Institute for Research in Fundamental Sciences

New Physics or hadronic corrections in the $B \to K^* \mu^+ \mu^-$ decay?

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based on arXiv:1603.00865 & 1702.02234

Rencontres de Moriond, QCD and High Energy Interactions

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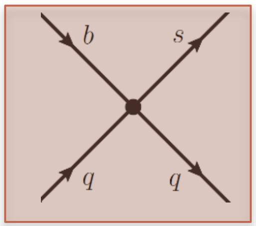
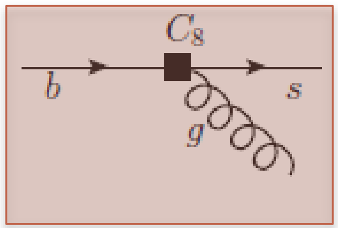
Effective Hamiltonian for $b \to s\ell^+\ell^-$ transitions: $\mathcal{H}_{\text{eff}} = \mathcal{H}_{\text{eff}}^{\text{had}} + \mathcal{H}_{\text{eff}}^{\text{sl}}$

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

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

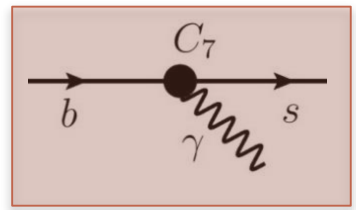


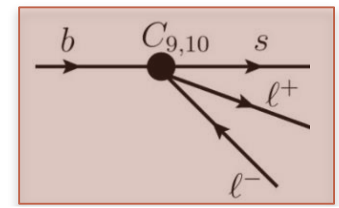


$$O_{1,2} \propto (\bar{s}\,\Gamma_m\,c)\,(\bar{c}\,\Gamma_n\,b)$$

$$O_8 \propto (\bar{s}\,\sigma^{\mu\nu} T^a P_R\, b)\, G_{\mu\nu}^a$$

$$O_{3-6} \propto (\bar{s}\,\Gamma_m\,b)\,\Sigma_q\,(\bar{q}\,\Gamma_n\,q)$$





$$O_7 = \frac{e}{(4\pi)^2} m_b (\bar{s}\sigma^{\mu\nu} P_R b) F_{\mu\nu}$$

$$O_9 = \frac{e^2}{(4\pi)^2} (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \ell)$$

$$O_{10} = \frac{e^2}{(4\pi)^2} (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \gamma_5 \ell)$$

+ chirality flipped operators (O_i')

Most relevant for (semi-) leptonic decays

Short-distance effects: Wilson coefficients $C_i(\mu)$ ($\mu = m_b$)

- Calculated *perturbatively* up to NNLL
- Contain all the contributions from scales higher than μ

Long-distance effects: matrix elements of operators $\langle O_i \rangle$:

- Require *non-perturbative* methods
- Introduce the main theoretical uncertainties

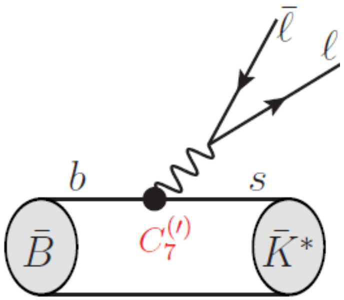
Theoretical framework for $B \to K^* \ell^+ \ell^-$

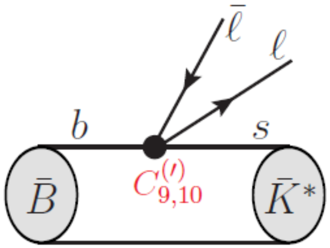
Effective Hamiltonian for $b \to s\ell^+\ell^-$ transitions: $\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm had} + \mathcal{H}_{\rm eff}^{\rm sl}$

Matrix elements of $B \to K^* \ell^+ \ell^-$ decay:

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

$\langle \bar{K}^* \ell^+ \ell^- | H_{\rm eff}^{\rm sl} | \bar{B} \rangle$:





⇨ $B \to K^*$ form factors $V, A_{0,1,2}, T_{1,2,3}$ or alternatively $\tilde{V}_\lambda, \tilde{T}_\lambda, \tilde{S}$ (λ = helicity of K^*)

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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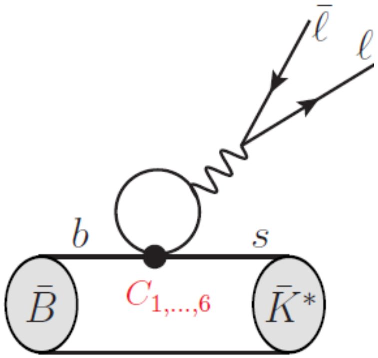
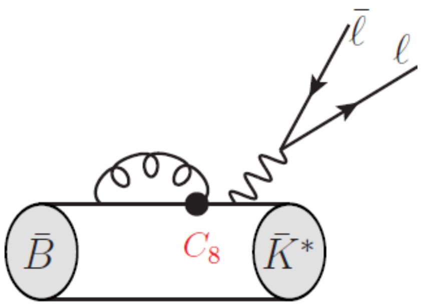
$\langle \bar{K}^* \ell^+ \ell^- | H_{\rm eff}^{\rm had} | \bar{B} \rangle$:





$H_{\rm eff}^{\rm had}$ contributes to $b \to s\bar{\ell}\ell$ through virtual photon exchange $\Rightarrow$ affect only the $H_V(\lambda)$

Helicity amplitudes:

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$\langle \bar{K}^* \ell^+ \ell^- | H_{\rm eff}^{\rm had} | \bar{B} \rangle$: $\mathcal{A}_\lambda^{(\rm had)} = -i\frac{e^2}{q^2} \int d^4x e^{-iq\cdot x} \langle \ell^+ \ell^- | j_\mu^{\rm em,lept}(x) | 0 \rangle \times \int d^4y\, e^{iq\cdot y} \langle \bar{K}_\lambda^* | T\{ j^{\rm em,had,\mu}(y) \mathcal{H}_{\rm eff}^{\rm had}(0) \} | \bar{B} \rangle$

In general "naïve" factorization not applicable

Helicity amplitudes:

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

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

Beneke et al: 106067; 0412400

Partial calculation from Khodjamirian et al. 1006.4945

Helicity amplitudes:

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

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

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

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

Helicity amplitudes:

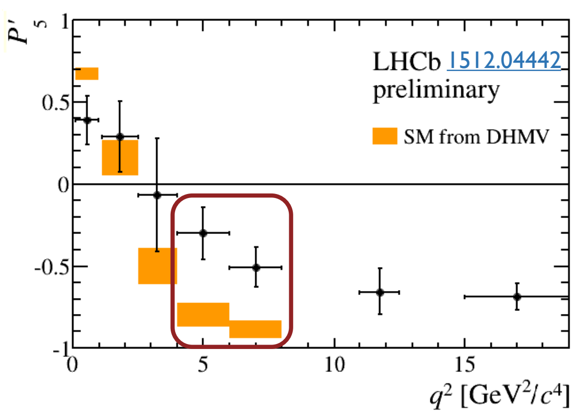
$$H_V(\lambda) = -i\, N' \Big\{ (C_9^{\text{eff}} - C_9') \tilde{V}_\lambda(q^2) + \frac{m_B^2}{q^2} \Big[\frac{2\,\hat{m}_b}{m_B} (C_7^{\text{eff}} - C_7') \tilde{T}_\lambda(q^2) - 16\pi^2 \mathcal{N}_\lambda(q^2) \Big] \Big\}$$

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

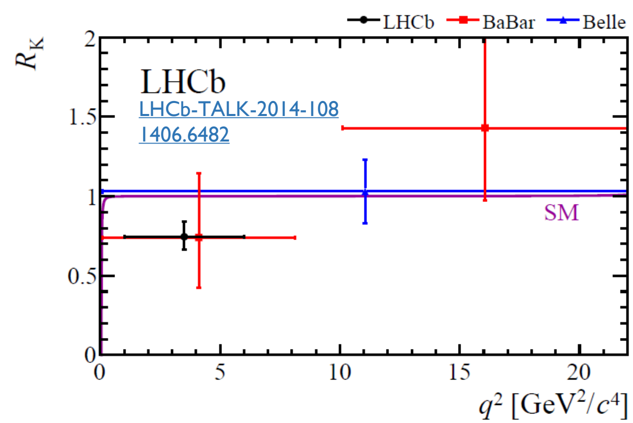
$$H_P = i\, N' \Big\{ \frac{2\, m_\ell \hat{m}_b}{q^2} (C_{10} - C_{10}') \Big(1 + \frac{m_s}{m_b} \Big) \tilde{S}(q^2) \Big\}$$

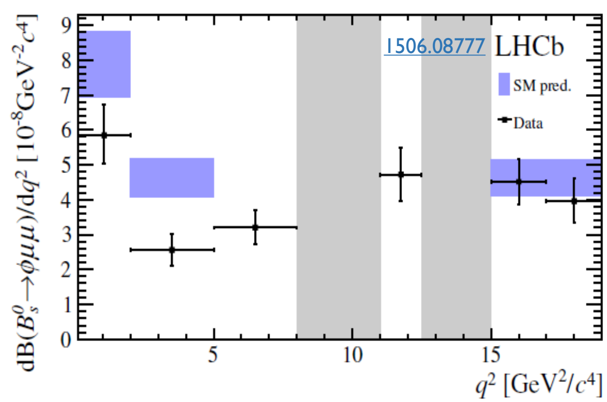
Three main LHCb anomalies observed in $b \to s\ell^+\ell^-$ decays:

- $B \to K^*\mu^+\mu^-$ angular observable P_5' (or S_5): 3.4σ tension with 3 fb^{-1} (2015) $\longleftarrow$ supported by Belle
- $R_K = \text{BR}(B^+ \to K^+\mu^+\mu^-)/\text{BR}(B^+ \to K^+e^+e^-)$: 2.6$\sigma$ tension in [1-6] GeV^2 bin
- $\text{BR}(B_s \to \phi\mu^+\mu^-)$: 3.2$\sigma$ tension in [1-6] GeV^2 bin



$q^2 = (p_{\ell^+} + p_{\ell^-})^2$





New Physics or underestimated hadronic uncertainties?

