC_i)	0.02 ± 0.01	0.03 ± 0.35
Im(δC_i)	0.01 ± 0.17	-1.10 ± 0.68
	$\delta C_7'$	$\delta C_8'$
Re(δC_i)	0.02 ± 0.03	-0.13 ± 1.18
Im(δC_i)	-0.07 ± 0.02	-0.45 ± 1.50

	δC_9^μ	δC_9^e	δC_{10}^μ	δC_{10}^e
Re(δC_i)	-1.25 ± 0.17	-0.45 ± 0.54	-0.20 ± 0.20	4.39 ± 3.27
Im(δC_i)	0.40 ± 4.27	-2.54 ± 0.47	0.02 ± 2.55	-0.29 ± 3.00
	$\delta C_9'^\mu$	$\delta C_9'^e$	$\delta C_{10}'^\mu$	$\delta C_{10}'^e$
Re(δC_i)	0.10 ± 0.31	0.00 ± 1.41	-0.10 ± 0.17	0.00 ± 1.41
Im(δC_i)	0.43 ± 0.59	0.32 ± 4.63	-0.14 ± 0.24	0.00 ± 5.01
	$\delta C_{Q_1}^\mu$	$\delta C_{Q_1}^e$	$\delta C_{Q_2}^\mu$	$\delta C_{Q_2}^e$
Re(δC_i)	-0.07 ± 0.02	-3.57 ± 0.96	0.10 ± 0.14	-0.01 ± 10.58
Im(δC_i)	0.00 ± 0.19	-3.53 ± 0.48	-0.01 ± 0.11	-0.02 ± 7.77
	$\delta C_{Q_1}'^\mu$	$\delta C_{Q_1}'^e$	$\delta C_{Q_2}'^\mu$	$\delta C_{Q_2}'^e$
Re(δC_i)	0.07 ± 0.02	0.00 ± 1.41	-0.06 ± 0.14	0.00 ± 1.41
Im(δC_i)	0.00 ± 0.19	-3.61 ± 0.94	0.02 ± 0.11	-0.07 ± 9.58

- Many parameters are not constrained, in particular the imaginary parts
- Significant contribution also from the electron scalar coefficient

Fit results with more than two operators: All observables except R_K and R_{K^*}

Preliminary!

104 observables

Set of WC	Nb parameters	χ^2_{min}	Pull$_{SM}$	Improv.
SM	0	89.84	-	-
$C_9^{(e,\mu)}$ real	2	71.05	3.93σ	3.93σ
$C_7, C_8, C_9^{(e,\mu)}, C_{10}^{(e,\mu)}$ real	6	70.04	2.97σ	0.13σ
All non-primed WC real	10	69.25	2.25σ	0.07σ
All WC real (incl. primed)	20	67.15	1.03σ	0.01σ
All WC complex (incl. primed)	40	58.24	0.22σ	0.02σ

- In the last column the significance of the improvement of the fit compared to the scenario of the previous line is given

➢ Similar results to the case with R_K and R_{K^*}

Fit results with more than two operators: All observables except R_K and R_{K^*}

Best fit points for when all Wilson coefficients (40 parameters) are varied

Preliminary!

All observables except $R_{K^{(*)}}$ $(\chi^2_{\rm SM} = 89.8,\ \chi^2_{\rm min} = 58.2)$

	δC_7	δC_8
$\mathrm{Re}(\delta C_i)$	0.02 ± 0.01	0.03 ± 0.35
$\mathrm{Im}(\delta C_i)$	0.02 ± 0.16	-0.96 ± 0.76
	$\delta C_7'$	$\delta C_8'$
$\mathrm{Re}(\delta C_i)$	0.02 ± 0.03	-0.28 ± 0.93
$\mathrm{Im}(\delta C_i)$	-0.07 ± 0.02	-0.55 ± 1.41

