Global flavour fits to rare B decay observables

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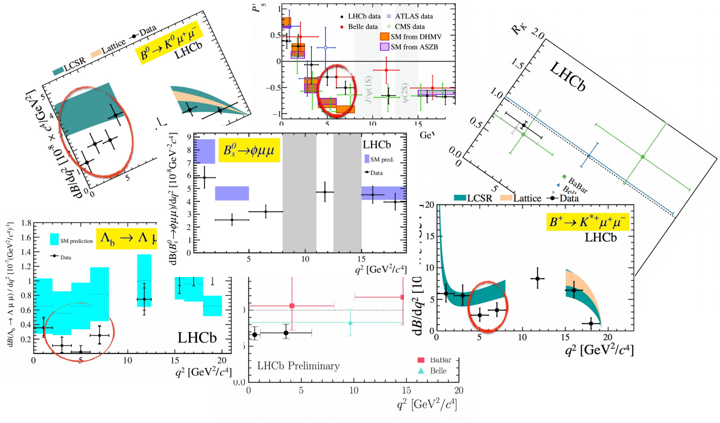
Thanks to T. Hurth, S. Neshatpour and Y. Monceaux

Measurements

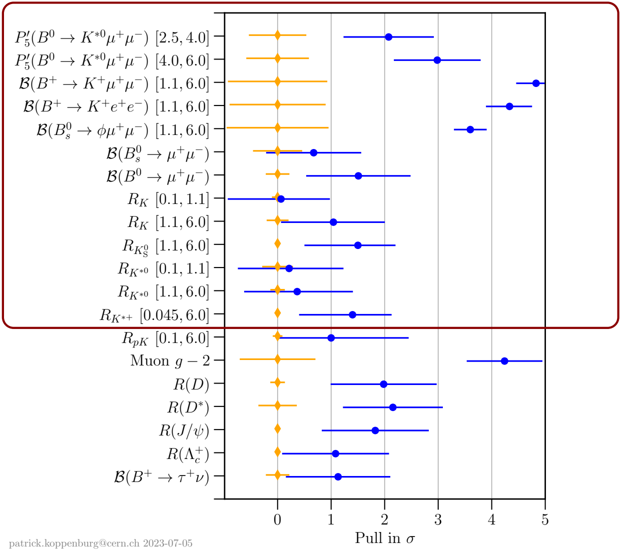
Several deviations from the SM predictions in $b \to s$ measurements with muons in the final state

Measurements by LHCb, and also ATLAS, CMS and Belle

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



Summary of anomalies



Rare decays

Tension in the angular observables

$B^0 \to K^{*0}\mu^+\mu^-$ angular observables, in particular P_5' / S_5

- 2013 (1 fb^{-1}): disagreement with the SM for P_2 and P_5' (PRL 111, 191801 (2013))
- March 2015 (3 fb^{-1}): confirmation of the deviations (LHCb-CONF-2015-002)
- Dec. 2015: 2 analysis methods, both show the deviations (JHEP 1602, 104 (2016))

3.7σ deviation in the 3rd bin

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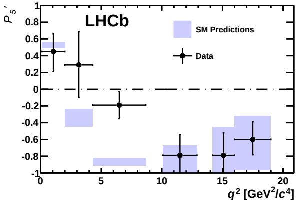

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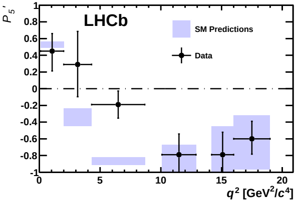

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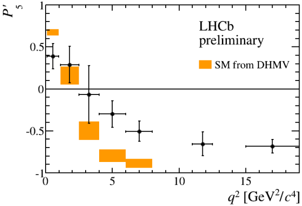

2.9σ in the 4th and 5th bins (3.7σ combined)

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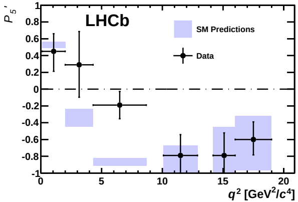