Model independent global fits

Many $b \to s\ell^+\ell^-$ observables

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

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

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

$\Rightarrow$ Global fits

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

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

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

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

"Guesstimate" of unknown power corrections:

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

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

Calculations done using SuperIso

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	$[-0.25, -0.09]$	$[-0.30, -0.03]$
$\delta C_9^\prime/C_9^{\rm SM}$	$+0.03$	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 $\delta C_9^{(\mu)} \sim -1$

Fits assuming two or more Wilson coefficients all have a best fit when $\delta C_9^{(\mu)} \sim -1$

Several groups doing global fits (with similar results):

based on latest LHCb data:

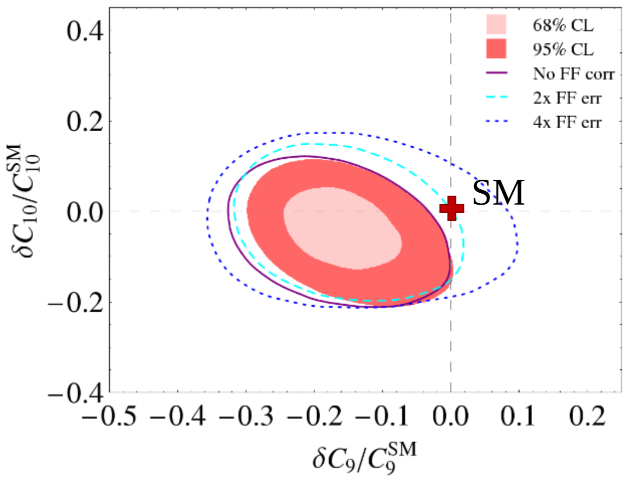
Descotes-Genon, Hofer, Matias, Virto: 1510.04239;
Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli: 1512.07157;
Hurth, Mahmoudi, SN: 1603.00865;
Capdevila, Descotes-Genon, Hofer, Matias: 1701.08672;
Chobanova, Hurth, Mahmoudi, Martinez-Santos, SN: 1702.02234

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 x form factor errors tensions goes below 2σ

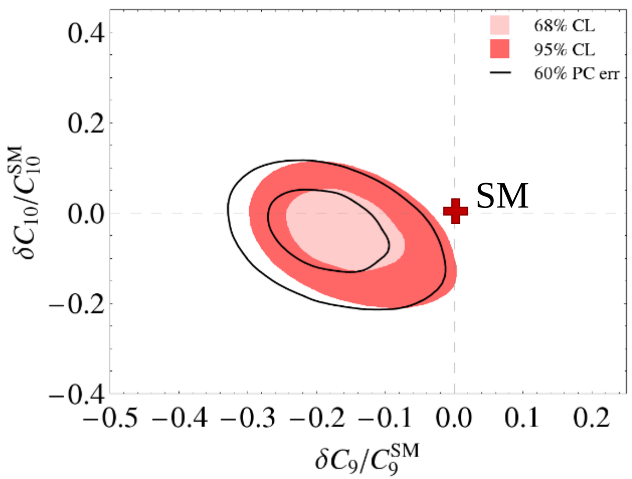
2. Different assumptions on the size of the non-factorisable power corrections

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)

Ciuchini et al.: 1512.07157

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 $+\ h_\lambda(q^2)$

A possible parametrisation of the non-factorisable power corrections

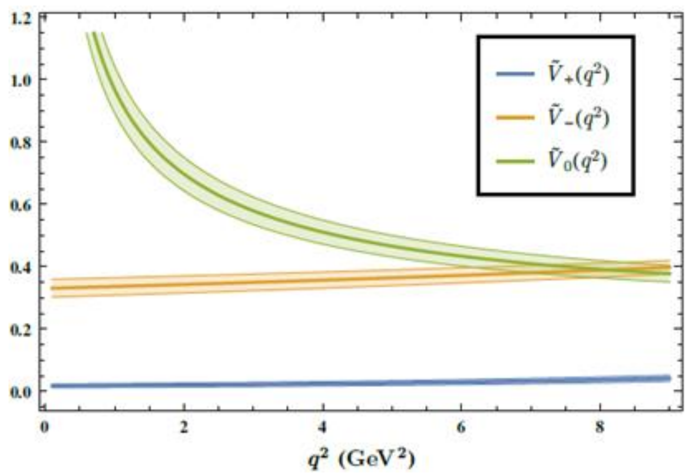
$$h_\lambda(q^2) = h_\lambda^{(0)} + \frac{q^2}{1\mathrm{GeV}^2}h_\lambda^{(1)} + \frac{q^4}{1\mathrm{GeV}^4}h_\lambda^{(2)} \qquad (\lambda = +,-,0)$$

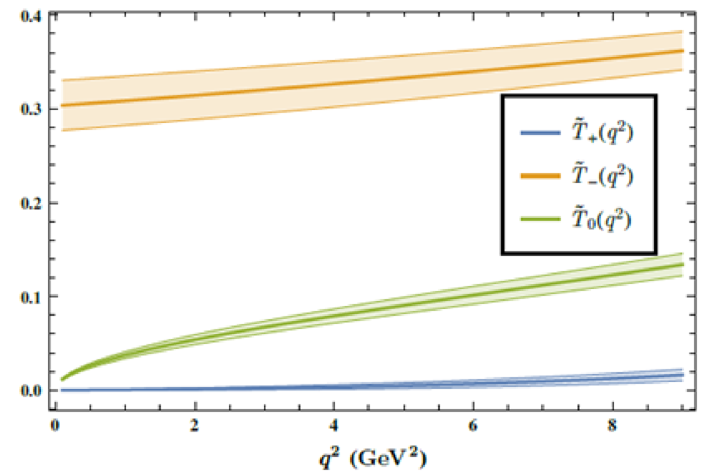
M. Ciuchini et al., 1512.07157
S. Jäger and J. Camalich: 1412.3183

It seems: $h_\lambda^{(0)} \longrightarrow C_7^{\rm NP}$, $h_\lambda^{(1)} \longrightarrow C_9^{\rm NP}$ and $h_\lambda^{(2)}$ term cannot be mimicked by $C_{7,9}$ M. Ciuchini et al., 1512.07157

However, $\lambda = +,-,0$

and $\tilde{V}_\lambda$ and $\tilde{T}_\lambda$ both have a q^2 dependence





Hadronic effects vs. New Physics

Non-factorisable contributions appear in:

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A possible parametrisation of the non-factorisable power corrections

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However, $\lambda = +,-,0$

and $\tilde{V}_\lambda$ and $\tilde{T}_\lambda$ both have a q^2 dependence

- Mild q^4-terms can rise due to form factor terms
- C_7^{NP} and C_9^{NP} can cause effects similar to $h_\lambda^{(0,1,2)}$

Hadronic power correction effect:

$$\delta H_V^{\text{p.c.}}(\lambda) = iN' m_B^2 \frac{16\pi^2}{q^2} h_\lambda(q^2) = iN' m_B^2 \frac{16\pi^2}{q^2} \left(h_\lambda^{(0)} + q^2 h_\lambda^{(1)} + q^4 h_\lambda^{(2)} \right)$$

New Physics effect:

$$\delta H_V^{C_9^{\text{NP}}}(\lambda) = -iN' \tilde{V}_\lambda(q^2) C_9^{\text{NP}} = iN' m_B^2 \frac{16\pi^2}{q^2} \left(a_\lambda^{\tilde{V}} C_9^{\text{NP}} + q^2 b_\lambda^{\tilde{V}} C_9^{\text{NP}} + q^4 c_\lambda^{\tilde{V}} C_9^{\text{NP}} \right)$$

and similarly for C_7

⇨ NP effects can be embedded in the more general form of hadronic effects

We can do a fit for both hadronic quantities $h_{+,-,0}^{(0,1,2)}$ (18 parameters)
and Wilson coefficients C_9^{NP} or $C_{7\&9}^{\text{NP}}$ (2 or 4 parameters)

Due to the embedding of the two fits there can be a direct comparison of the fits with the Wilks' test

Wilks' test

Fit to NP and power corrections using only $B \to K^* \mu^+ \mu^-$ observables at low-q^2 to keep the embedding

Comparison of the hadronic fit with the NP fit through likelihood ratio tests

p-values can be obtained (via Wilks' theorem)

$\Longrightarrow$ p-value indicates the significance of the new 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)

- 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

Outlook

Outlook for identifying the origin of the anomalies:

- Assuming a possible future LHCb upgrade, with an integrated luminosity of 300 fb^{-1}
  - Scaling down the present LHCb uncertainties by a factor 10
  - If data shows q^2 dependence which cannot be produced by any NP contribution, NP can be ruled out
  - Due to the embedding, the hadronic option cannot be ruled out in favour of the NP option although it would be peculiar if hadronic effects ($h_{+,-,0}(q^2)$) all conspired to mimic NP

- Crosscheck with other (clean) observable of ratios of decays to muons over electrons $R(\mu/e)$
  - Deviations would indirectly confirm that the tension in P_5' is due to NP and would rule out the hadronic effects option

- Crosscheck with inclusive mode $B \to X_s\, \mu^+\mu^-$ where power corrections can be estimated
  - If tension in P_5' due to NP effect in C_9, it is large enough to be checked at Belle-II

Hurth, Mahmoudi, S.N. 1410.4545

- Theory calculation of the non-factorisable power corrections
  - Complete calculation exists for $B \to K\ell^+\ell^-$ Khodjamirian et al. 1211.0234
  - Only partial calculations exist for $B \to K^*\ell^+\ell^-$ Khodjamirian et al. 1006.4945

Thank you for listening!