	δC_9^μ	δC_9^e	δC_{10}^μ	δC_{10}^e
$\mathrm{Re}(\delta C_i)$	-1.26 ± 0.17	0.45 ± 0.51	-0.18 ± 0.23	4.48 ± 3.78
$\mathrm{Im}(\delta C_i)$	0.29 ± 4.38	-1.51 ± 0.58	0.00 ± 0.98	-0.16 ± 3.35
	$\delta C_9'^\mu$	$\delta C_9'^e$	$\delta C_{10}'^\mu$	$\delta C_{10}'^e$
$\mathrm{Re}(\delta C_i)$	0.09 ± 0.36	0.00 ± 1.41	-0.10 ± 0.19	0.00 ± 1.41
$\mathrm{Im}(\delta C_i)$	0.42 ± 0.59	0.93 ± 3.98	-0.14 ± 0.23	0.03 ± 9.20

	$\delta C_{Q_1}^\mu$	$\delta C_{Q_1}^e$	$\delta C_{Q_2}^\mu$	$\delta C_{Q_2}^e$
$\mathrm{Re}(\delta C_i)$	-0.06 ± 0.02	-2.90 ± 4.51	0.06 ± 0.04	-2.82 ± 4.00
$\mathrm{Im}(\delta C_i)$	0.00 ± 0.19	-2.89 ± 2.33	0.05 ± 0.04	-2.88 ± 2.09
	$\delta C_{Q_1}'^\mu$	$\delta C_{Q_1}'^e$	$\delta C_{Q_2}'^\mu$	$\delta C_{Q_2}'^e$
$\mathrm{Re}(\delta C_i)$	0.06 ± 0.02	0.00 ± 1.41	-0.04 ± 0.04	0.00 ± 1.41
$\mathrm{Im}(\delta C_i)$	0.00 ± 0.19	-2.85 ± 4.16	-0.01 ± 0.04	-2.81 ± 4.09

- Similar results to the case with R_K and R_{K^*}
- The value of δC_9^e is shifted

Conclusions

- Global analysis of $b \to s$ data favours a 25% reduction in C_9 with respect to the SM
- Significance of the anomalies depends on the assumptions for the hadronic uncertainties
- At the moment, from a statistical point of view, the New Physics explanation describes the anomalies better than underestimated hadronic contributions
- The recent measurement of R_{K^*} supports the NP hypothesis, but the experimental errors are still large and the update of $R_{K^{(*)}}$ and other ratios is eagerly awaited!
- If the tensions remain, even in the pessimistic case that there will be no theoretical progress in non-factorisable power corrections, Belle II and/or LHCb upgrade can resolve it
- When adding more parameters in the fit, no significant improvement is obtained
- With the full set of free parameters, the tensions with the SM fall below 1σ

