Model independent analysis of $bs\ell\ell$ data

Nazila Mahmoudi

Lyon University and CERN

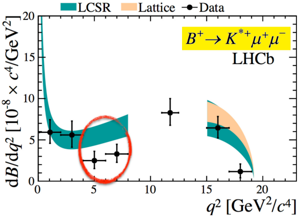
In collaboration with T. Hurth, S. Neshatpour and D. Martinez Santos
(mostly based on arXiv:2104.10058)

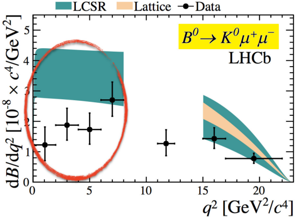
Workshop on Anomalies and Precision in the Belle II Era

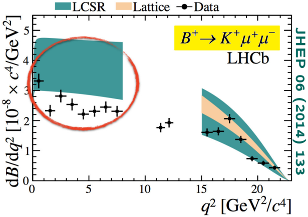
Vienna, 6-8 September 2021

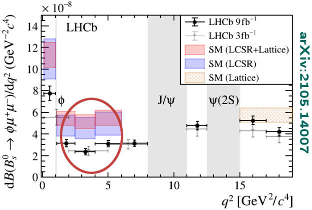
LHCb anomalies

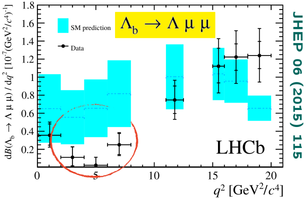
A consistent deviation pattern with the SM predictions in $b \to s$ measurements with muons in the final state:







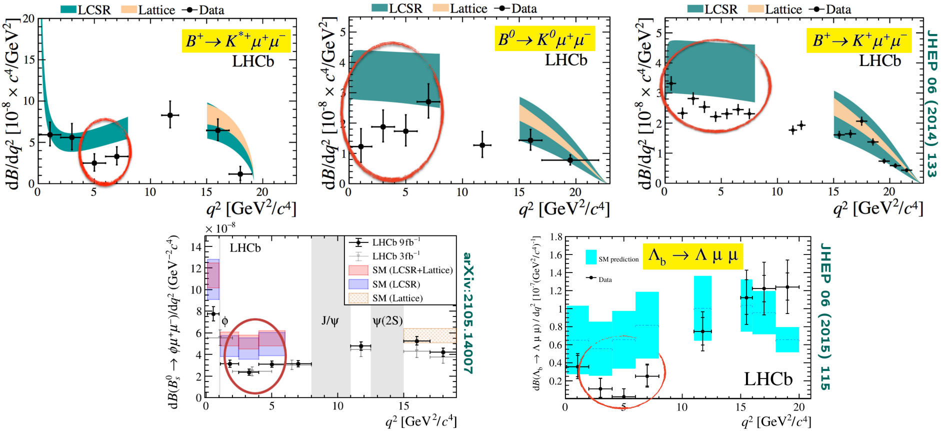




- deviations with the SM predictions between ~ 2 and $3.5\ \sigma$
- general trend: EXP < SM in low q^2
- ... but the branching ratios have very large theory uncertainties!

LHCb anomalies

A consistent deviation pattern with the SM predictions in $b \to s$ measurements with muons in the final state:

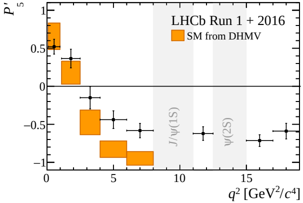


- deviations with the SM predictions between ~ 2 and $3.5\ \sigma$
- general trend: EXP < SM in low q^2
- ... but the branching ratios have very large theory uncertainties!

Tension in the angular observables

$P'_5(B^0 \to K^{*0}\mu^+\mu^-)$: Long standing tension since 2013

2020 LHCb update with 4.7 fb^{-1}: $\sim 3\sigma$ local tension



By construction cleaner than branching ratios

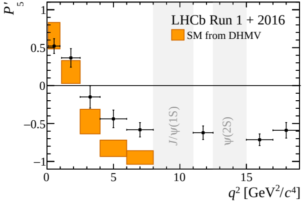
Still residual uncertainties from non-local effects

Phys. Rev. Lett. 125, 011802 (2020)

Tension in the angular observables

$P_5'(B^0 \to K^{*0}\mu^+\mu^-)$: Long standing tension since 2013

2020 LHCb update with 4.7 fb^{-1}: $\sim 3\sigma$ local tension



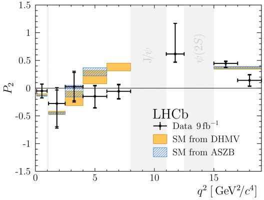
By construction cleaner than branching ratios

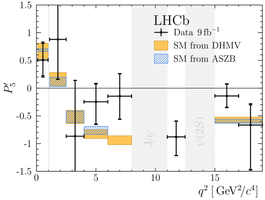
Still residual uncertainties from non-local effects

Phys. Rev. Lett. 125, 011802 (2020)

First measurement of $B^+ \to K^{*+}\mu^+\mu^-$ angular observables

using the full Run 1 and Run 2 dataset (9 fb^{-1}):





Phys. Rev. Lett. 126, 161802 (2021)

The results confirm the global tension with respect to the SM!

Lepton flavour universality tests

Lepton flavour universality in $B^0 \to K^{*0} \ell^+ \ell^-$

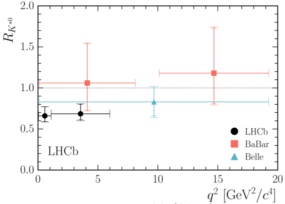
$$R_{K^*} = BR(B^0 \to K^{*0}\mu^+\mu^-)/BR(B^0 \to K^{*0}e^+e^-)$$

- LHCb measurement from April 2017 using 3 fb^{-1}
- Two q^2 regions: [0.045-1.1] and [1.1-6.0] GeV^2

$$R_{K^*}^{\text{exp,bin1}} = 0.66^{+0.11}_{-0.07}(\text{stat}) \pm 0.03(\text{syst})$$

$$R_{K^*}^{\text{exp,bin2}} = 0.69^{+0.11}_{-0.07}(\text{stat}) \pm 0.05(\text{syst})$$

- **2.2-2.5σ** tension in each bin



JHEP 08 (2017) 055

Lepton flavour universality tests

Lepton flavour universality in $B^0 \to K^{*0}\ell^+\ell^-$

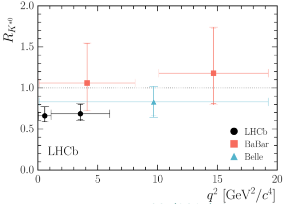
$$R_{K^*} = BR(B^0 \to K^{*0}\mu^+\mu^-)/BR(B^0 \to K^{*0}e^+e^-)$$