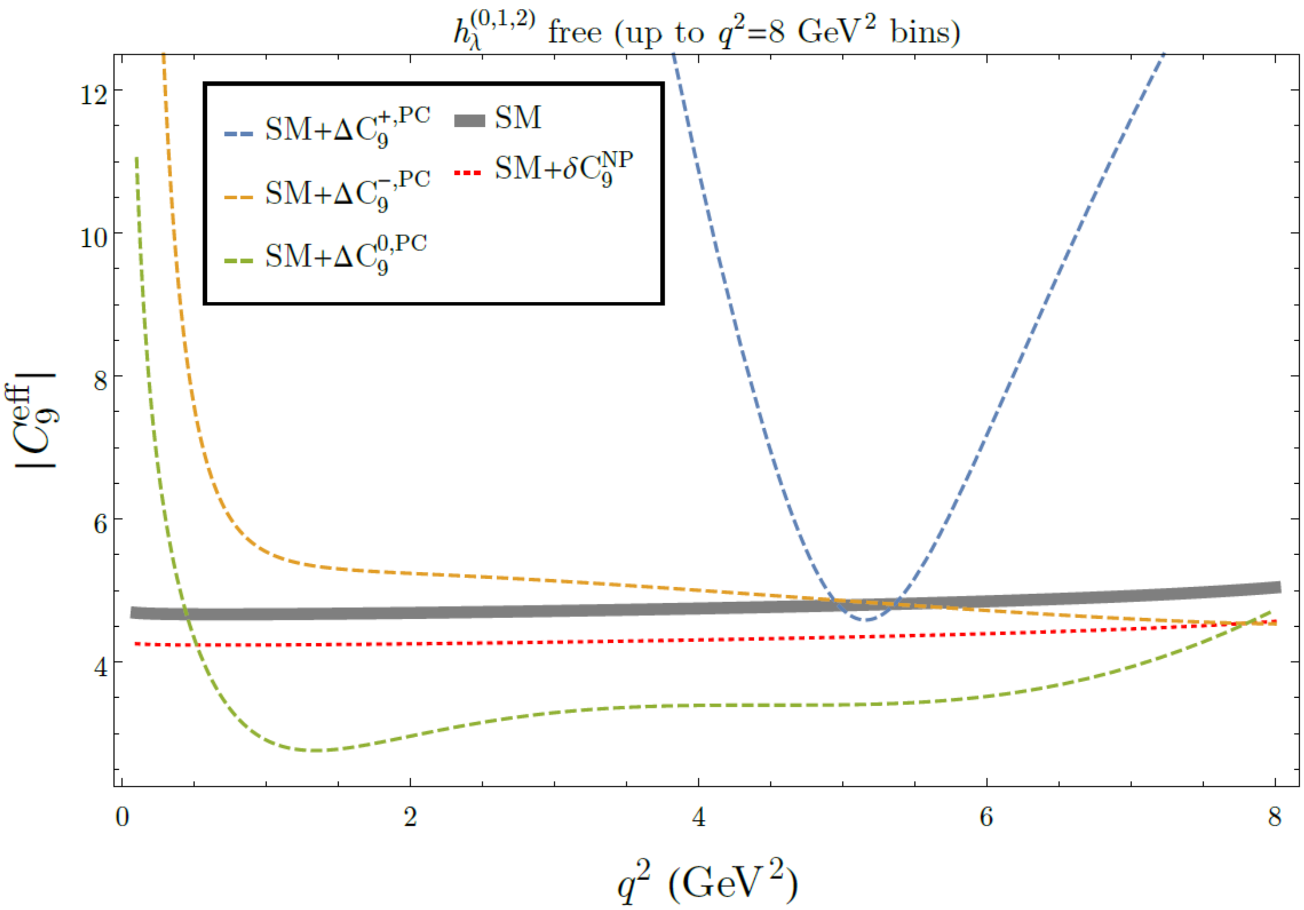
Backup

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

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



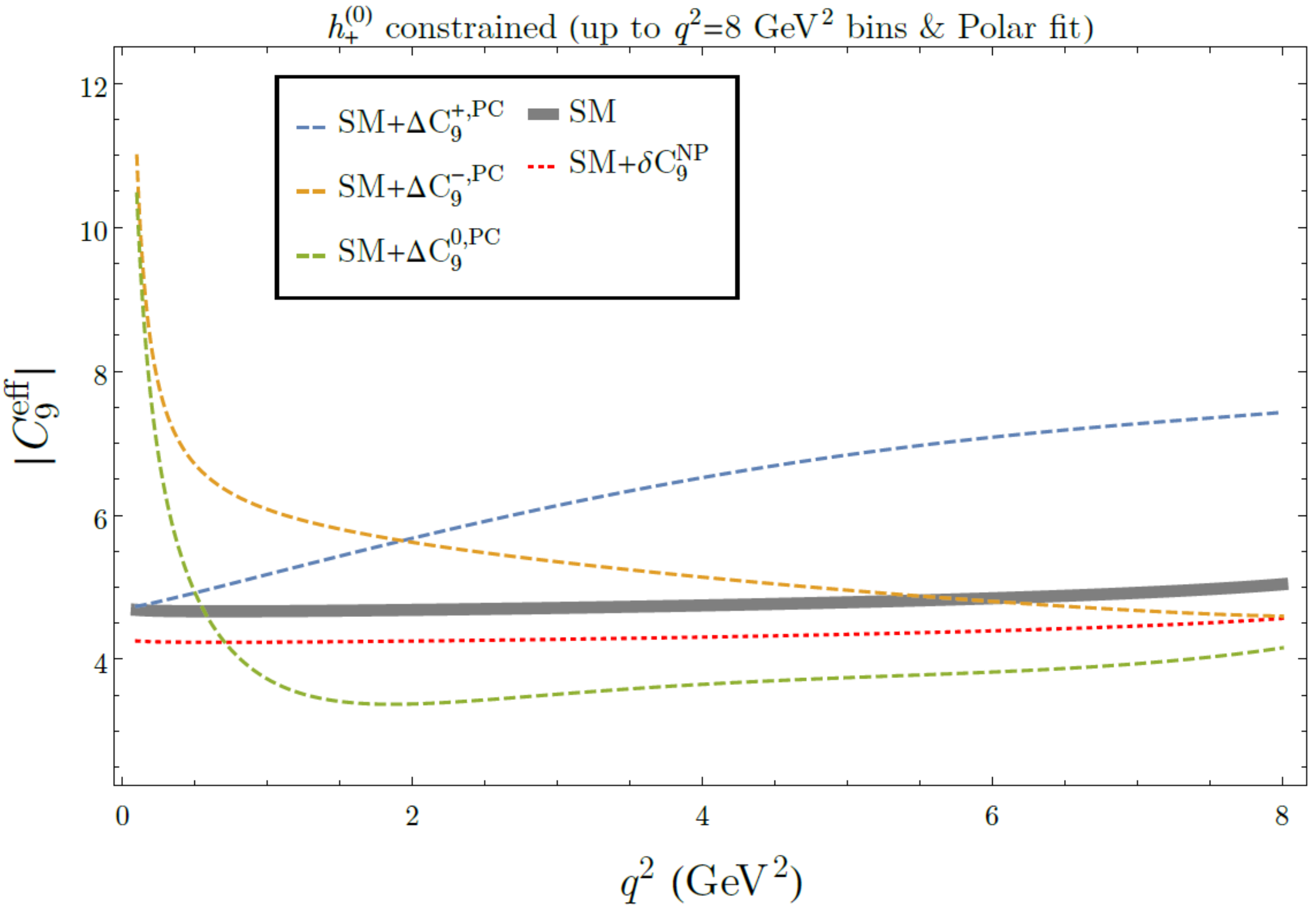
Hadronic corrections as shift to C_9 assuming $h_+^{(0)}$ to be constrained

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

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

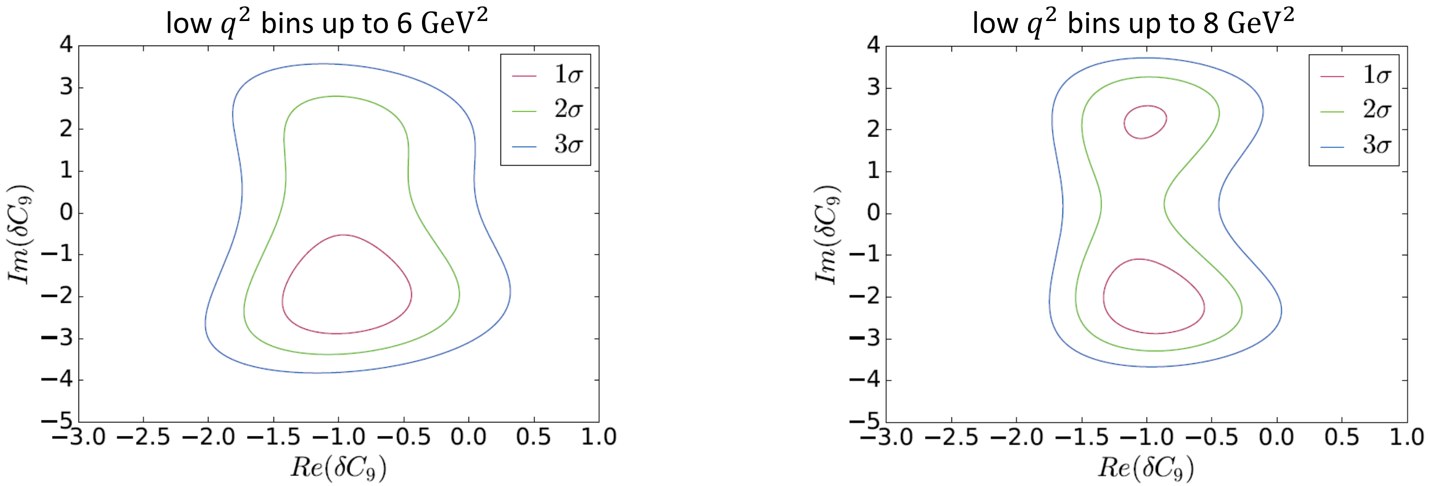
$$\Delta C_9^{\lambda,\rm PC} = -16\pi^2 \frac{m_B^2}{q^2}\frac{h_\lambda(q^2)}{\tilde{V}_\lambda(q^2)}$$