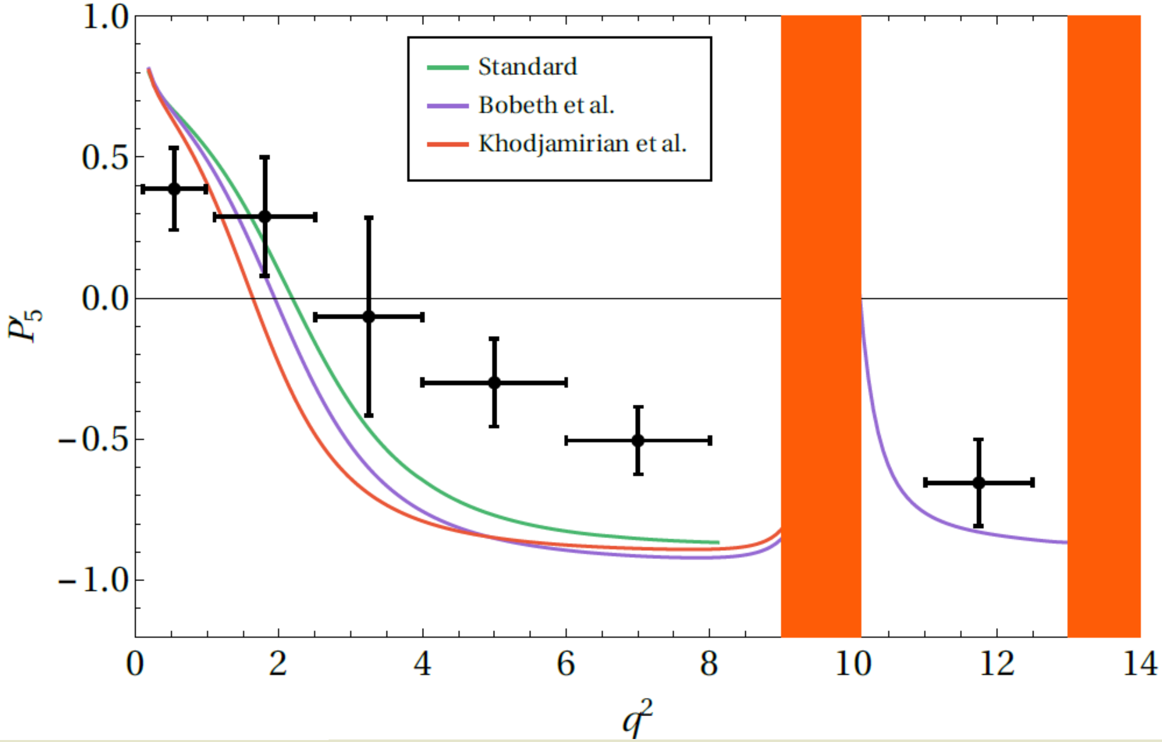
Thank you for listening!

Backup

Estimates of hadronic effects

$$\frac{e^2}{q^2}\epsilon_\mu L_V^\mu \Big[\;\; Y(q^2)\tilde{V}_\lambda \;\; + \text{LO in } \mathcal{O}(\frac{\Lambda}{m_b}, \frac{\Lambda}{E_{K^*}}) + \;\; h_\lambda(q^2) \;\; \Big]$$

	factorisable	non-factorisable	power corrections (soft gluon)	region of calculation	physical region of interest
Standard	✓	✓	×	$q^2 \lesssim 7$ GeV^2	directly
Khodjamirian et al. [1006.4945]	✓	×	✓	$q^2 < 1$ GeV^2	extrapolation by dispersion relation
Bobeth et al. [1707.07305]	✓	✓	✓	$q^2 < 0$ GeV^2	extrapolation by analyticity



➢ The various prediction are similar in the critical bins

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

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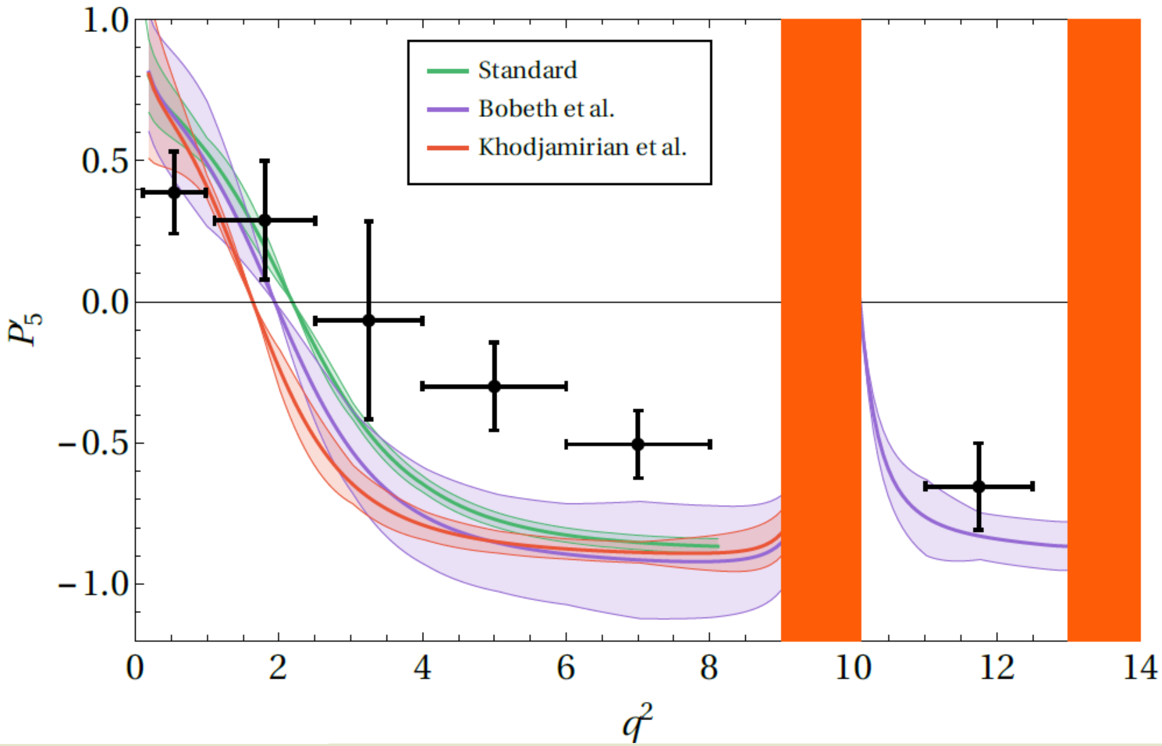