- LHCb measurement from April 2017 using 3 fb^{-1}
- Two q^2 regions: [0.045-1.1] and [1.1-6.0] GeV^2

$$R_{K^*}^{\rm exp,bin1} = 0.66^{+0.11}_{-0.07}({\rm stat}) \pm 0.03({\rm syst})$$

$$R_{K^*}^{\rm exp,bin2} = 0.69^{+0.11}_{-0.07}({\rm stat}) \pm 0.05({\rm syst})$$

- **2.2-2.5σ** tension in each bin



JHEP 08 (2017) 055

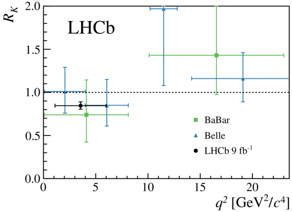
Lepton flavour universality in $B^+ \to K^+\ell^+\ell^-$

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

- Theoretical description similar to $B \to K^*\mu^+\mu^-$, but different since K is scalar
- SM prediction very accurate: $R_K^{\rm SM} = 1.0006 \pm 0.0004$
- Latest update: March 2021 using 9 fb^{-1}

$$R_K^{\rm exp} = 0.846^{+0.042}_{-0.039}({\rm stat})^{+0.013}_{-0.012}({\rm syst})$$

- **3.1σ** tension in the [1.1-6] GeV^2 bin

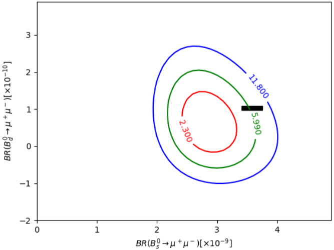


arXiv:2103.11769

$B_s \to \mu^+\mu^-$

SM prediction: $\mathrm{BR}(B_s \to \mu^+\mu^-)^{\mathrm{SM}} = (3.58 \pm 0.17) \times 10^{-9}$

Combination of LHCb, ATLAS and CMS measurements:



$$\mathrm{BR}(B_s \to \mu^+\mu^-)^{\mathrm{exp(comb.)}} = (2.85^{+0.34}_{-0.31}) \times 10^{-9}$$

LHCb (9 fb^{-1}): arXiv:2108.09283
ATLAS: JHEP 04 (2019) 098
CMS: JHEP 04 (2020) 188

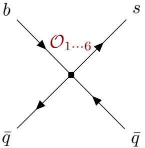
Theoretical framework

Theoretical framework: Effective Hamiltonian

separation between low and high energies using Operator Product Expansion

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

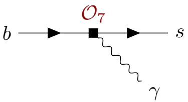
4-quark operators



$\mathcal{O}_{1,2} \propto (\bar{s}\Gamma_\mu c)(\bar{c}\Gamma^\mu b)$

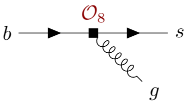
$\mathcal{O}_{3,4} \propto (\bar{s}\Gamma_\mu b)\sum_q(\bar{q}\Gamma^\mu q)$

electromagnetic dipole operator



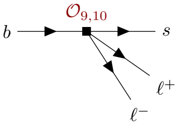
$\mathcal{O}_7 \propto (\bar{s}\sigma^{\mu\nu} P_R)F^a_{\mu\nu}$

chromomagnetic dipole operator



$\mathcal{O}_8 \propto (\bar{s}\sigma^{\mu\nu} T^a P_R)G^a_{\mu\nu}$

semileptonic operators



$\mathcal{O}_9^\ell \propto (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell)$

$\mathcal{O}_{10}^\ell \propto (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\gamma_5 \ell)$

In the SM: $C_7 = -0.29$ $C_9 = 4.20$ $C_{10} = -4.15$

New physics:

- Corrections to the Wilson coefficients: $C_i \to C_i^{\rm SM} + \delta C_i^{\rm NP}$
- Additional operators: Chirally flipped ($\mathcal{O}'_i$), (pseudo)scalar ($\mathcal{O}_S$ and $\mathcal{O}_P$), $\cdots$

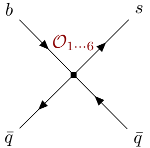
Theoretical framework

Theoretical framework: Effective Hamiltonian

separation between low and high energies using Operator Product Expansion

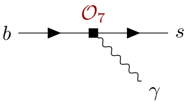
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(\sum_{i=1\cdots 10,S,P} \left(C_i(\mu) \mathcal{O}_i(\mu) + C'_i(\mu) \mathcal{O}'_i(\mu) \right) \right)$$

4-quark operators



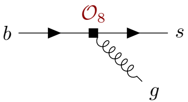
$\mathcal{O}_{1,2} \propto (\bar{s}\Gamma_\mu c)(\bar{c}\Gamma^\mu b)$
$\mathcal{O}_{3,4} \propto (\bar{s}\Gamma_\mu b)\sum_q(\bar{q}\Gamma^\mu q)$

electromagnetic dipole operator



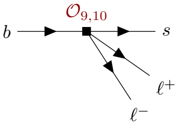
$\mathcal{O}_7 \propto (\bar{s}\sigma^{\mu\nu} P_R) F^a_{\mu\nu}$

chromomagnetic dipole operator



$\mathcal{O}_8 \propto (\bar{s}\sigma^{\mu\nu} T^a P_R) G^a_{\mu\nu}$

semileptonic operators



$\mathcal{O}^\ell_9 \propto (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell)$
$\mathcal{O}^\ell_{10} \propto (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\gamma_5 \ell)$

In the SM: $C_7 = -0.29$ $\quad C_9 = 4.20$ $\quad C_{10} = -4.15$

New physics:

- Corrections to the Wilson coefficients: $C_i \to C_i^{\rm SM} + \delta C_i^{\rm NP}$
- Additional operators: Chirally flipped ($\mathcal{O}'_i$), (pseudo)scalar ($\mathcal{O}_S$ and $\mathcal{O}_P$), $\cdots$

Issue of the hadronic power corrections

Effective Hamiltonian has two parts: $\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm had} + \mathcal{H}_{\rm eff}^{\rm sl}$

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

$\langle \bar{K}^* | \mathcal{H}_{\rm eff}^{\rm sl} | \bar{B} \rangle$: $B \to K^*$ **form factors** $V, A_{0,1,2}, T_{1,2,3}$

Transversity amplitudes:

$$A_{\perp}^{L,R} \simeq N_{\perp} \left\{ (C_9^+ \mp C_{10}^+) \frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2} C_7^+ T_1(q^2) \right\}$$

$$A_{\parallel}^{L,R} \simeq N_{\parallel} \left\{ (C_9^- \mp C_{10}^-) \frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2} C_7^- T_2(q^2) \right\}$$

$$A_0^{L,R} \simeq N_0 \Big\{ (C_9^- \mp C_{10}^-) \big[(\ldots) A_1(q^2) + (\ldots) A_2(q^2) \big] + 2m_b C_7^- \big[(\ldots) T_2(q^2) + (\ldots) T_3(q^2) \big] \Big\}$$

$$A_S = N_S (C_S - C_S') A_0(q^2)$$

$$(C_i^{\pm} \equiv C_i \pm C_i')$$

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

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

$$\equiv \frac{e^2}{q^2} \epsilon_{\mu} L_V^{\mu} \Big[\underbrace{\text{LO in } \mathcal{O}(\frac{\Lambda}{m_b}, \frac{\Lambda}{E_{K^*}})}_{\text{Non-Fact., QCDf}} + \underbrace{h_{\lambda}(q^2)}_{\text{power corrections}} \Big]$$