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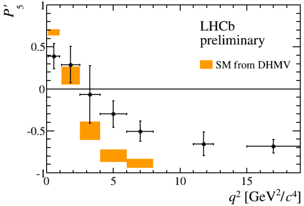

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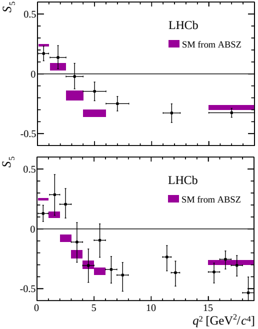

3.4σ combined fit (likelihood)

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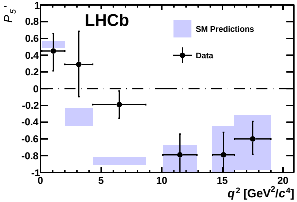

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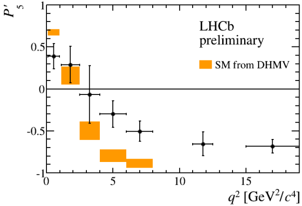

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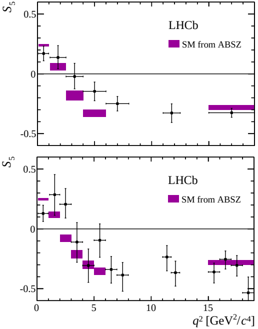

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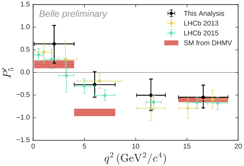
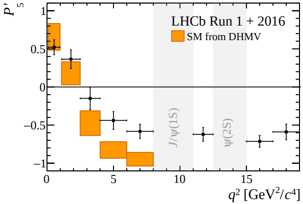
Belle supports LHCb (arXiv:1604.04042) tension at 2.1σ



$P'_5(B^0 \to K^{*0}\mu^+\mu^-)$: 2020 LHCb update with 4.7 fb^{-1}: $\sim 2.9\sigma$ local tension



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

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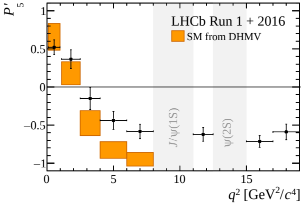

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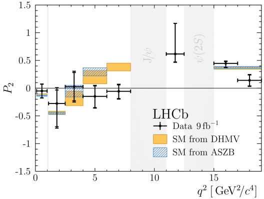
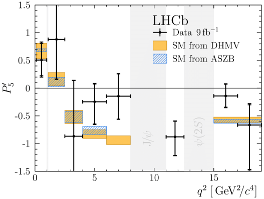
First measurement of $B^+ \to K^{*+}\mu^+\mu^-$ angular observables

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!

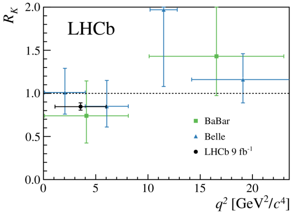
Lepton flavour universality in $B^+ \to K^+\ell^+\ell^-$

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

- SM prediction very accurate: $R_K^{\rm SM} = 1.0006 \pm 0.0004$
- 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



Nature Phys. 18 (2022) 3, 277

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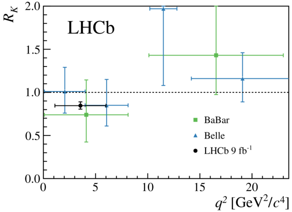


Nature Phys. 18 (2022) 3, 277

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

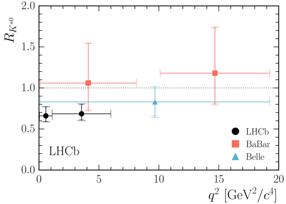
$$R_{K^*} = BR(B^0 \to K^{*0}\mu^+\mu^-)/BR(B^0 \to K^{*0}e^+e^-)$$