- The various prediction are similar in the critical bins
- There is agreement within 1σ
- Large errors of Bobeth et al. method mostly due to not including the correlations

Estimates of hadronic effects

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

	factorisable	non-factorisable	power corrections (soft gluon)	region of calculation	physical region of interest
Standard	✓	✓	×	$q^2 \lesssim 7$ GeV^2	directly
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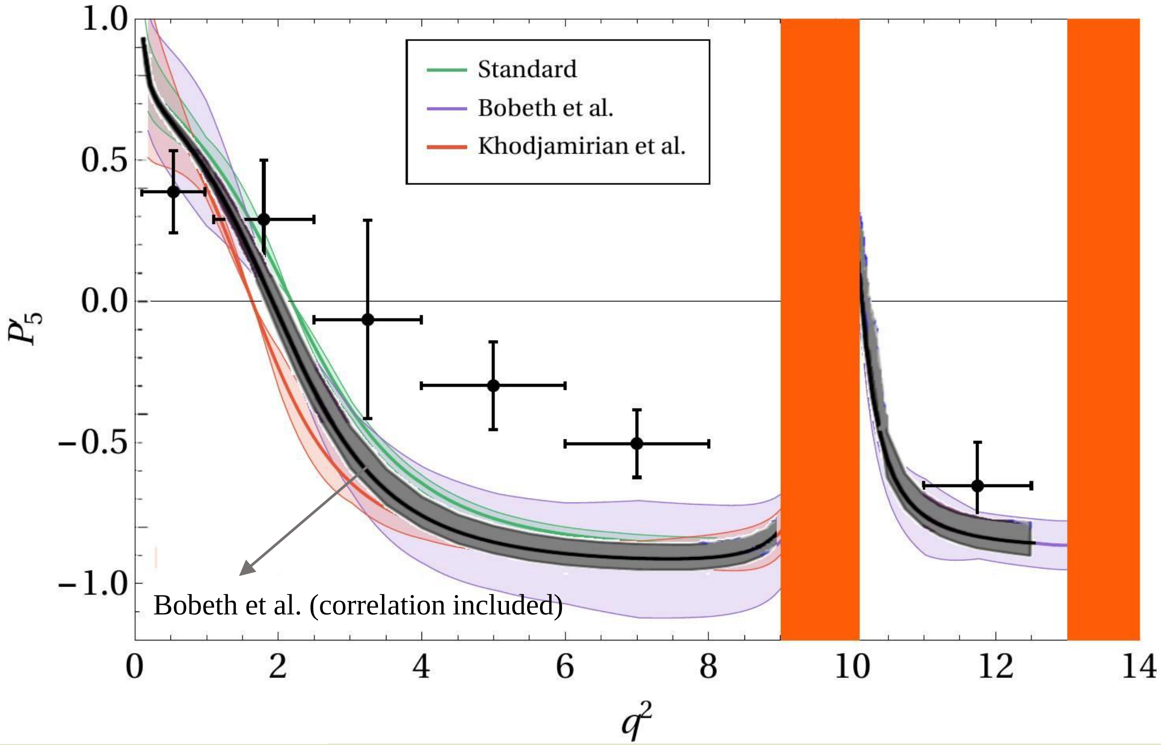