Issue of the hadronic power corrections

Effective Hamiltonian has two parts: $\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm had} + \mathcal{H}_{\rm eff}^{\rm sl}$

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

$\langle \bar{K}^* | \mathcal{H}_{\rm eff}^{\rm sl} | \bar{B}\rangle$: $B \to K^*$ **form factors** $V, A_{0,1,2}, T_{1,2,3}$

Transversity amplitudes:

$$A_\perp^{L,R} \simeq N_\perp \left\{ (C_9^+ \mp C_{10}^+) \frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2} C_7^+ T_1(q^2) \right\}$$

$$A_\parallel^{L,R} \simeq N_\parallel \left\{ (C_9^- \mp C_{10}^-) \frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2} C_7^- T_2(q^2) \right\}$$

$$A_0^{L,R} \simeq N_0 \Big\{ (C_9^- \mp C_{10}^-) \big[(\ldots) A_1(q^2) + (\ldots) A_2(q^2)\big] + 2m_b C_7^- \big[(\ldots) T_2(q^2) + (\ldots) T_3(q^2)\big] \Big\}$$

$$A_S = N_S (C_S - C_S') A_0(q^2)$$

$$(C_i^\pm \equiv C_i \pm C_i')$$

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

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

$$\equiv \frac{e^2}{q^2} \epsilon_\mu L_V^\mu \Big[\underbrace{\text{LO in } \mathcal{O}\big(\frac{\Lambda}{m_b}, \frac{\Lambda}{E_{K^*}}\big)}_{\text{Non-Fact., QCDf}} + \underbrace{h_\lambda(q^2)}_{\text{power corrections}} \Big]$$

$\to$ **unknown**

Recent progress show that these corrections should be very small (2011.09813)

Issue of the hadronic power corrections

Effective Hamiltonian has two parts: $\mathcal{H}_{\rm eff} = \mathcal{H}^{\rm had}_{\rm eff} + \mathcal{H}^{\rm sl}_{\rm eff}$

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

$\langle \bar{K}^*|\mathcal{H}^{\rm sl}_{\rm eff}|\bar{B}\rangle$: $B \to K^*$ form factors $V, A_{0,1,2}, T_{1,2,3}$

Transversity amplitudes:

$$A_\perp^{L,R} \simeq N_\perp \left\{ (C_9^+ \mp C_{10}^+)\frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2} C_7^+ T_1(q^2) \right\}$$

$$A_\parallel^{L,R} \simeq N_\parallel \left\{ (C_9^- \mp C_{10}^-)\frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2} C_7^- T_2(q^2) \right\}$$

$$A_0^{L,R} \simeq N_0 \Big\{ (C_9^- \mp C_{10}^-)\big[(\ldots)A_1(q^2) + (\ldots)A_2(q^2)\big] + 2m_b C_7^- \big[(\ldots)T_2(q^2) + (\ldots)T_3(q^2)\big] \Big\}$$

$$A_S = N_S(C_S - C_S')A_0(q^2)$$

$$(C_i^\pm \equiv C_i \pm C_i')$$

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

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

$$\equiv \frac{e^2}{q^2}\epsilon_\mu L_V^\mu \Big[\underbrace{\text{LO in } \mathcal{O}\Big(\frac{\Lambda}{m_b}, \frac{\Lambda}{E_{K^*}}\Big)}_{\text{Non-Fact., QCDf}} + \underbrace{h_\lambda(q^2)}_{\text{power corrections}} \Big]$$

$\rightarrow$ **unknown**

Recent progress show that these corrections should be very small (2011.09813)

Significance of the anomalies depends on the assumptions on the power corrections

Issue of the hadronic power corrections

Effective Hamiltonian has two parts: $\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm had} + \mathcal{H}_{\rm eff}^{\rm sl}$

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

$\langle \bar{K}^* | \mathcal{H}_{\rm eff}^{\rm sl} | \bar{B} \rangle$: $B \to K^*$ **form factors** $V, A_{0,1,2}, T_{1,2,3}$

Transversity amplitudes:

$$A_{\perp}^{L,R} \simeq N_{\perp} \left\{ (C_9^+ \mp C_{10}^+) \frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2} C_7^+ T_1(q^2) \right\}$$

$$A_{\parallel}^{L,R} \simeq N_{\parallel} \left\{ (C_9^- \mp C_{10}^-) \frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2} C_7^- T_2(q^2) \right\}$$

$$A_0^{L,R} \simeq N_0 \Big\{ (C_9^- \mp C_{10}^-) \left[(\ldots)A_1(q^2) + (\ldots)A_2(q^2) \right] + 2m_b C_7^- \left[(\ldots)T_2(q^2) + (\ldots)T_3(q^2) \right] \Big\}$$

$$A_S = N_S (C_S - C_S') A_0(q^2)$$

$$\left(C_i^{\pm} \equiv C_i \pm C_i' \right)$$

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

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

$$\equiv \frac{e^2}{q^2} \epsilon_\mu L_V^\mu \Big[\underbrace{\text{LO in } \mathcal{O}\big(\frac{\Lambda}{m_b}, \frac{\Lambda}{E_{K^*}}\big)}_{\text{Non-Fact., QCDf}} + \underbrace{h_\lambda(q^2)}_{\text{power corrections}} \Big]$$

$\rightarrow$ **unknown**

Recent progress show that these corrections should be very small (2011.09813)

Significance of the anomalies depends on the assumptions on the power corrections

This does not affect R_K and R_{K^*}

$\rightarrow$ Separate R_K and R_{K^*} (and $B_s \to \mu^+\mu^-$) from the less clean observables

Global fits

How to make sense of the data?

Many observables → **Global fits**

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

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

→ Scans over the values of δC_i
→ Calculation of flavour observables

Theoretical uncertainties and correlations

- variation of the "standard" input parameters: masses, scales, CKM, ...
- decay constants taken from the latest lattice results
- $B \to K^{(*)}$ and $B_s \to \phi$ form factors are obtained from the lattice+LCSR combinations, including all the correlations
- Parameterisation of uncertainties from power corrections:

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

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

⇒ Computation of a (theory + exp) correlation matrix

Global fits

Global fits of the observables obtained by minimisation of

$$\chi^2 = \left(\vec{O}^{\rm th} - \vec{O}^{\rm exp}\right) \cdot (\Sigma_{\rm th} + \Sigma_{\rm exp})^{-1} \cdot \left(\vec{O}^{\rm th} - \vec{O}^{\rm exp}\right)$$

$(\Sigma_{\rm th} + \Sigma_{\rm exp})^{-1}$ is the inverse covariance matrix.