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

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

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

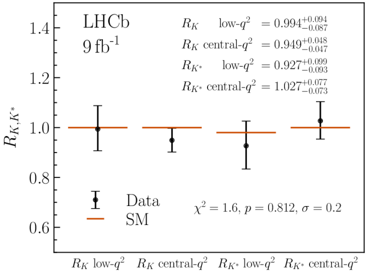
- **2.2-2.5σ** tension in each bin



JHEP 08 (2017) 055

December 2022 update

- LHCb measurement from Dec 2022 using 9 fb^{-1}
- New modelling of residual backgrounds due to misidentified hadronic decays
- Results fully compatible with the SM



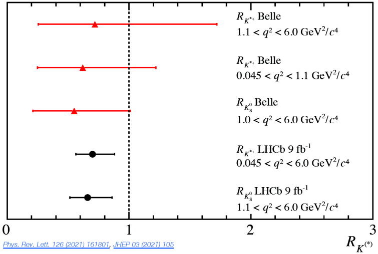
LHCb, arXiv:2212.09152, arXiv:2212.09153

Two other LFU measurements (October 2021) with 9 fb^{-1}:

$B^+ \to K^{*+}\ell^+\ell^-$ and $B^0 \to K^0_S\,\ell^+\ell^-$

$R_{K^{*+}} = 0.70^{+0.18}_{-0.13}(stat)^{+0.03}_{-0.04}(syst)$ and $R_{K^0_S} = 0.66^{+0.20}_{-0.15}(stat)^{+0.02}_{-0.04}(syst)$

Phys.Rev.Lett. 128 (2022) 19, 191802



More measurements to come:

$B^0_s \to \phi\ell^+\ell^-$, $B \to \pi\ell^+\ell^-$, $B \to K\pi^+\pi^-\ell^+\ell^-$,...

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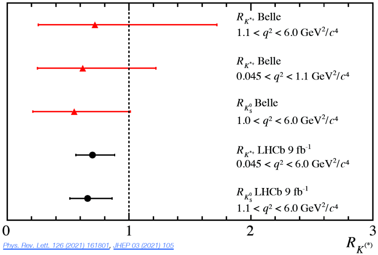


More measurements to come:

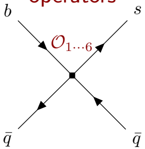
$$B^0_s \to \phi\ell^+\ell^-,\ B \to \pi\ell^+\ell^-,\ B \to K\pi^+\pi^-\ell^+\ell^-, \ldots$$

Effective field theory

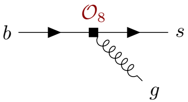
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \Big(\sum_{i=1\cdots 10,S,P} \big(C_i(\mu)\mathcal{O}_i(\mu) + C'_i(\mu)\mathcal{O}'_i(\mu)\big)\Big)$$

Operator set for $b \to s$ transitions:

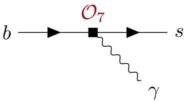
4-quark operators



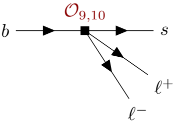
chromomagnetic dipole operator



electromagnetic dipole operator



semileptonic operators



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

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

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

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

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

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

+ the chirality flipped counter-parts of the above operators, $\mathcal{O}'_i$

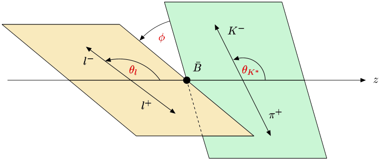
Wilson coefficients:

The Wilson coefficients are calculated perturbatively and are process independent.
SM contributions known to NNLL **(Bobeth, Misiak, Urban '99; Misiak, Steinhauser '04, Gorbahn, Haisch '04; Gorbahn, Haisch, Misiak '05; Czakon, Haisch, Misiak '06,...)**

$$C_7 \sim -0.3 \qquad C_9 \sim 4.2 \qquad C_{10} \sim -4.2$$

$B \to K^*(\to K^+\pi^-)\mu^+\mu^-$ Angular distributions

Angular behavior of K^+ and π^- $\to$ additional information on the helicity of K^*