- The various prediction are similar in the critical bins
- There is agreement within 1σ
- Large errors of Bobeth et al. method mostly due to not including the correlations

Estimates of hadronic effects

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

	factorisable	non-factorisable	power corrections (soft gluon)	region of calculation	physical region of interest
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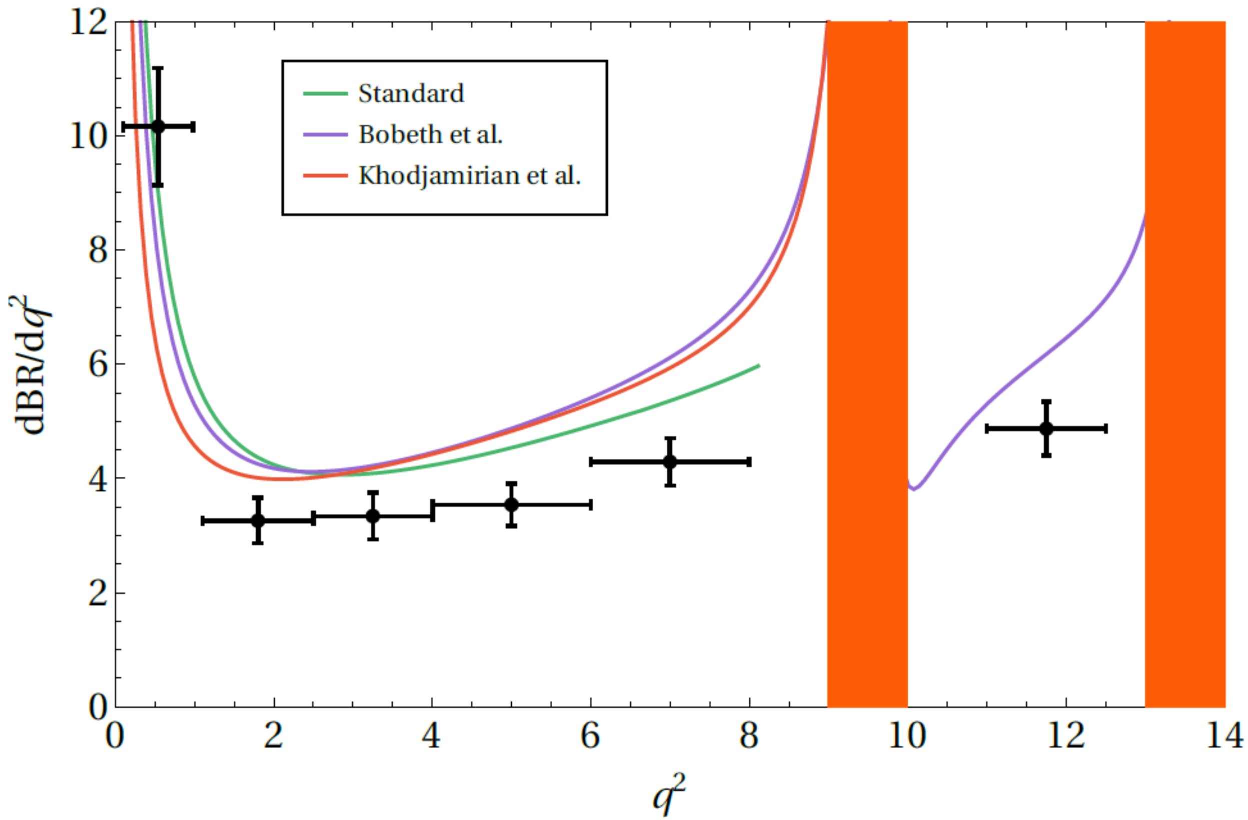