173 observables relevant for leptonic and semileptonic decays:

- $\mathrm{BR}(B \to X_s\gamma)$
- $\mathrm{BR}(B \to X_d\gamma)$
- $\mathrm{BR}(B \to K^*\gamma)$
- $\Delta_0(B \to K^*\gamma)$
- $\mathrm{BR}^{\rm low}(B \to X_s\mu^+\mu^-)$
- $\mathrm{BR}^{\rm high}(B \to X_s\mu^+\mu^-)$
- $\mathrm{BR}^{\rm low}(B \to X_s e^+e^-)$
- $\mathrm{BR}^{\rm high}(B \to X_s e^+e^-)$
- $\mathrm{BR}(B_s \to \mu^+\mu^-)$
- $\mathrm{BR}(B_s \to e^+e^-)$
- $\mathrm{BR}(B_d \to \mu^+\mu^-)$
- R_K in the low q^2 bin
- R_{K^*} in 2 low q^2 bins
- $\mathrm{BR}(B \to K^0\mu^+\mu^-)$
- $\mathrm{BR}(B \to K^+\mu^+\mu^-)$
- $\mathrm{BR}(B \to K^* e^+e^-)$
- $B \to K^{*0}\mu^+\mu^-$: 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^2 bins
- $B^+ \to K^{*+}\mu^+\mu^-$: BR, F_L, A_{FB}, S_3, S_4, S_5, S_7, S_8, S_9
  in 5 low q^2 and 2 high q^2 bins
- $B_s \to \phi\mu^+\mu^-$: BR, F_L, S_3, S_4, S_7
  in 3 low q^2 and 2 high q^2 bins
- $\Lambda_b \to \Lambda\mu^+\mu^-$: BR, A_{FB}^{ℓ}, A_{FB}^{h}, $A_{FB}^{\ell h}$, F_L in the high q^2 bin

Computations performed using **SuperIso** public program

Single operator fits

Comparison of one-operator NP fits:

Only $R_{K^{(*)}}, B_{s,d} \to \mu^+\mu^-$ ($\chi^2_{\rm SM} = 28.19$)			
	b.f. value	$\chi^2_{\rm min}$	$\mathrm{Pull_{SM}}$
δC_9	-1.00 ± 6.00	28.1	0.2σ
δC_9^e	0.80 ± 0.21	11.2	4.1σ
δC_9^μ	-0.77 ± 0.21	11.9	4.0σ
δC_{10}	0.43 ± 0.24	24.6	1.9σ
δC_{10}^e	-0.78 ± 0.20	9.5	4.3σ
δC_{10}^μ	0.64 ± 0.15	7.3	4.6σ
$\delta C_{\rm LL}^e$	0.41 ± 0.11	10.3	4.2σ
$\delta C_{\rm LL}^\mu$	-0.38 ± 0.09	7.1	4.6σ

$\downarrow$

Clean observables

$\delta C^\ell_{\rm LL}$ basis corresponds to $\delta C_{\mathbf{9}}^\ell = -\delta C_{\mathbf{10}}^\ell$.

Single operator fits

Comparison of one-operator NP fits:

Only $R_{K^{(*)}}, B_{s,d} \to \mu^+\mu^-$ ($\chi^2_{\rm SM} = 28.19$)			
	b.f. value	$\chi^2_{\rm min}$	${\rm Pull_{SM}}$
δC_9	-1.00 ± 6.00	28.1	0.2σ
δC_9^e	0.80 ± 0.21	11.2	4.1σ
δC_9^μ	-0.77 ± 0.21	11.9	4.0σ
δC_{10}	0.43 ± 0.24	24.6	1.9σ
δC_{10}^e	-0.78 ± 0.20	9.5	4.3σ
δC_{10}^μ	0.64 ± 0.15	7.3	4.6σ
$\delta C_{\rm LL}^e$	0.41 ± 0.11	10.3	4.2σ
$\delta C_{\rm LL}^\mu$	-0.38 ± 0.09	7.1	4.6σ

$\downarrow$

Clean observables

All observables except $R_{K^{(*)}}, B_{s,d} \to \mu^+\mu^-$ ($\chi^2_{\rm SM} = 200.1$)			
	b.f. value	$\chi^2_{\rm min}$	${\rm Pull_{SM}}$
δC_9	-1.01 ± 0.13	158.2	6.5σ
δC_9^e	0.70 ± 0.60	198.8	1.1σ
δC_9^μ	-1.03 ± 0.13	156.0	6.6σ
δC_{10}	0.34 ± 0.23	197.7	1.5σ
δC_{10}^e	-0.50 ± 0.50	199.0	1.0σ
δC_{10}^μ	0.41 ± 0.23	196.5	1.9σ
$\delta C_{\rm LL}^e$	0.33 ± 0.29	198.9	1.1σ
$\delta C_{\rm LL}^\mu$	-0.75 ± 0.13	167.9	5.7σ

$\delta C_{\rm LL}^\ell$ basis corresponds to $\delta C_{\mathbf{9}}^\ell = -\delta C_{\mathbf{10}}^\ell$.

Single operator fits

Comparison of one-operator NP fits:

Only $R_{K^{(*)}}, B_{s,d} \to \mu^+\mu^-$ ($\chi^2_{\rm SM} = 28.19$)	b.f. value	$\chi^2_{\rm min}$	${\rm Pull}_{\rm SM}$
δC_9	-1.00 ± 6.00	28.1	0.2σ
δC_9^e	0.80 ± 0.21	11.2	4.1σ
δC_9^μ	-0.77 ± 0.21	11.9	4.0σ
δC_{10}	0.43 ± 0.24	24.6	1.9σ
δC_{10}^e	-0.78 ± 0.20	9.5	4.3σ
δC_{10}^μ	0.64 ± 0.15	7.3	4.6σ
$\delta C_{\rm LL}^e$	0.41 ± 0.11	10.3	4.2σ
$\delta C_{\rm LL}^\mu$	-0.38 ± 0.09	7.1	4.6σ

All observables except $R_{K^{(*)}}, B_{s,d} \to \mu^+\mu^-$ ($\chi^2_{\rm SM} = 200.1$)	b.f. value	$\chi^2_{\rm min}$	${\rm Pull}_{\rm SM}$
δC_9	-1.01 ± 0.13	158.2	6.5σ
δC_9^e	0.70 ± 0.60	198.8	1.1σ
δC_9^μ	-1.03 ± 0.13	156.0	6.6σ
δC_{10}	0.34 ± 0.23	197.7	1.5σ
δC_{10}^e	-0.50 ± 0.50	199.0	1.0σ
δC_{10}^μ	0.41 ± 0.23	196.5	1.9σ
$\delta C_{\rm LL}^e$	0.33 ± 0.29	198.9	1.1σ
$\delta C_{\rm LL}^\mu$	-0.75 ± 0.13	167.9	5.7σ

All observables ($\chi^2_{\rm SM} = 225.8$)	b.f. value	$\chi^2_{\rm min}$	${\rm Pull}_{\rm SM}$
δC_9	-0.99 ± 0.13	186.2	6.3σ
δC_9^e	0.79 ± 0.20	207.7	4.3σ
δC_9^μ	-0.95 ± 0.12	168.6	7.6σ
δC_{10}	0.32 ± 0.18	222.3	1.9σ
δC_{10}^e	-0.74 ± 0.18	206.3	4.4σ
δC_{10}^μ	0.55 ± 0.13	205.2	4.5σ
$\delta C_{\rm LL}^e$	0.40 ± 0.10	206.9	4.3σ
$\delta C_{\rm LL}^\mu$	-0.49 ± 0.08	180.5	6.7σ

Clean observables

Dependent on the assumptions on the non-factorisable power corrections

$\delta C_{\rm LL}^\ell$ basis corresponds to $\delta C_{\mathbf{9}}^\ell = -\delta C_{\mathbf{10}}^\ell$.