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

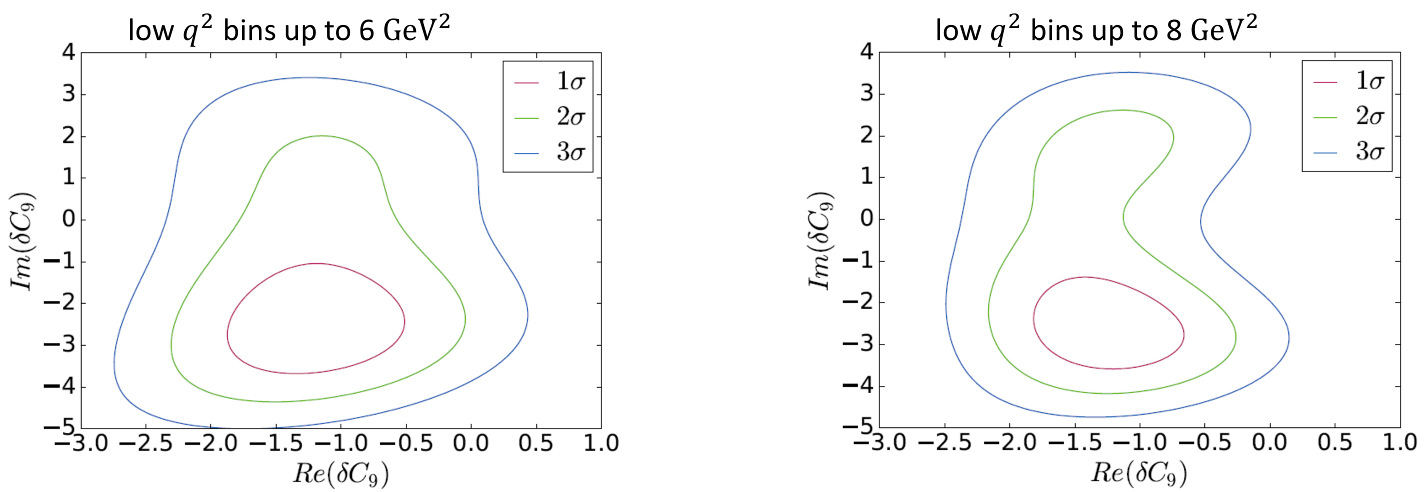


New Physics fit using only low-q^2 $B \to K^* \mu^+ \mu^-$ observables

Fit with 2 parameters (complex C_9)



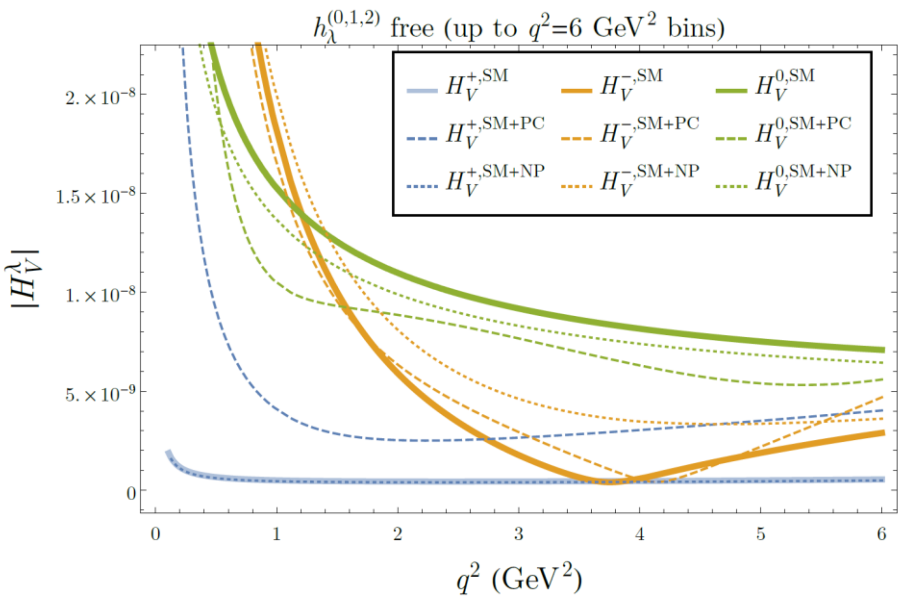
Fit with 4 parameters (complex C_7 and C_9)

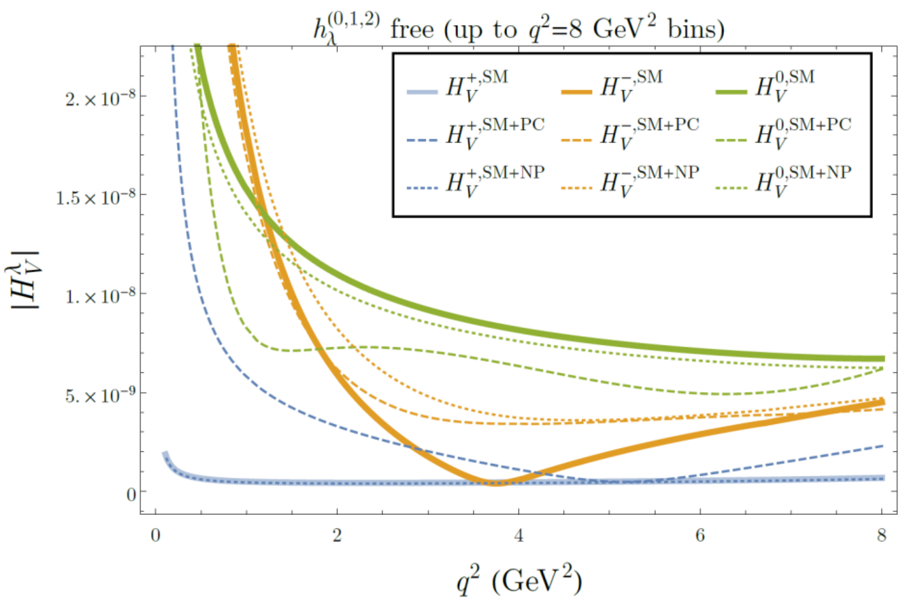


Fit parameters of power corrections and shapes of the different corrections

up to $q^2 = 6$ GeV^2 obs.		
	Real	Imaginary
$h_+^{(0)}$	$(2.3 \pm 2.3) \times 10^{-4}$	$(-2.0 \pm 2.3) \times 10^{-4}$
$h_+^{(1)}$	$(-1.2 \pm 3.5) \times 10^{-4}$	$(3.3 \pm 38.6) \times 10^{-5}$
$h_+^{(2)}$	$(1.2 \pm 6.8) \times 10^{-5}$	$(-3.5 \pm 8.1) \times 10^{-5}$
$h_-^{(0)}$	$(-7.7 \pm 19.8) \times 10^{-5}$	$(4.5 \pm 3.6) \times 10^{-4}$
$h_-^{(1)}$	$(-3.7 \pm 20.8) \times 10^{-5}$	$(-7.4 \pm 4.2) \times 10^{-4}$
$h_-^{(2)}$	$(2.7 \pm 3.9) \times 10^{-5}$	$(1.5 \pm 0.8) \times 10^{-4}$
$h_0^{(0)}$	$(-6.1 \pm 38.4) \times 10^{-5}$	$(7.8 \pm 4.0) \times 10^{-4}$
$h_0^{(1)}$	$(3.8 \pm 5.2) \times 10^{-4}$	$(-1.0 \pm 0.6) \times 10^{-3}$
$h_0^{(2)}$	$(-4.7 \pm 8.7) \times 10^{-5}$	$(1.6 \pm 1.3) \times 10^{-4}$

up to $q^2 = 8$ GeV^2 obs.		
	Real	Imaginary
$h_+^{(0)}$	$(1.2 \pm 2.0) \times 10^{-4}$	$(-1.6 \pm 2.1) \times 10^{-4}$
$h_+^{(1)}$	$(1.2 \pm 2.3) \times 10^{-4}$	$(-1.1 \pm 3.0) \times 10^{-4}$
$h_+^{(2)}$	$(-2.6 \pm 3.4) \times 10^{-5}$	$(2.3 \pm 4.4) \times 10^{-5}$
$h_-^{(0)}$	$(-1.0 \pm 1.8) \times 10^{-4}$	$(2.9 \pm 3.2) \times 10^{-4}$
$h_-^{(1)}$	$(2.5 \pm 13.3) \times 10^{-5}$	$(-3.4 \pm 3.2) \times 10^{-4}$
$h_-^{(2)}$	$(9.2 \pm 18.7) \times 10^{-6}$	$(1.7 \pm 4.8) \times 10^{-5}$
$h_0^{(0)}$	$(-2.6 \pm 3.3) \times 10^{-4}$	$(6.5 \pm 3.9) \times 10^{-4}$
$h_0^{(1)}$	$(7.5 \pm 4.4) \times 10^{-4}$	$(-8.7 \pm 3.6) \times 10^{-4}$
$h_0^{(2)}$	$(-8.6 \pm 5.8) \times 10^{-5}$	$(9.6 \pm 6.2) \times 10^{-5}$





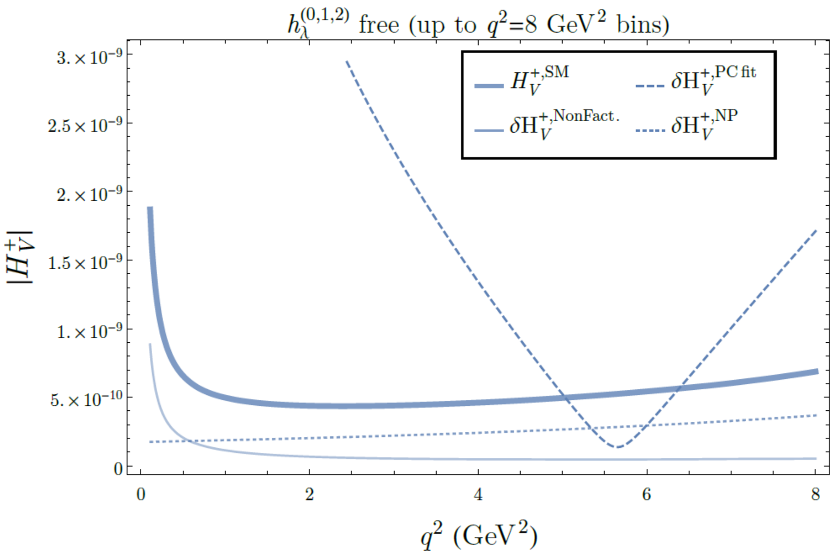
Wilks' test

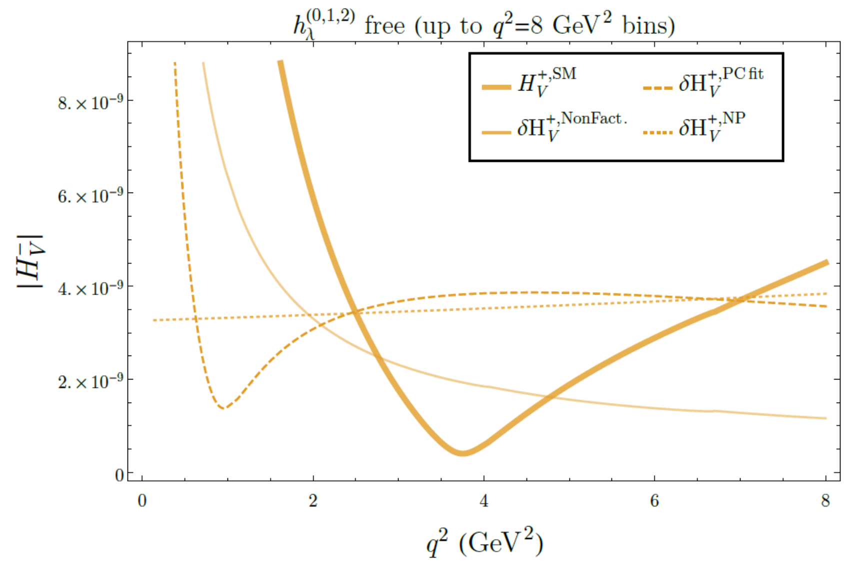
Comparison of the hadronic fit with the NP fit through likelihood ratio tests