Differential decay distribution:

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

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

↘ angular coefficients J_{1-9}

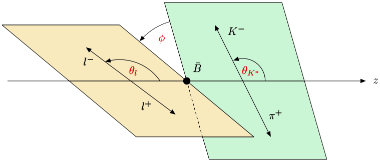
↘ functions of the spin amplitudes A_0, $A_\parallel$, $A_\perp$, A_t, and A_S

Spin amplitudes: functions of Wilson coefficients and form factors

Main operators:

$$\mathcal{O}_9 = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell), \quad \mathcal{O}_{10} = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\gamma_5 \ell)$$
$$\mathcal{O}_S = \frac{e^2}{16\pi^2}(\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\,\ell), \quad \mathcal{O}_P = \frac{e^2}{16\pi^2}(\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\gamma_5 \ell)$$

$B \to K^*(\to K^+\pi^-)\mu^+\mu^-$ Angular distributions



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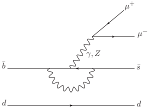
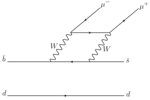


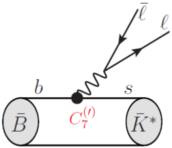


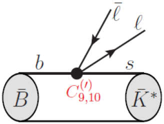
Effective Hamiltonian for $b \to s\ell^+\ell^-$ transitions: $\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm had} + \mathcal{H}_{\rm eff}^{\rm sl}$

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:

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

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

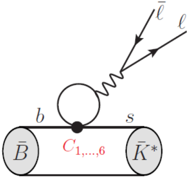
$$H_P = i\,N'\Big\{\frac{2\,m_\ell \hat{m}_b}{q^2}(C_{10} - C_{10}')\Big(1 + \frac{m_s}{m_b}\Big)\tilde{S}(q^2)\Big\}$$

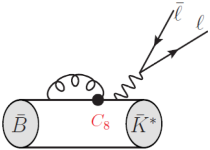
Effective Hamiltonian for $b \to s\ell^+\ell^-$ transitions: $\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm had} + \mathcal{H}_{\rm eff}^{\rm sl}$

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

$$\mathcal{H}_{\rm eff}^{\rm had} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \Big[\sum_{i=1...6} C_i(\mu) O_i(\mu) + C_8(\mu) O_8(\mu) \Big]$$

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





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

Helicity amplitudes:

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

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Issue of the hadronic power corrections

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:

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

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

In general "naïve" factorization not applicable

Helicity amplitudes:

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

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

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Issue of the hadronic power corrections

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:

$$\mathcal{H}_{\rm eff}^{\rm had} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \Big[\sum_{i=1...6} C_i(\mu)O_i(\mu) + C_8(\mu)O_8(\mu) \Big]$$

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

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

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

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Relevant operators:

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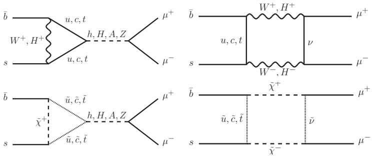

$$\mathrm{BR}(B_s \to \mu^+\mu^-) = \frac{G_F^2\alpha^2}{64\pi^3} f_{B_s}^2 \tau_{B_s} m_{B_s}^3 |V_{tb}V_{ts}^*|^2 \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}} \times \left\{ \left(1 - \frac{4m_\mu^2}{m_{B_s}^2}\right) \left|C_S - C_S'\right|^2 + \left|(C_P - C_P') + 2\,(C_{10} - C_{10}')\frac{m_\mu}{m_{B_s}}\right|^2 \right\}$$

Largest contributions in SM from a Z penguin top loop and a W box diagram

Main source of uncertainty:

- f_{B_s} : $\sim 1.5\%$
- CKM : $\sim 2.5\%$
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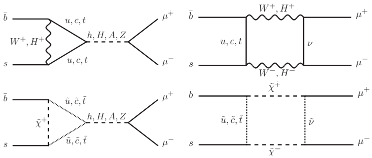

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LHCb, March 2021 (PRL 128, 4, 041801, 2022)

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T. Hurth, FM, D. Martinez Santos, S. Neshatpour, 2210.07221

SM prediction:

Using the latest FLAG combination: $f_{B_s} = 0.2303(13)$ GeV

SM prediction: $\mathrm{BR}(B_s \to \mu^+\mu^-) = (3.61 \pm 0.17) \times 10^{-9}$

SuperIso v4.1
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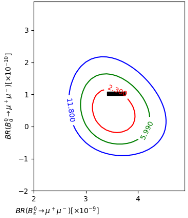

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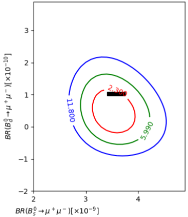

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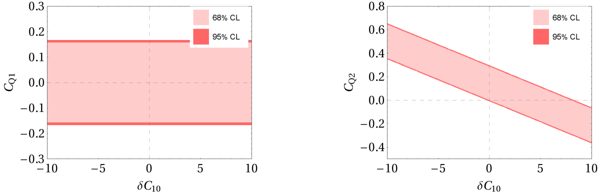

A. Arbey, T. Hurth, FM, S. Neshatpour, Phys.Rev.D 98 (2018) 9, 095027

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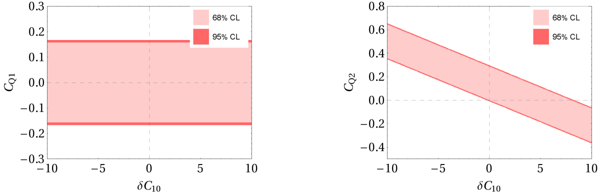
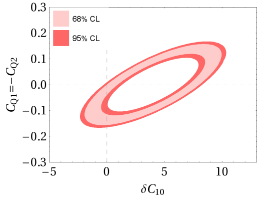


Even if $C_S = -C_P$, allowing for small variations of $C_{S,P}$ alleviates the constraints from $B_s \to \mu^+\mu^-$ on C_{10}



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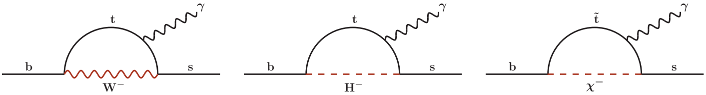
Inclusive branching ratio of $B \to X_s\gamma$

Contributing loops:



Main operator: $\mathcal{O}_7$
but higher order contributions from $\mathcal{O}_1$, ..., $\mathcal{O}_8$

- Standard OPE for inclusive decays
- Very precise theory prediction (at NNLO)

$$\mathrm{BR}(\bar{B} \to X_s\gamma)_{E_\gamma > E_0} = \mathrm{BR}(\bar{B} \to X_c e\bar{\nu}) \left|\frac{V_{ts}^* V_{tb}}{V_{cb}}\right| \frac{6\alpha_{em}}{\pi C}\left[P(E_0) + N(E_0)\right]$$

$P(E_0)$ ↓ pert $\sim 96\%$; $N(E_0)$ ↓ non-pert $\sim 4\%$

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Experimental value (HFAG 2022): $\mathrm{BR}(\bar{B} \to X_s\gamma) = (3.49 \pm 0.19) \times 10^{-4}$
With the full BELLE-II dataset, a $\pm 2.6\%$ uncertainty in the world average for $\mathrm{BR}(\bar{B} \to X_s\gamma)_{\mathrm{exp}}$ is expected.