Single operator fits

Comparison of one-operator NP fits:

Only $R_{K^{(*)}}, B_{s,d} \to \mu^+\mu^-$ ($\chi^2_{\rm SM} = 28.19$)	b.f. value	$\chi^2_{\rm min}$	$\mathrm{Pull}_{\rm SM}$
δC_9	-1.00 ± 6.00	28.1	0.2σ
δC_9^e	0.80 ± 0.21	11.2	4.1σ
δC_9^μ	-0.77 ± 0.21	11.9	4.0σ
δC_{10}	0.43 ± 0.24	24.6	1.9σ
δC_{10}^e	-0.78 ± 0.20	9.5	4.3σ
δC_{10}^μ	0.64 ± 0.15	7.3	4.6σ
$\delta C_{\rm LL}^e$	0.41 ± 0.11	10.3	4.2σ
$\delta C_{\rm LL}^\mu$	-0.38 ± 0.09	7.1	4.6σ

All observables except $R_{K^{(*)}}, B_{s,d} \to \mu^+\mu^-$ ($\chi^2_{\rm SM} = 200.1$)	b.f. value	$\chi^2_{\rm min}$	$\mathrm{Pull}_{\rm SM}$
δC_9	-1.01 ± 0.13	158.2	6.5σ
δC_9^e	0.70 ± 0.60	198.8	1.1σ
δC_9^μ	-1.03 ± 0.13	156.0	6.6σ
δC_{10}	0.34 ± 0.23	197.7	1.5σ
δC_{10}^e	-0.50 ± 0.50	199.0	1.0σ
δC_{10}^μ	0.41 ± 0.23	196.5	1.9σ
$\delta C_{\rm LL}^e$	0.33 ± 0.29	198.9	1.1σ
$\delta C_{\rm LL}^\mu$	-0.75 ± 0.13	167.9	5.7σ

All observables ($\chi^2_{\rm SM} = 225.8$)	b.f. value	$\chi^2_{\rm min}$	$\mathrm{Pull}_{\rm SM}$
δC_9	-0.99 ± 0.13	186.2	6.3σ
δC_9^e	0.79 ± 0.20	207.7	4.3σ
δC_9^μ	-0.95 ± 0.12	168.6	7.6σ
δC_{10}	0.32 ± 0.18	222.3	1.9σ
δC_{10}^e	-0.74 ± 0.18	206.3	4.4σ
δC_{10}^μ	0.55 ± 0.13	205.2	4.5σ
$\delta C_{\rm LL}^e$	0.40 ± 0.10	206.9	4.3σ
$\delta C_{\rm LL}^\mu$	-0.49 ± 0.08	180.5	6.7σ

↓ Clean observables

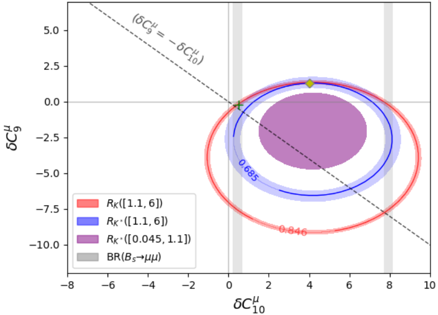
↓ ↓ Dependent on the assumptions on the non-factorisable power corrections

$\delta C_{\rm LL}^\ell$ basis corresponds to $\delta C_9^\ell = -\delta C_{10}^\ell$.

- Compatible NP scenarios between different sets
- Hierarchy of the preferred NP scenarios have remained the same with updated data (C_9^μ followed by $C_{\rm LL}^\mu$)
- Significance increased by more than 2σ in the preferred scenarios compared to 2019

$R_{K^{(*)}}$ and $B_{s,d} \to \mu^+\mu^-$

Clean observables within 1σ of experimental central value:



Colored regions: 1σ range (th + exp uncertainties added in quadrature) with the experimental central value.

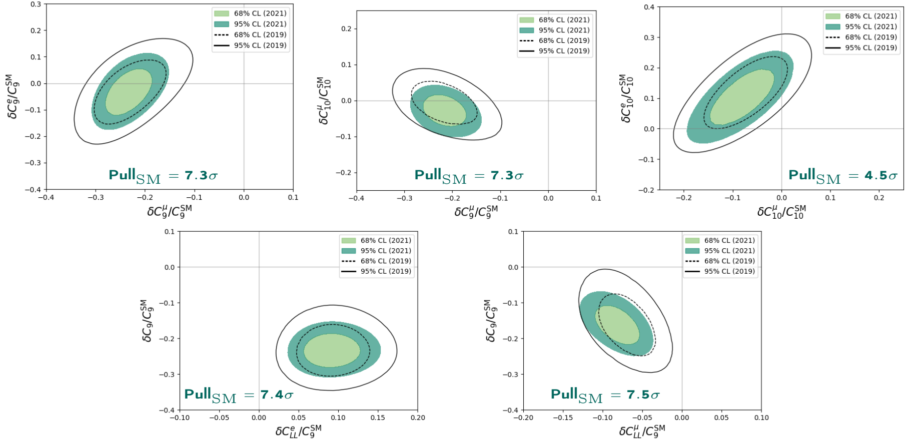
Red (blue) solid line: central value of the experimental measurements of R_K and R_{K^*}

Yellow diamond: best fit point of the fit to only $R_{K^{(*)}}$

Green cross: best fit value when fitting to $R_{K^{(*)}}$ and BR($B_{s,d} \to \mu^+\mu^-$).