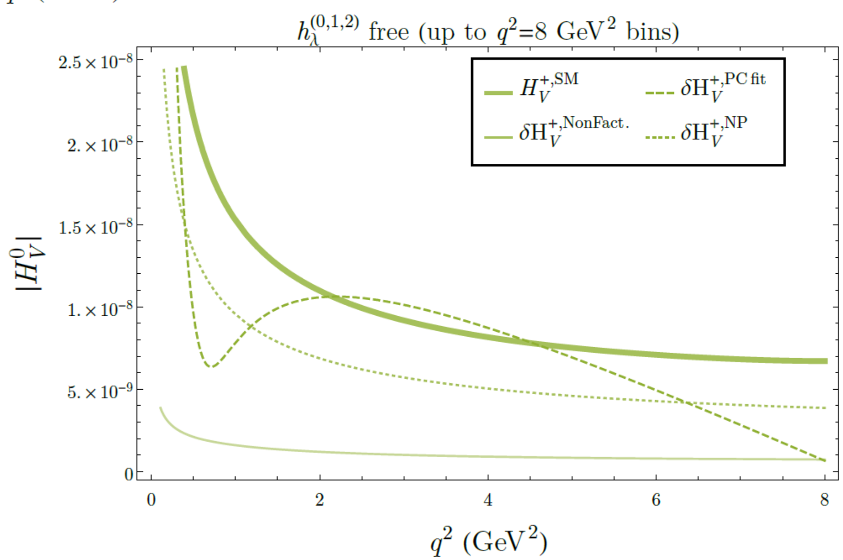
up to 6 GeV^2 observables			
	δC_9	$\delta C_7, \delta C_9$	Hadronic fit
Plain SM	4.5×10^{-3} (2.8σ)	9.4×10^{-3} (2.6σ)	6.2×10^{-2} (1.9σ)
δC_9	--	0.27 (1.1σ)	0.37 (0.89σ)
δC_7 & δC_9	--	--	0.41 (0.86σ)

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)

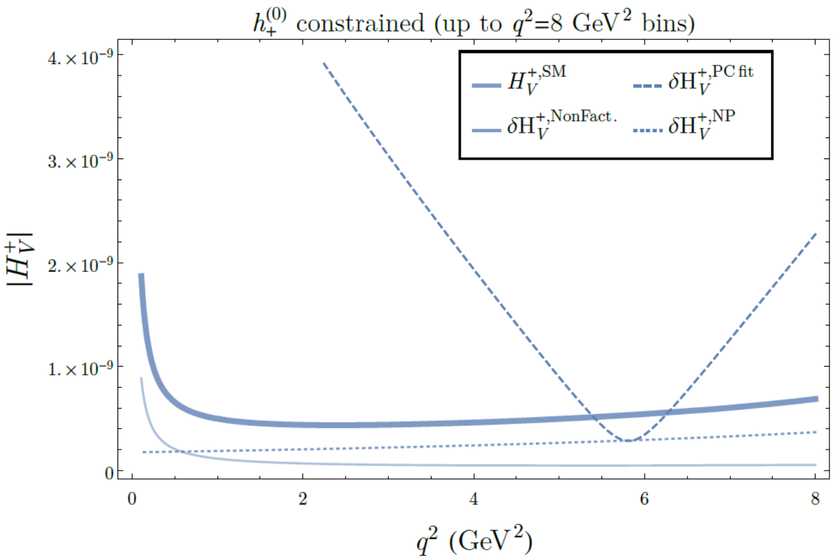
Size of different contributions to the helicity amplitudes

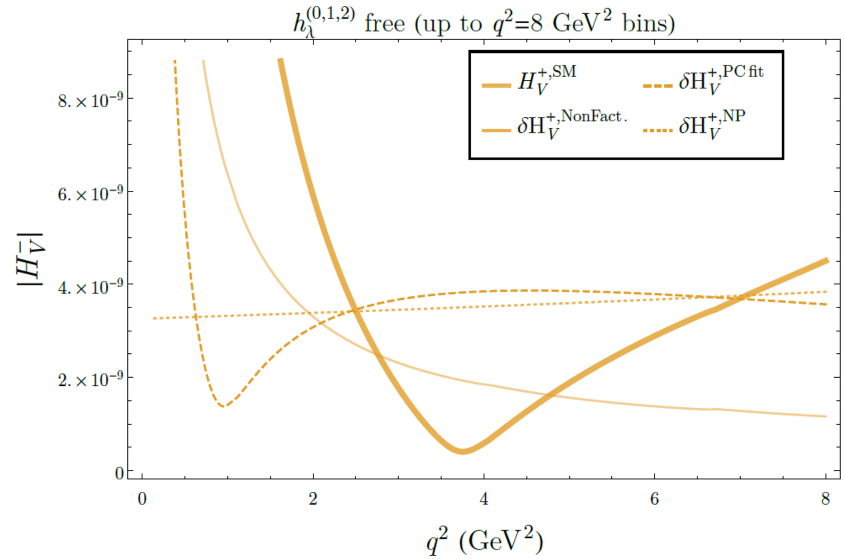


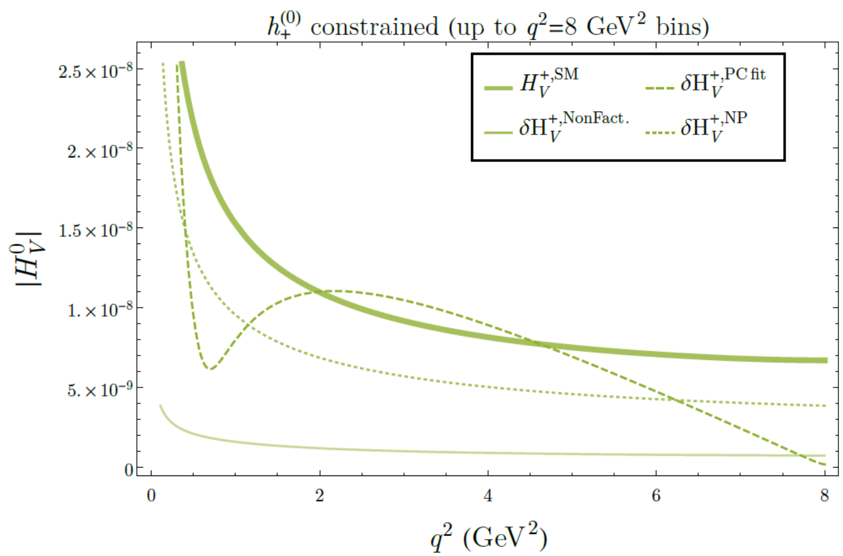




Assuming $h_+^{(0)}$ to be constrained $\quad (|h_+^{(0)}/h_-^{(0)}| < 0.2)$

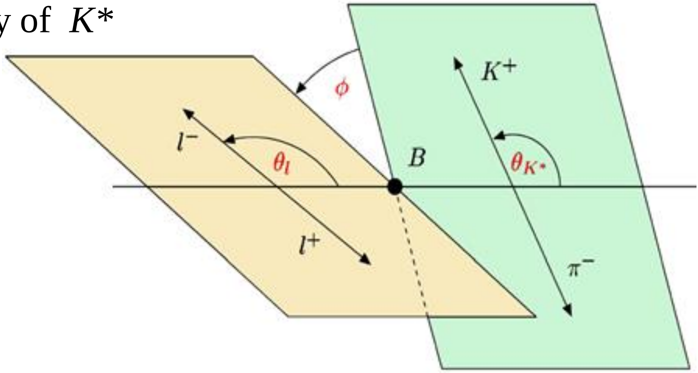






Observed in experiment: $B \to K^*(\to K^+ \pi^-)\ell^+\ell^-$

Angular behaviour of K^+ and π^- ⟶ additional information on the helicity of K^*



Angular distribution described by four independent kinematic variables

q^2 and three angles θ_ℓ, θ_{K^*}, ϕ

$$\sum_{\text{final state spins}} |\mathcal{M}|^2 \longrightarrow \frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi} J(q^2, \theta_l, \theta_K, \phi)$$

$$\begin{aligned} J(q^2, \theta_\ell, \theta_{K^*}, \phi) = {} & J_1^s \sin^2\theta_{K^*} + J_1^c \cos^2\theta_{K^*} + (J_2^s \sin^2\theta_{K^*} + J_2^c \cos^2\theta_{K^*}) \cos 2\theta_\ell \\ & + J_3 \sin^2\theta_{K^*} \sin^2\theta_\ell \cos 2\phi + J_4 \sin 2\theta_{K^*} \sin 2\theta_\ell \cos\phi + J_5 \sin 2\theta_{K^*} \sin\theta_\ell \cos\phi \\ & + (J_6^s \sin^2\theta_{K^*} + J_6^c \cos^2\theta_{K^*}) \cos\theta_\ell + J_7 \sin 2\theta_{K^*} \sin\theta_\ell \sin\phi \\ & + J_8 \sin 2\theta_{K^*} \sin 2\theta_\ell \sin\phi + J_9 \sin^2\theta_{K^*} \sin^2\theta_\ell \sin 2\phi \end{aligned}$$

J_i: functions of helicity amplitudes $H_V(\lambda), H_A(\lambda), H_P$ (or transversity amplitudes $A_\perp^{L,R}, A_\parallel^{L,R}, A_0^{L,R}, A_t$)