Estimates of hadronic effects

$$\frac{e^2}{q^2}\epsilon_\mu L_V^\mu \Big[\quad Y(q^2)\tilde{V}_\lambda \quad + \text{LO in } \mathcal{O}(\frac{\Lambda}{m_b}, \frac{\Lambda}{E_{K^*}}) + \quad h_\lambda(q^2) \quad \Big]$$

	factorisable	non-factorisable	power corrections (soft gluon)	region of calculation	physical region of interest
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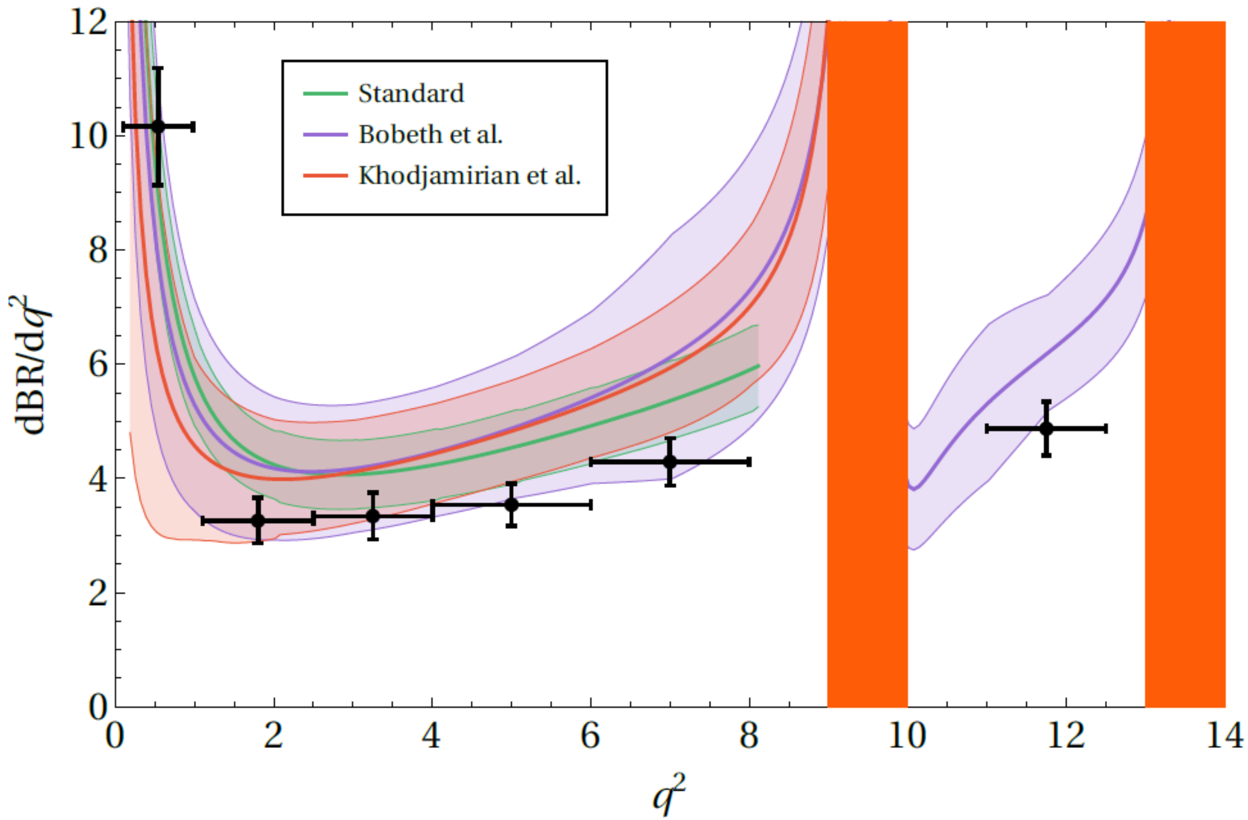


Fit results with more than two operators: Only R_K and R_{K^*} ($+B_{s,d} \to \ell\ell$ + B $\to X_s\ell\ell$)

Preliminary!