Two operator fits

Two operator fits to NP to all observables (with the assumption of 10% power corrections):

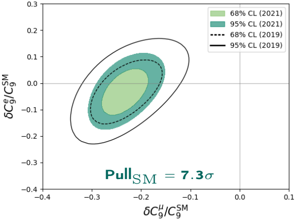


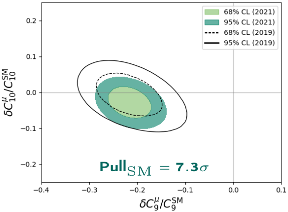
Colored bands (black contours): 68 and 95% CL regions considering 2021 (2019) data

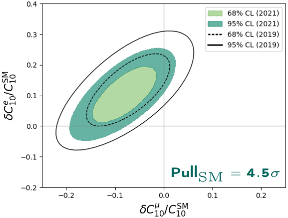
Similar fits by other groups: Geng et al. arXiv:2103.12738, Altmannshofer al. 2103.13370, Alguero et al. arXiv:2104.08921, Ciuchini et al . arXiv:2011.01212, Datta et al. 1903.10086, Kowalska et al., arXiv:1903.10932, · · ·

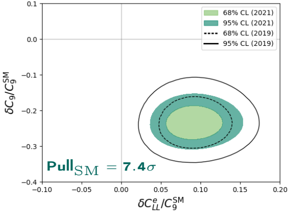
Two operator fits

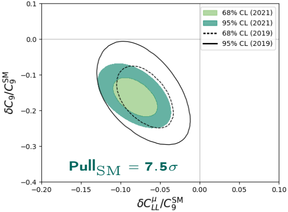
Two operator fits to NP to all observables (with the assumption of 10% power corrections):











Colored bands (black contours): 68 and 95% CL regions considering 2021 (2019) data

Similar fits by other groups: Geng et al. arXiv:2103.12738, Altmannshofer al. 2103.13370, Alguero et al. arXiv:2104.08921, Ciuchini et al . arXiv:2011.01212, Datta et al. 1903.10086, Kowalska et al., arXiv:1903.10932, · · ·

More complete analyses

In a New Physics model:

- new vector bosons: C_7, C_9, C_{10}
- new fermions: C_7, C_8, C_9, C_{10}
- extended Higgs sector/new scalars: C_S, C_P

e.g. in the MSSM, 2HDM, ...: $C_7, C_8, C_9, C_{10}, C_S, C_P$

Considering only one or two Wilson coefficients may not give the full picture!

A generic set of Wilson coefficients:

$$\text{complex } C_7, C_8, C_9^\ell, C_{10}^\ell, C_S^\ell, C_P^\ell + \text{primed coefficients}$$

The available observables are mainly insensitive to the imaginary parts, one can limit the set to

$$\text{real } C_7, C_8, C_9^\ell, C_{10}^\ell, C_S^\ell, C_P^\ell + \text{primed coefficients}$$

corresponding to 20 degrees of freedom.

Considering the most general NP description, look-elsewhere effect is avoided!

More complete analyses

In a New Physics model:

- new vector bosons: C_7, C_9, C_{10}
- new fermions: C_7, C_8, C_9, C_{10}
- extended Higgs sector/new scalars: C_S, C_P

e.g. in the MSSM, 2HDM, ...: $C_7, C_8, C_9, C_{10}, C_S, C_P$

Considering only one or two Wilson coefficients may not give the full picture!

A generic set of Wilson coefficients:

complex $C_7, C_8, C_9^\ell, C_{10}^\ell, C_S^\ell, C_P^\ell$ + primed coefficients

The available observables are mainly insensitive to the imaginary parts, one can limit the set to

real $C_7, C_8, C_9^\ell, C_{10}^\ell, C_S^\ell, C_P^\ell$ + primed coefficients

corresponding to 20 degrees of freedom.

Considering the most general NP description, look-elsewhere effect is avoided!

More complete analyses

In a New Physics model:

- new vector bosons: C_7, C_9, C_{10}
- new fermions: C_7, C_8, C_9, C_{10}
- extended Higgs sector/new scalars: C_S, C_P

e.g. in the MSSM, 2HDM, ...: $C_7, C_8, C_9, C_{10}, C_S, C_P$

Considering only one or two Wilson coefficients may not give the full picture!

A generic set of Wilson coefficients:

$$\text{complex } C_7, C_8, C_9^\ell, C_{10}^\ell, C_S^\ell, C_P^\ell + \text{primed coefficients}$$

The available observables are mainly insensitive to the imaginary parts, one can limit the set to

$$\text{real } C_7, C_8, C_9^\ell, C_{10}^\ell, C_S^\ell, C_P^\ell + \text{primed coefficients}$$

corresponding to 20 degrees of freedom.

Considering the most general NP description, look-elsewhere effect is avoided!

Full fit - results

Set: real C_7, C_8, C_9^ℓ, C_{10}^ℓ, C_S^ℓ, C_P^ℓ + primed coefficients, 20 degrees of freedom

All observables with $\chi^2_{\rm SM} = 225.8$ $\chi^2_{\rm min} = 151.6$; $\quad \mathrm{Pull}_{\rm SM} = 5.5(5.6)\sigma$			
δC_7 0.05 ± 0.03		δC_8 -0.70 ± 0.40	
$\delta C_7'$ -0.01 ± 0.02		$\delta C_8'$ 0.00 ± 0.80	
δC_9^μ -1.16 ± 0.17	δC_9^e -6.70 ± 1.20	δC_{10}^μ 0.20 ± 0.21	δC_{10}^e degenerate w/ $C_{10}'^e$
$\delta C_9'^\mu$ 0.09 ± 0.34	$\delta C_9'^e$ 1.90 ± 1.50	$\delta C_{10}'^\mu$ -0.12 ± 0.20	$\delta C_{10}'^e$ degenerate w/ C_{10}^e
$C_{Q_1}^\mu$ 0.04 ± 0.10 $[-0.08 \pm 0.11]$	$C_{Q_1}^e$ -1.50 ± 1.50 $[-0.20 \pm 1.60]$	$C_{Q_2}^\mu$ -0.09 ± 0.10 $[-0.11 \pm 0.10]$	$C_{Q_2}^e$ -4.10 ± 1.5 $[4.50 \pm 1.5]$
$C_{Q_1}'^\mu$ 0.15 ± 0.10 $[0.02 \pm 0.12]$	$C_{Q_1}'^e$ -1.70 ± 1.20 $[-0.30 \pm 1.10]$	$C_{Q_2}'^\mu$ -0.14 ± 0.11 $[-0.16 \pm 0.10]$	$C_{Q_2}'^e$ -4.20 ± 1.2 $[4.40 \pm 1.2]$

- No real improvement in the fits when going beyond the C_9^μ case
- Many parameters are weakly constrained at the moment
- Effective d.o.f is (19) leading to 5.6σ significance

Wilks' test

Pull_{SM} of $1, 2, 6, 10$ and 20 dimensional fit:

Set of WC	param.	χ^2_{min}	Pull_{SM}	Improvement
SM	0	225.8	-	-
C_9^μ	1	168.6	7.6σ	7.6σ
C_9^μ, C_{10}^μ	2	167.5	7.3σ	1.0σ
$C_7, C_8, C_9^{(e,\mu)}, C_{10}^{(e,\mu)}$	6	158.0	7.1σ	2.0σ
All non-primed WC	10	157.2	6.5σ	0.1σ
All WC (incl. primed)	20 (19)	151.6	$5.5\,(5.6)\sigma$	$0.2\,(0.3)\sigma$

The "All non-primed WC" includes in addition to the previous row, the scalar and pseudoscalar Wilson coefficients.

The last row also includes the chirality-flipped counterparts of the Wilson coefficients.