- Besides the standard observables (BR, A_{FB}, F_L) angular observables $P_i^{(\prime)}$ or S_i constructed as ratios of different J_i
  - ✓ Minimize form factor dependence
  - ✓ Sensitivity to certain Wilson coefficient

Kruger, Matias: 0502060; U. Egede et al.: 0807.2589; W. Altmannshofer et al.: 0811.1214; U. Egede et al.: 1005.0571; Becirevic, Schneider: 1106.3283; J. Matias et al.: 1202.4266; S. Descotes-Genon et al.: 1303.5794

Angular coefficients

$$
\begin{aligned}
I_1^c &= F\left\{\frac{1}{2}\left(|H_V^0|^2+|H_A^0|^2\right)+|H_P|^2+\frac{2m_\ell^2}{q^2}\left(|H_V^0|^2-|H_A^0|^2\right)+\beta^2|H_S|^2\right\}\\
I_1^s &= F\left\{\frac{\beta^2+2}{8}\left(|H_V^+|^2+|H_V^-|^2+(V\to A)\right)+\frac{m_\ell^2}{q^2}\left(|H_V^+|^2+|H_V^-|^2-(V\to A)\right)\right\}\\
I_2^c &= -F\,\frac{\beta^2}{2}\left(|H_V^0|^2+|H_A^0|^2\right)\\
I_2^s &= F\,\frac{\beta^2}{8}\left(|H_V^+|^2+|H_V^-|^2\right)+(V\to A)\\
I_3 &= -\frac{F}{2}\mathrm{Re}\left[H_V^+(H_V^-)^*\right]+(V\to A)\\
I_4 &= F\,\frac{\beta^2}{4}\mathrm{Re}\left[\left(H_V^-+H_V^+\right)\left(H_V^0\right)^*\right]+(V\to A)\\
I_5 &= F\left\{\frac{\beta}{2}\mathrm{Re}\left[\left(H_V^--H_V^+\right)\left(H_A^0\right)^*\right]+(V\leftrightarrow A)-\frac{\beta\,m_\ell}{\sqrt{q^2}}\mathrm{Re}\left[H_S^*(H_V^++H_V^-)\right]\right\}\\
I_6^s &= F\beta\,\mathrm{Re}\left[H_V^-(H_A^-)^*-H_V^+(H_A^+)^*\right]\\
I_6^c &= 2F\frac{\beta\,m_\ell}{\sqrt{q^2}}\mathrm{Re}\left[H_S^*H_V^0\right]\\
I_7 &= F\left\{\frac{\beta}{2}\,\mathrm{Im}\left[\left(H_A^++H_A^-\right)\left(H_V^0\right)^*+(V\leftrightarrow A)\right]-\frac{\beta\,m_\ell}{\sqrt{q^2}}\,\mathrm{Im}\left[H_S^*(H_V^--H_V^+)\right]\right\}\\
I_8 &= F\,\frac{\beta^2}{4}\mathrm{Im}\left[(H_V^--H_V^+)(H_V^0)^*\right]+(V\to A)\\
I_9 &= F\,\frac{\beta^2}{2}\mathrm{Im}\left[H_V^+(H_V^-)^*\right]+(V\to A)
\end{aligned}
$$

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

Differential decay rate: $\frac{d\Gamma}{dq^2} = \frac{3}{4}(J_1 - J_2/3)$

Forward Backward Asymmetry: $A_{FB}(q^2) = [\int_{-1}^{0} - \int_{0}^{1}]\, d\cos\theta_l \frac{d^2\Gamma}{dq^2\, d\cos\theta_l} / \frac{d\Gamma}{dq^2} = -\frac{3}{8} J_6 / \frac{d\Gamma}{dq^2}$

Forward-Backward Asymmetry zero-crossing: $q_0^2 = 2m_b \frac{C_7^{\text{eff}}}{C_9^{\text{eff}}} + O(\alpha_s, \Lambda/m_b)$

Longitudinal Polarization Fraction: $F_L = -2J_2^c / \frac{d\Gamma}{dq^2}$

Optimized obervables:

$$\langle P_1 \rangle_{\text{bin}} = \frac{1}{2} \frac{\int_{\text{bin}} dq^2 [J_3 + \bar{J}_3]}{\int_{\text{bin}} dq^2 [J_{2s} + \bar{J}_{2s}]} \qquad \langle P_2 \rangle_{\text{bin}} = \frac{1}{8} \frac{\int_{\text{bin}} dq^2 [J_{6s} + \bar{J}_{6s}]}{\int_{\text{bin}} dq^2 [J_{2s} + \bar{J}_{2s}]} \qquad \langle P_4' \rangle_{\text{bin}} = \frac{1}{\mathcal{N}'_{\text{bin}}} \int_{\text{bin}} dq^2 [J_4 + \bar{J}_4]$$

$$\langle P_5' \rangle_{\text{bin}} = \frac{1}{2\mathcal{N}'_{\text{bin}}} \int_{\text{bin}} dq^2 [J_5 + \bar{J}_5] \qquad \langle P_6' \rangle_{\text{bin}} = \frac{-1}{2\mathcal{N}'_{\text{bin}}} \int_{\text{bin}} dq^2 [J_7 + \bar{J}_7] \qquad \langle P_8' \rangle_{\text{bin}} = \frac{-1}{\mathcal{N}'_{\text{bin}}} \int_{\text{bin}} dq^2 [J_8 + \bar{J}_8]$$

$$\mathcal{N}'_{\text{bin}} = \sqrt{-\int_{\text{bin}} dq^2 [J_{2s} + \bar{J}_{2s}] \int_{\text{bin}} dq^2 [J_{2c} + \bar{J}_{2c}]}$$

U. Egede et al., JHEP 0811 (2008) 032
U. Egede et al.,JHEP 1010 (2010) 056
J. Matias et al., JHEP 1204 (2012) 104
S. Descotes-Genon et al., JHEP 1305 (2013) 137

Or alternatively : $S_i = (J_i^{(s,c)} + \bar{J}_i^{(s,c)}) / (\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2})$

W. Altmannshofer et al., JHEP 0901 (2009) 019

P_5' in terms of helicity amplitudes: $P_5' = \frac{\text{Re}[(H_V^- - H_V^+) H_A^{0*} + (H_A^- - H_A^+) H_V^{0*}]}{\sqrt{(|H_V^0|^2 + |H_A^0|^2)(|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2)}}$

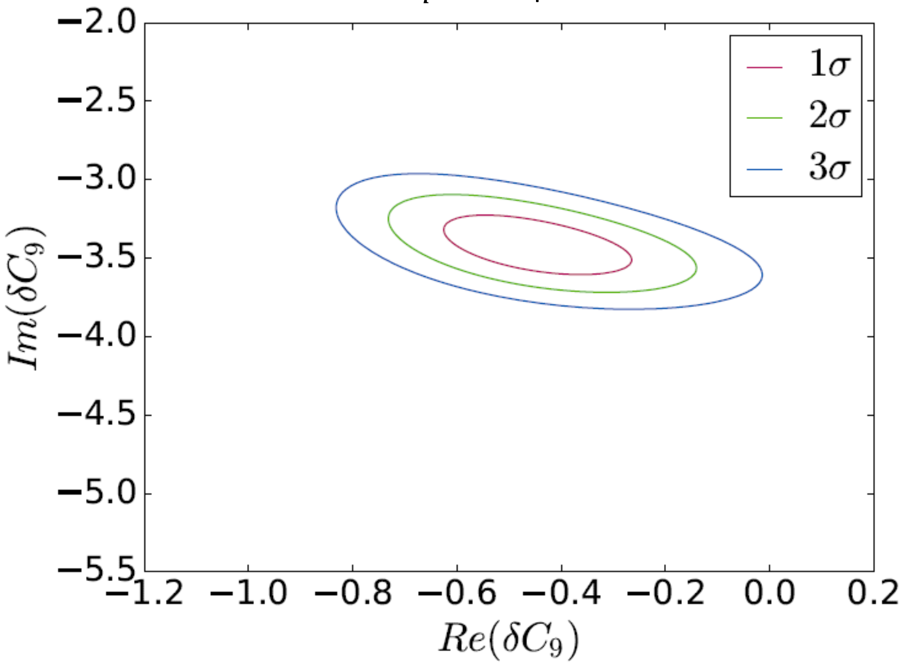
Identifying the origin of the anomalies:

Assuming a possible future upgrade, with an integrated luminosity of 300 fb^{-1}

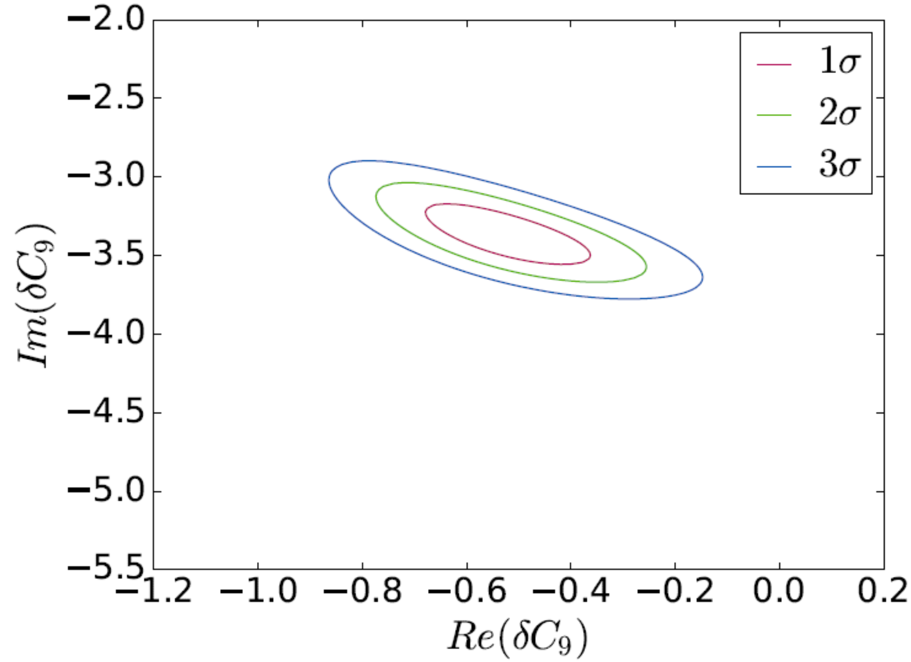
- Scaling down the present LHCb uncertainties by a factor 10
- Assuming the current central values