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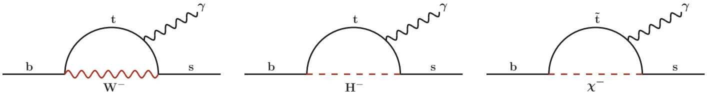

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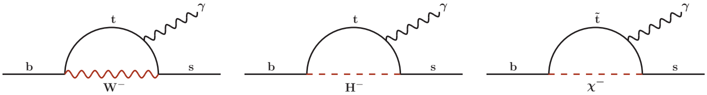

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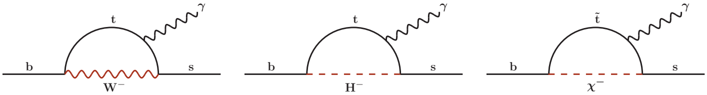

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Global fits

IF the deviations are from New Physics...

Many observables → **Global fits** of the available data

Relevant $\mathcal{O}$perators:

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

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

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

→ Scans over the values of δC_i

→ Calculation of flavour observables

→ Comparison with experimental results

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Theoretical uncertainties and correlations

- Monte Carlo analysis
- 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%, $b_k \sim 2.5 a_k$
Low recoil: $b_k = 0$

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

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.

183 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
- $\mathrm{BR}(B \to K^0\mu^+\mu^-)$
- $B \to K^+\mu^+\mu^-$: BR, F_H
- $B \to K^*e^+e^-$: BR, F_L, A_T^2, A_T^{Re}
- $B \to K^{*0}\mu^+\mu^-$: 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

Comparison of one-operator NP fits:

T. Hurth, FM, D. Martinez Santos, S. Neshatpour, PLB 824 (2022) 136838, updated with the latest results

All observables 2022 ($\chi^2_{\rm SM} = 253.3$)			
	b.f. value	$\chi^2_{\rm min}$	$\rm Pull_{SM}$
δC_9	-0.93 ± 0.13	218.4	5.9σ
δC_9^e	0.82 ± 0.19	232.3	4.6σ
δC_9^μ	-0.90 ± 0.11	197.7	7.5σ
δC_{10}	0.27 ± 0.17	250.5	1.7σ
δC_{10}^e	-0.78 ± 0.18	230.4	4.8σ
δC_{10}^μ	0.54 ± 0.12	231.5	4.7σ
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$\delta C^\ell_{\rm LL}$ basis corresponds to $\delta C^\ell_9 = -\delta C^\ell_{10}$.

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$\delta C_{\rm LL}^\mu$	-0.46 ± 0.07	208.2	6.7σ

All observables **2023** ($\chi^2_{\rm SM} = 231.3$)			
	b.f. value	$\chi^2_{\rm min}$	${\rm Pull_{SM}}$
δC_9	-0.95 ± 0.13	193.6	6.1σ
δC_9^e	0.22 ± 0.16	229.4	1.4σ
δC_9^μ	-0.68 ± 0.12	202.3	5.4σ
δC_{10}	0.08 ± 0.16	231.1	0.4σ
δC_{10}^e	-0.18 ± 0.14	229.5	1.3σ
δC_{10}^μ	0.14 ± 0.10	229.5	1.3σ
$\delta C_{\rm LL}^e$	0.10 ± 0.08	229.4	1.7σ
$\delta C_{\rm LL}^\mu$	-0.22 ± 0.06	219.6	3.4σ

$\delta C^\ell_{\rm LL}$ basis corresponds to $\delta C^\ell_9 = -\delta C^\ell_{10}$.