8 observables

Set of WC	Nb parameters	χ^2_{min}	Pull$_{SM}$	Improv.
SM	0	16.74	-	-
$C_9^{(e,\mu)}$ real	2	9.78	2.16σ	2.16σ
$C_7, C_8, C_9^{(e,\mu)}, C_{10}^{(e,\mu)}$ real	6	8.89	1.16σ	0.09σ
All non-primed WC real	10	8.87	0.47σ	0.00σ
All WC real (incl. primed)	20	7.75	0.02σ	0.00σ
All WC complex (incl. primed)	40	7.35	0.00σ	0.00σ

Fit results with more than two operators: Only R_K and R_{K^*} $(+B_{s,d} \to \ell\ell + \mathrm{B} \to X_s\ell\ell)$

Only R_K and R_{K^*} $(\chi^2_{\rm SM} = 16.74,\ \chi^2_{\rm min} = 7.35)$	$\mathrm{Re}(\delta C_i)$	$\mathrm{Im}(\delta C_i)$
δC_7	0.18 ± 0.03	0.02 ± 0.25
δC_8	0.80 ± 0.49	0.03 ± 11.93
$\delta C'_7$	-0.17 ± 0.03	-0.01 ± 0.17
$\delta C'_8$	-2.04 ± 0.18	-0.41 ± 2.78
δC_9^μ	6.59 ± 1.70	0.00 ± 1.41
δC_9^e	3.38 ± 5.48	3.38 ± 5.48
δC_{10}^μ	-3.02 ± 0.44	0.00 ± 1.41
δC_{10}^e	-3.29 ± 5.65	-3.29 ± 5.65
$\delta C_9^{\prime\mu}$	11.18 ± 1.70	0.35 ± 3.11
$\delta C_9^{\prime e}$	0.00 ± 1.41	-10.26 ± 5.83
$\delta C_{10}^{\prime\mu}$	-7.11 ± 0.44	0.00 ± 3.43
$\delta C_{10}^{\prime e}$	0.00 ± 1.41	-24.01 ± 2.49
$\delta C_{Q_1}^\mu$	0.00 ± 1.41	0.00 ± 1.58
$\delta C_{Q_1}^e$	-0.56 ± 8.03	-0.60 ± 6.18
$\delta C_{Q_2}^\mu$	-0.07 ± 0.02	0.00 ± 1.41
$\delta C_{Q_2}^e$	-0.31 ± 8.43	-0.29 ± 6.45
$\delta C_{Q_1}^{\prime\mu}$	0.00 ± 1.41	0.00 ± 1.58
$\delta C_{Q_1}^{\prime e}$	0.00 ± 1.41	-0.66 ± 6.09
$\delta C_{Q_2}^{\prime\mu}$	0.07 ± 0.02	0.00 ± 1.41
$\delta C_{Q_2}^{\prime e}$	0.00 ± 1.41	-0.25 ± 8.40