In the last column the significance of improvement of the fit compared to the scenario of the previous row is given.

The number in parentheses corresponds to the effective degrees of freedom (19).

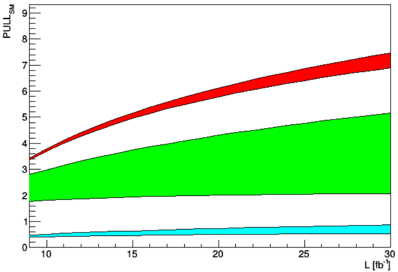
Future prospects

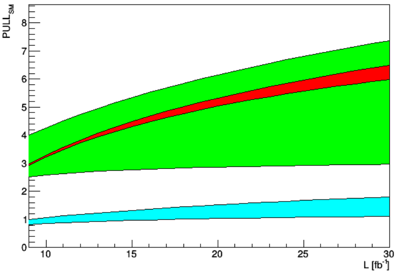
for clean observables

Experimental prospects

Evolution of the tension between the SM and the experimental values

Assuming the best fit values of C_9^μ (left) and C_{10}^μ (right)





red: $R_K^{[1.1,6]}$ green: $R_{K^*}^{[1.1,6]}$ blue: $R_{K^*}^{[0.045,1.1]}$

Upper limit: assuming ultimate systematic uncertainties (1% for ratios & 4% for $B_s \to \mu^+\mu^-$)

Lower limit: assuming current systematic uncertainties do not improve

Projections

Predictions of $\mathrm{Pull_{SM}}$ for the fit to δC_9^μ, δC_{10}^μ and δC_{LL}^μ

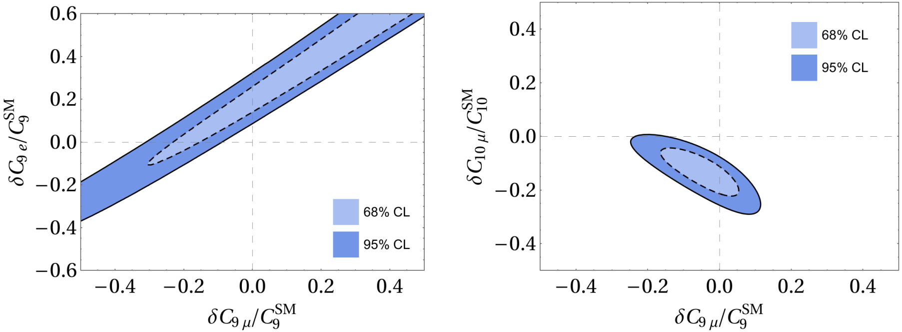
For LHCb upgrade scenarios with 18, 50 and 300 fb^{-1} collected luminosity:

$\mathrm{Pull_{SM}}$ with $R_{K^{(*)}}$ and $\mathrm{BR}(B_s \to \mu^+\mu^-)$ prospects			
LHCb lum.	18 fb^{-1}	50 fb^{-1}	300 fb^{-1}
δC_9^μ	6.5σ	14.7σ	21.9σ
δC_{10}^μ	7.1σ	16.6σ	25.1σ
δC_{LL}^μ	7.5σ	17.7σ	26.6σ

For all three scenarios, NP significance will be larger than 6σ already with 18 fb^{-1}!

Projections

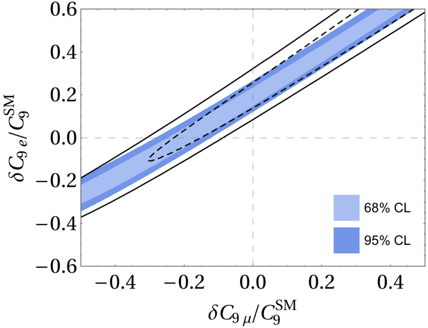
With $B_s \to \mu^+\mu^-$ and $R_{K^{(*)}}$ only

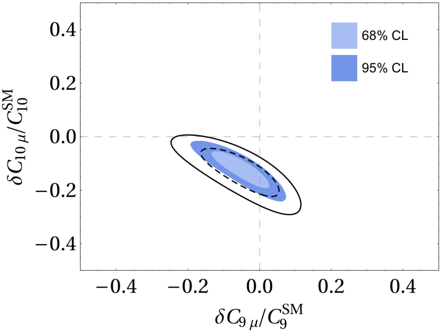


Current data

Projections

With $B_s \to \mu^+\mu^-$ and $R_{K^{(*)}}$ only

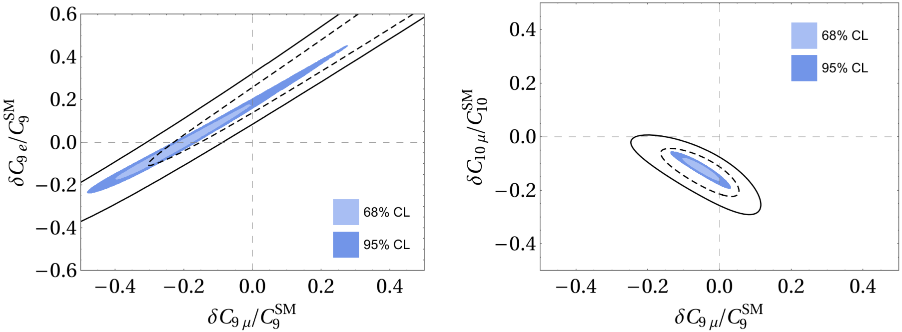




Projections for 18 fb^{-1}

Projections

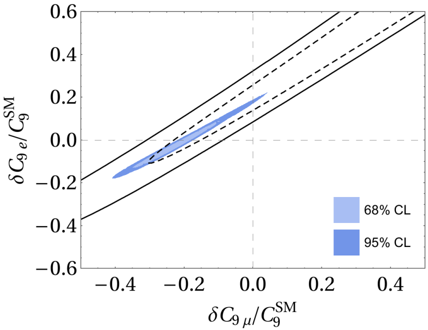
With $B_s \to \mu^+\mu^-$ and $R_{K^{(*)}}$ only