Fit with 2 parameters (complex C_9)

low q^2 bins up to 6 GeV^2



low q^2 bins up to 8 GeV^2



Crosscheck: lepton non-universality in other observables

Crosscheck with (clean) ratios $R(\mu/e)$

- Theoretically very clean compared to the angular observables

Hiller, Kruger arXiv: 0310219, Altmannshofer, Straub arXiv:1503.06199

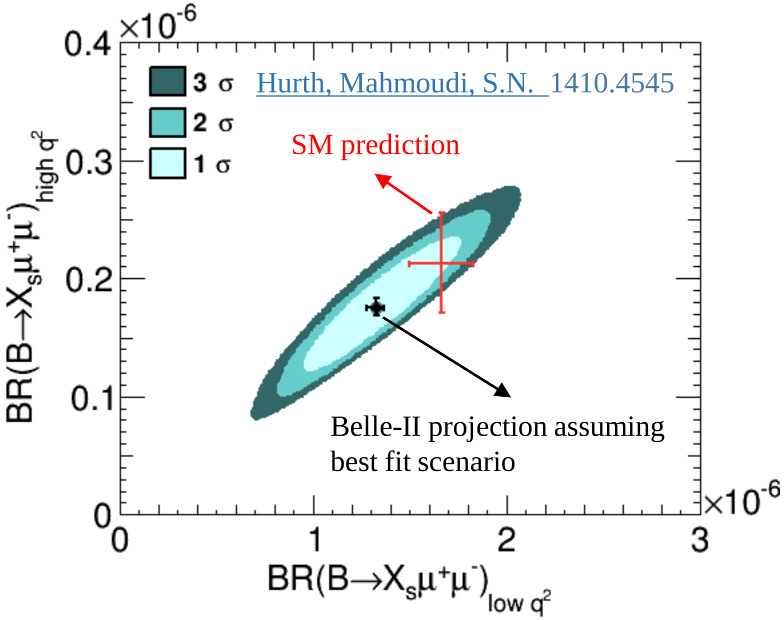
Using the best fit point for C_9^μ and C_9^e, make predictions of ratios of decays to muons versus electrons

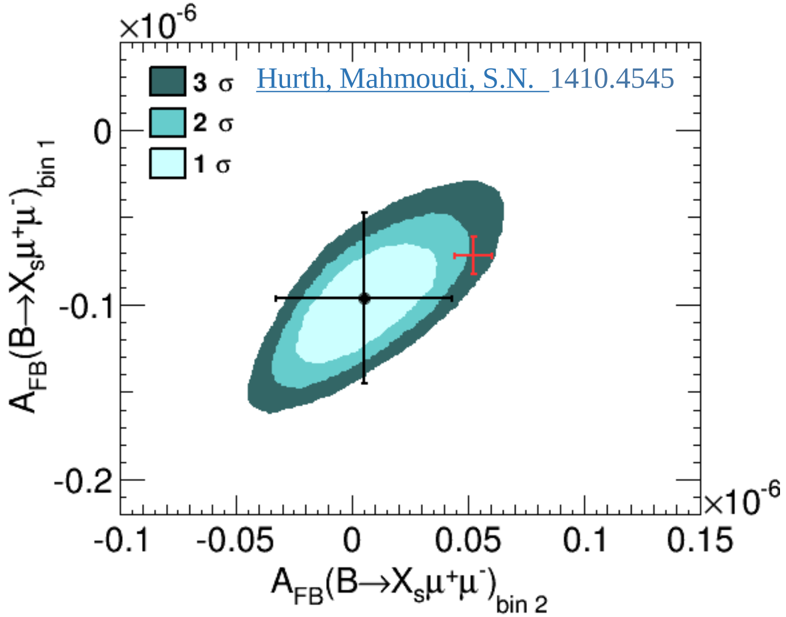
Observable	95% C.L. prediction
$\mathrm{BR}(B \to X_s \mu^+\mu^-)/\mathrm{BR}(B \to X_s e^+e^-)_{q^2 \in [1,6](\mathrm{GeV})^2}$	$[0.61, 0.93]$
$\mathrm{BR}(B \to X_s \mu^+\mu^-)/\mathrm{BR}(B \to X_s e^+e^-)_{q^2 > 14.2(\mathrm{GeV})^2}$	$[0.68, 1.13]$
$\mathrm{BR}(B^0 \to K^{*0}\mu^+\mu^-)/\ \mathrm{BR}(B^0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

Crosscheck: inclusive mode

Crosschecking with the inclusive mode $B \to X_s\, \mu^+\mu^-$

- Using the best fit point of C_7, C_9, C_{10} we predict the branching ratio at low- and high-q^2 at 1,2 and 3σ ranges also for A_{FB}
- The black cross corresponds to the future Belle-II measurement assuming the best fit scenario
- 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 < q2 < 3.5 GeV^2), 0.054 in the low-q^2 bin 2 (3.5 < q2 < 6 GeV^2) for the normalised A_{FB}

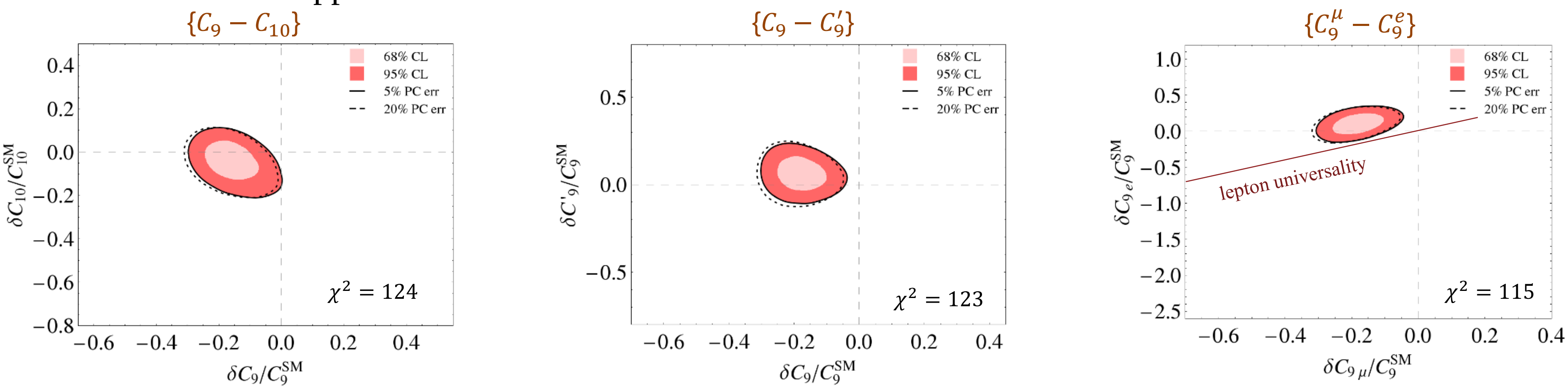




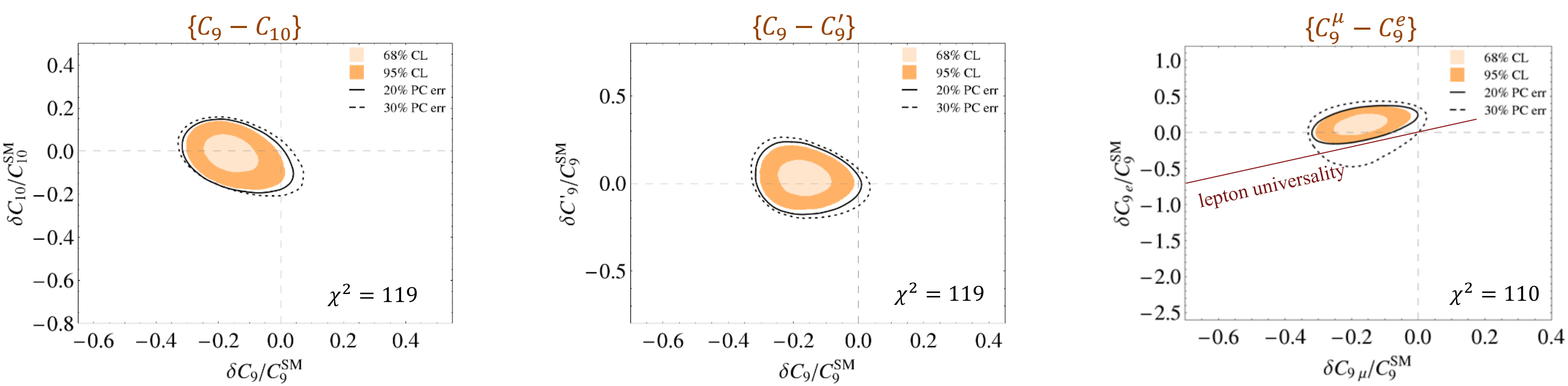
NP effect of C_9 is large enough to be checked by the theoretically cleaner inclusive modes at Belle-II