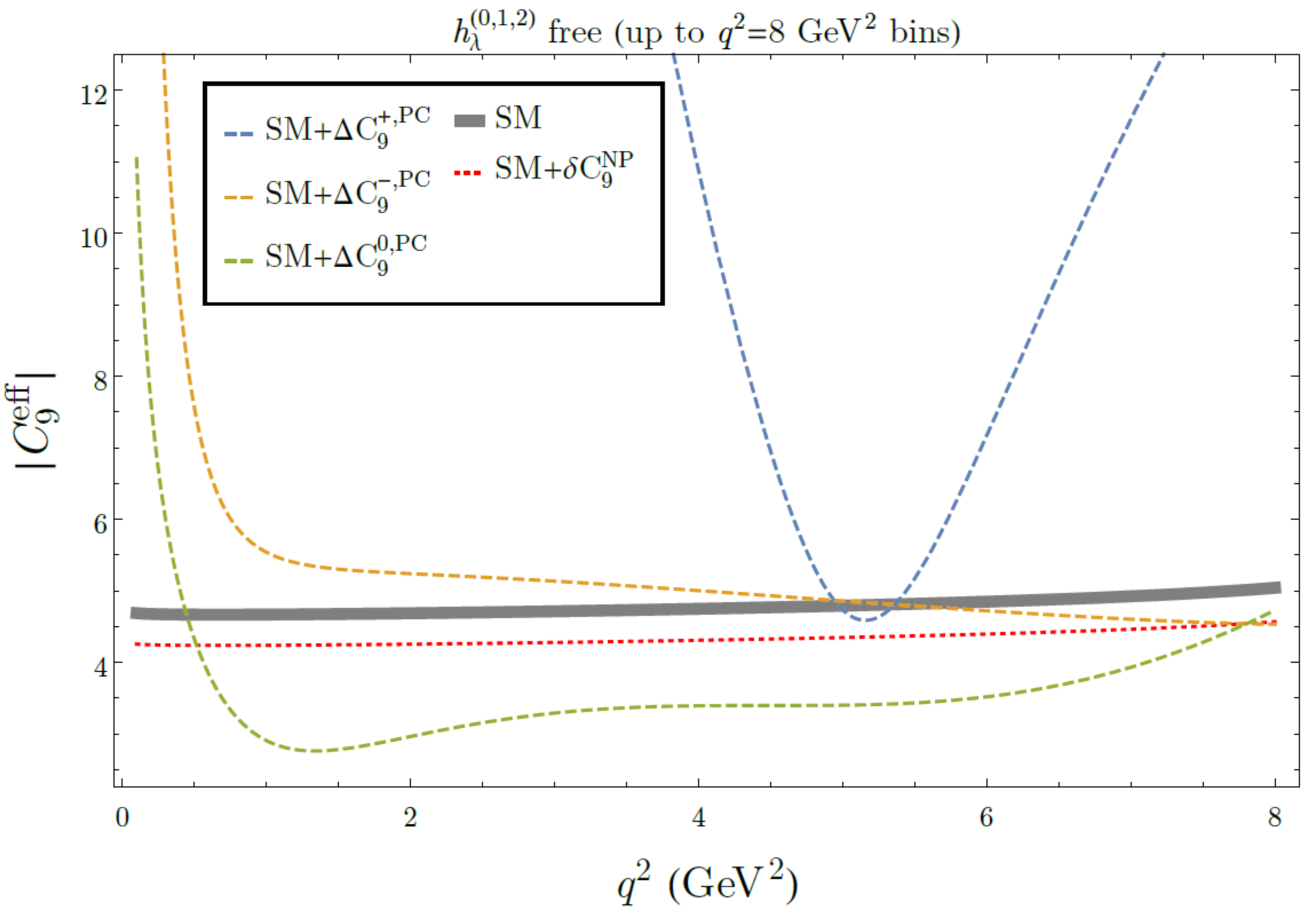
- R_K and R_{K^*} points to a best fit point different from the previous fits
- The value of δC_{10}^μ and $\delta C_{10}^{\prime\mu}$ are more constrained than δC_9

Hadronic corrections as shift to C_9

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

The effect of the power corrections could also be described through a q^2-dependent shift in C_9 via

$$\Delta C_9^{\lambda,\rm PC} = -16\pi^2 \frac{m_B^2}{q^2}\frac{h_\lambda(q^2)}{\tilde{V}_\lambda(q^2)}$$



Hadronic corrections as shift to C_9 assuming $h_+^{(0)}$ to be constrained

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

The effect of the power corrections could also be described through a q^2-dependent shift in C_9 via

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$(|h_+^{(0)}/h_-^{(0)}| < 0.2)$