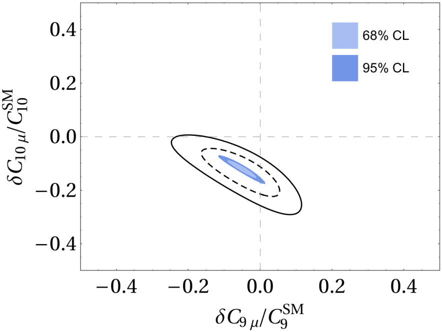


Projections for 50 fb^{-1}

Projections

With $B_s \to \mu^+\mu^-$ and $R_{K^{(*)}}$ only





Projections for 300 fb^{-1}

Predictions for other ratios

Predictions for various μ/e ratios

Assuming the central values of the Wilson coefficients remain the same

	Predictions assuming 50 fb^{-1} luminosity					
Obs.	C_9^μ	C_9^e	C_{10}^μ	C_{10}^e	C_{LL}^μ	C_{LL}^e
$R_{F_L}^{[1.1,6.0]}$	$[0.922, 0.932]$	$[0.941, 0.944]$	$[0.995, 0.998]$	$[0.996, 0.997]$	$[0.961, 0.964]$	$[1.006, 1.010]$
$R_{A_{FB}}^{[1.1,6.0]}$	$[4.791, 5.520]$	$[-0.416, -0.358]$	$[0.938, 0.939]$	$[0.963, 0.970]$	$[2.822, 3.089]$	$[0.279, 0.307]$
$R_{S_3}^{[1.1,6.0]}$	$[0.922, 0.931]$	$[0.914, 0.922]$	$[0.832, 0.852]$	$[0.858, 0.870]$	$[0.853, 0.870]$	$[1.027, 1.032]$
$R_{S_5}^{[1.1,6.0]}$	$[0.453, 0.543]$	$[0.723, 0.742]$	$[1.014, 1.014]$	$[1.040, 1.048]$	$[0.773, 0.801]$	$[1.298, 1.361]$
$R_{F_L}^{[15,19]}$	$[0.998, 0.999]$	$[0.998, 0.998]$	$[0.998, 0.998]$	$[0.998, 0.998]$	$[0.998, 0.998]$	$[0.998, 0.998]$
$R_{A_{FB}}^{[15,19]}$	$[0.929, 0.944]$	$[0.988, 0.989]$	$[1.009, 1.010]$	$[1.036, 1.042]$	$[0.996, 0.996]$	$[1.023, 1.028]$
$R_{S_3}^{[15,19]}$	$[0.998, 0.998]$	$[0.998, 0.998]$	$[0.999, 0.999]$	$[0.999, 0.999]$	$[0.999, 0.999]$	$[0.998, 0.998]$
$R_{S_5}^{[15,19]}$	$[0.929, 0.944]$	$[0.988, 0.989]$	$[1.009, 1.010]$	$[1.036, 1.042]$	$[0.996, 0.996]$	$[1.023, 1.028]$
$R_{K^*}^{[15,19]}$	$[0.825, 0.847]$	$[0.815, 0.835]$	$[0.828, 0.846]$	$[0.799, 0.820]$	$[0.804, 0.825]$	$[1.093, 1.107]$
$R_{K}^{[15,19]}$	$[0.823, 0.847]$	$[0.819, 0.838]$	$[0.854, 0.870]$	$[0.825, 0.844]$	$[0.820, 0.839]$	$[1.098, 1.113]$
$R_{\phi}^{[1.1,6.0]}$	$[0.862, 0.879]$	$[0.841, 0.858]$	$[0.824, 0.843]$	$[0.795, 0.816]$	$[0.819, 0.839]$	$[1.070, 1.080]$
$R_{\phi}^{[15,19]}$	$[0.825, 0.847]$	$[0.815, 0.835]$	$[0.826, 0.845]$	$[0.797, 0.819]$	$[0.803, 0.824]$	$[1.093, 1.107]$

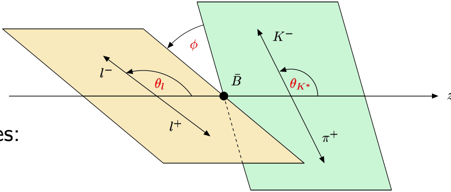
$\rightarrow$ Possible to discriminate between different new physics hypotheses!

Conclusion

- The latest LHCb measurements still show persistent tensions with the SM predictions in $b \to s\ell\ell$ transitions
- With the updated data the hierarchy of preferred NP scenarios remains the same with increased significance
- Fit to clean observables and the rest of $b \to s\ell\ell$ observables point to compatible NP scenarios
- Assuming the central values of the current fits, with already 18 fb^{-1} significances above 6σ can be reached with only clean observables
- The LHCb upgrade will have enough precision to distinguish between NP scenarios

Backup

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:

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_{K^*}\, d\phi} = \frac{9}{32\pi} J(q^2, \theta_\ell, \theta_{K^*}, \phi)$$

$J(q^2, \theta_\ell, \theta_{K^*}, \phi) = \sum_i J_i(q^2)\, f_i(\theta_\ell, \theta_{K^*}, \phi)$

$\searrow$ angular coefficients J_{1-9}

$\searrow$ 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

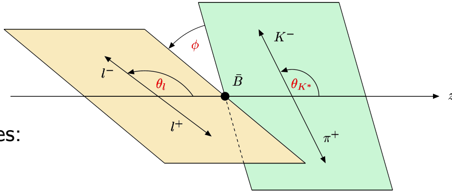
Main operators:

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

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

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:

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_{K^*}\, d\phi} = \frac{9}{32\pi} J(q^2, \theta_\ell, \theta_{K^*}, \phi)$$

$J(q^2, \theta_\ell, \theta_{K^*}, \phi) = \sum_i J_i(q^2)\, f_i(\theta_\ell, \theta_{K^*}, \phi)$

$\searrow$ angular coefficients J_{1-9}

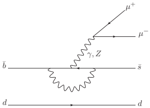
$\searrow$ functions of the spin amplitudes A_0, $A_\parallel$, $A_\perp$, A_t, and A_S

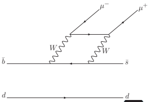
Spin amplitudes: functions of Wilson coefficients and form factors

Main operators:

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

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





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:

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

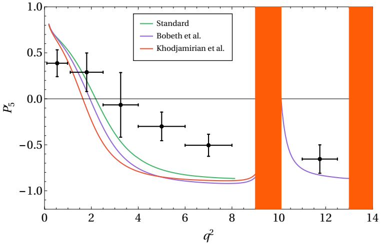
W. Altmannshofer et al., JHEP 0901 (2009) 019

Estimates of hadronic effects

Various methods for hadronic effects

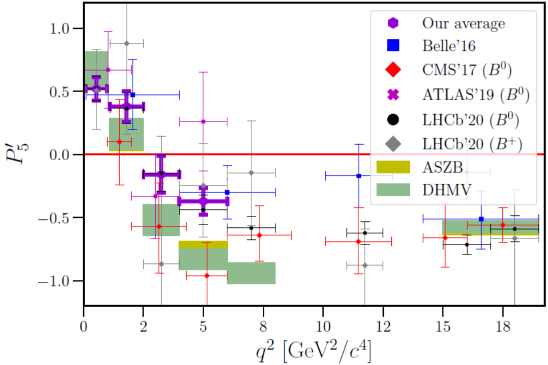
$$\frac{e^2}{q^2}\epsilon_\mu L_V^\mu \left[Y(q^2)\tilde{V}_\lambda + \text{LO in } \mathcal{O}\left(\frac{\Lambda}{m_b}, \frac{\Lambda}{E_{K^*}}\right) + h_\lambda(q^2) \right]$$

	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



Recent revisit of Khodjamirian et al. calculation (N. Gubernari, D. van Dyk, J. Virto, JHEP 02 (2021) 088):
soft-gluon effect is two orders of magnitude smaller than the previous calculation!

Current picture



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