Different theoretical approaches

- Full form factor approach



- Soft form factor approach



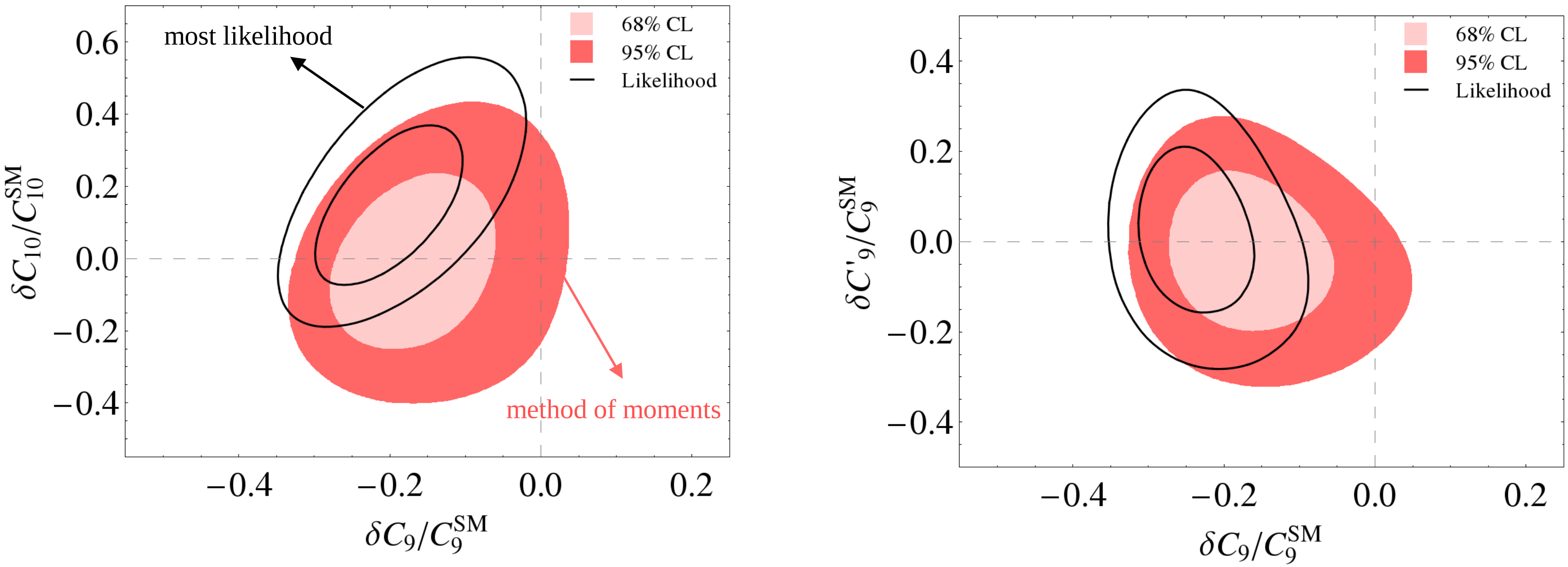
Dependence on experimental results: maximum likelihood vs. method of moment

LHCb uses two different analysis methods for the angular observables

- Method of moments: larger uncertainties but more robust
- Most likelihood method: smaller uncertainties but involves model dependent assumptions

How does the choice of method affect fit?

→ fitting by considering only $B \to K^* \mu^+ \mu^-$ observables

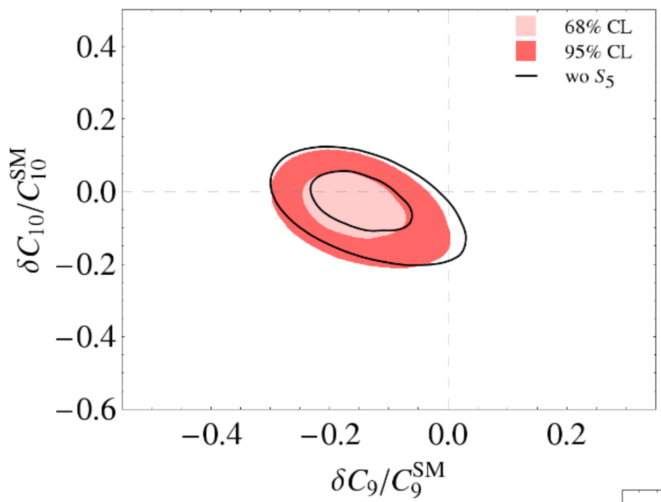


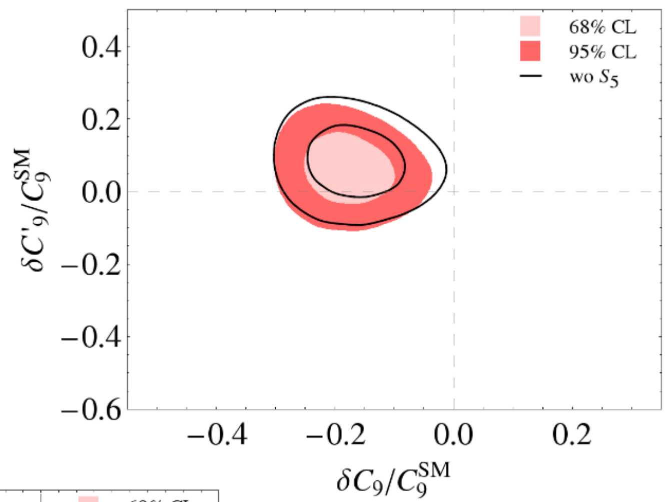
- Tension of best fit point with SM is decreased with the method of moments

  ↘ mostly due larger (experimental) error of the method of moment results (central values very similar)

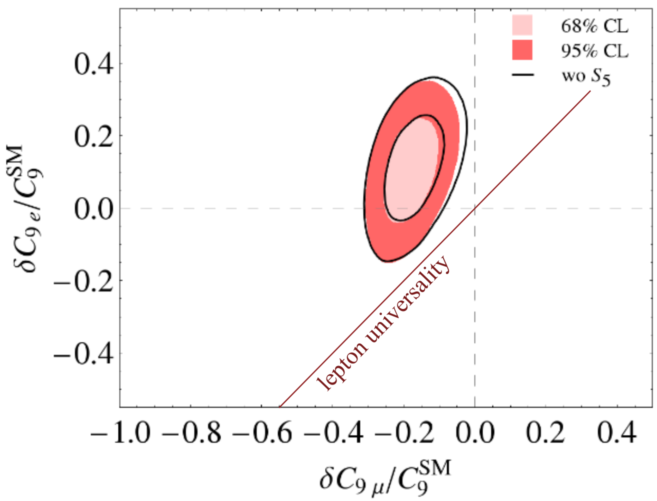
Dependence on experimental results: fit results when omitting S_5

Removing S_5 (P_5') from the global fit $\left(P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}\right)$





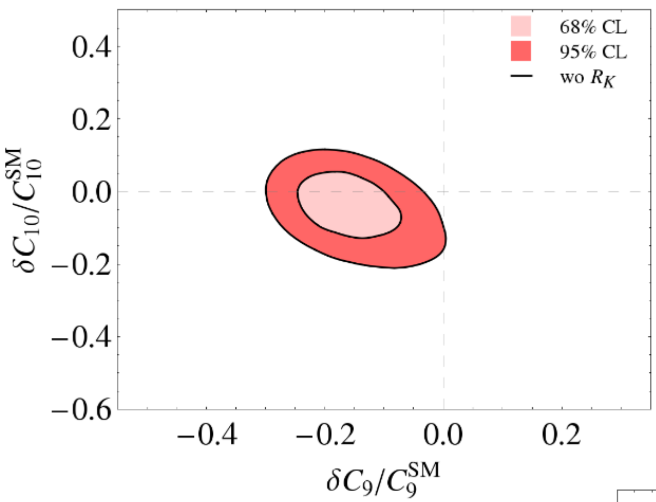
Filled area: global fit using all observables
Solid contour: fit removing only S_5

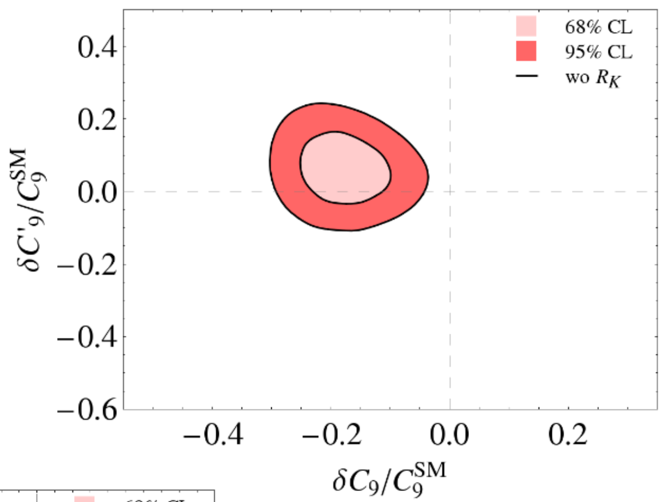


- Tension of best fit point is slightly reduced for C_9 but still more than 2σ

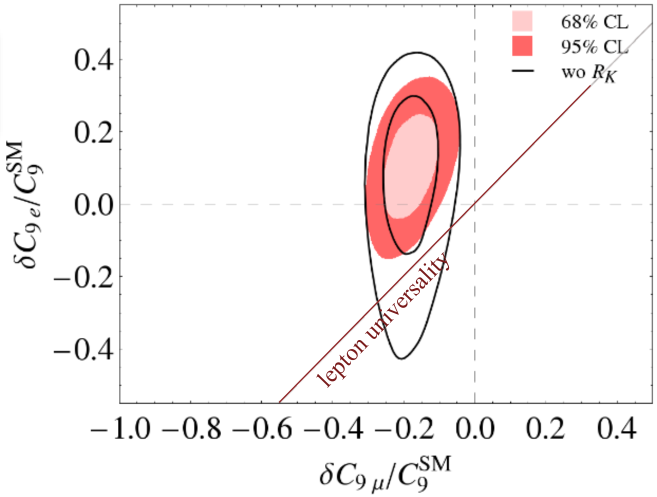
⟹ It is **not** only S_5 (P_5') which drives C_9 to negative values

Removing R_K from the global fit





Filled area: global fit using all observables
Solid contour: fit removing only R_K



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

Motivation

Traditional form factors:

$$\langle \bar{K}^* | \bar{s}\gamma^\mu b | \bar{B} \rangle \longrightarrow V(q^2)$$

$$\langle \bar{K}^* | \bar{s}\gamma^\mu \gamma_5 b | \bar{B} \rangle \longrightarrow A_0(q^2), A_1(q^2), A_2(q^2)$$

$$\langle \bar{K}^* | \bar{s}\sigma^{\mu\nu} b | \bar{B} \rangle \longrightarrow T_1(q^2), T_2(q^2), T_3(q^2)$$

Helicity form factors:

$$\langle \bar{K}^*_\lambda | \bar{s} \not\epsilon^*(\lambda) P_{L(R)} b | \bar{B} \rangle \longrightarrow \tilde{V}_{L(R)\lambda}(q^2)$$

$$\epsilon^*(\lambda) q^\nu \langle \bar{K}^*_\lambda | \bar{s}\sigma_{\mu\nu} P_{L(R)} b | \bar{B} \rangle \longrightarrow \tilde{T}_{L(R)\lambda}(q^2)$$

$$\langle \bar{K}^*_{\lambda(=0)} | \bar{s} P_{L(R)} b | \bar{B} \rangle \longrightarrow \tilde{S}(q^2)$$