12-D fits

Set: real C_7, C_8, C_9, C_{10}, C_S, C_P + primed coefficients, 12 degrees of freedom

All observables with $\chi^2_{\rm SM} = 231.3$			
July 2023 ($\chi^2_{\rm min} = 187.7$; ${\rm Pull}_{\rm SM} = 4.3\sigma$)			
δC_7 0.06 ± 0.03		δC_8 -0.70 ± 0.40	
$\delta C_7'$ -0.01 ± 0.01		$\delta C_8'$ -0.40 ± 1.00	
δC_9 -1.14 ± 0.20	$\delta C_9'$ 0.04 ± 0.30	δC_{10} 0.20 ± 0.21	$\delta C_{10}'$ -0.03 ± 0.18
C_{Q_1} -0.28 ± 0.15	C_{Q_1}' -0.16 ± 0.15	C_{Q_2} 0.01 ± 0.03	C_{Q_2}' -0.03 ± 0.06

- Many parameters are weakly constrained at the moment
- The global tension is at the level of 4.3σ (assuming 10% uncertainty for the power corrections)

Set: real $C_7, C_8, C_9, C_{10}, C_S, C_P$ + primed coefficients, 12 degrees of freedom

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July 2023 ($\chi^2_{\rm min} = 187.7$; $\mathrm{Pull}_{\rm SM} = 4.3\sigma$)			
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0.06 ± 0.03		-0.70 ± 0.40	
$\delta C_7'$		$\delta C_8'$	
-0.01 ± 0.01		-0.40 ± 1.00	
δC_9	$\delta C_9'$	δC_{10}	$\delta C_{10}'$
-1.14 ± 0.20	0.04 ± 0.30	0.20 ± 0.21	-0.03 ± 0.18
C_{Q_1}	C_{Q_1}'	C_{Q_2}	C_{Q_2}'
-0.28 ± 0.15	-0.16 ± 0.15	0.01 ± 0.03	-0.03 ± 0.06

- Many parameters are weakly constrained at the moment
- The global tension is at the level of 4.3σ (assuming 10% uncertainty for the power corrections)

Pull$_{\mathrm{SM}}$ of $1, 2, 4, 6$ and 12 dimensional fit:

Set of WC	param.	χ^2_{min}	Pull$_{\mathrm{SM}}$	Improvement
SM	0	231.3	–	–
C_9	1	193.6	6.1σ	6.1σ
C_9, C_{10}	2	193.6	5.8σ	0.0σ
C_7, C_8, C_9, C_{10}	4	190.2	5.6σ	1.3σ
All non-primed WC	6	189.3	5.2σ	0.5σ
All WC (incl. primed)	12	187.7	4.3σ	0.1σ

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

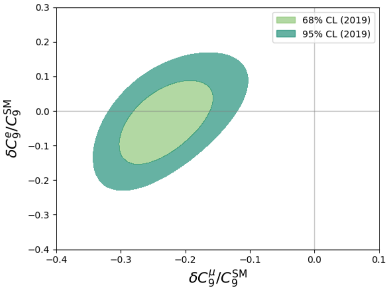
The last row also includes the chirality-flipped counterparts of the Wilson coefficients.

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

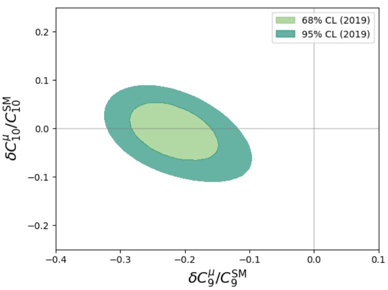
Fit results for two operators

2D fits to all available data:

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



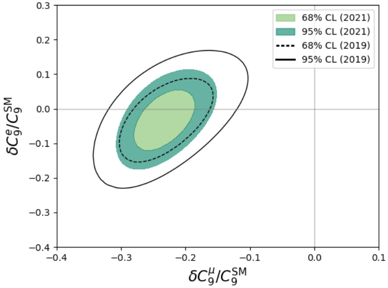
$(C_9^\mu - C_{10}^\mu)$



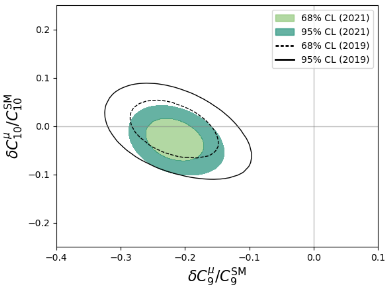
2019: Run I results

2D fits to all available data:

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



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



2019: Run I results

2021: (partial) Run II updates, mainly for $B \to K^* \mu^+ \mu^-$, R_K and $B_s \to \mu^+ \mu^-$ (LHCb)

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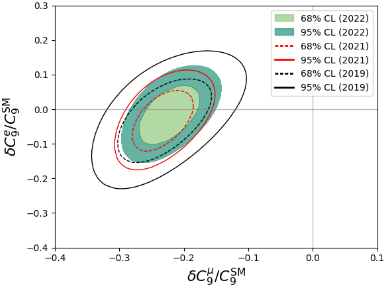
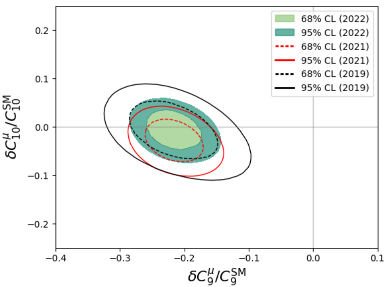


$(C_9^\mu - C_{10}^\mu)$



2019: Run I results

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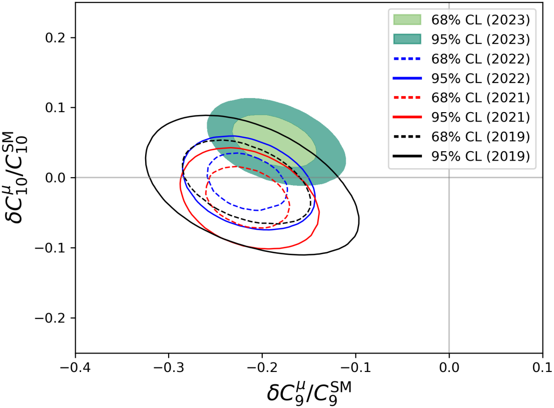
2022: (partial) Run II updates, mainly for $B_s \to \mu^+\mu^-$ (CMS), $R_{K^{*+}}$, $R_{K_S^0}$ and $B_s \to \phi\mu^+\mu^-$

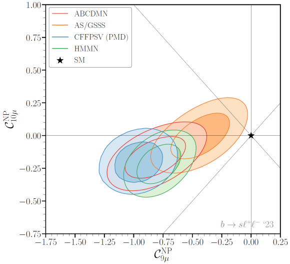
Fit results

Current situation



Comparison between the groups

One dimensional fits:

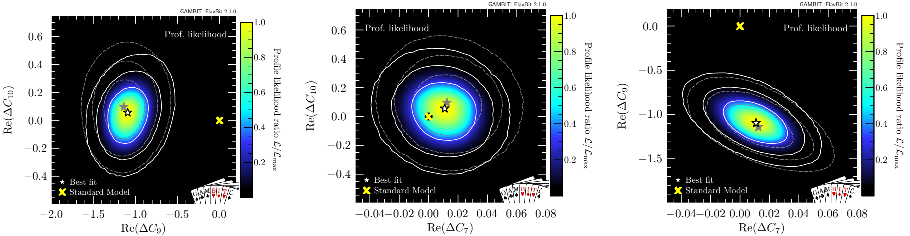


- ACDMN (M. Algueró, B. Capdevila, S. Descotes-Genon, J. Matias, M. Novoa-Brunet)
  Statistical framework: χ^2-fit, based on private code
- AS (W. Altmannshofer, P. Stangl)
  Statistical framework: χ^2-fit, based on public code `flavio`
- CFFPSV (M. Ciuchini, M. Fedele, E. Franco, A. Paul, L. Silvestrini, M. Valli)
  Statistical framework: Bayesian MCMC fit, based on public code `HEPfit`
- HMMN (T. Hurth, F. Mahmoudi, D. Martínez-Santos, S. Neshatpour)
  Statistical framework: χ^2-fit, based on public code `SuperIso`

See also similar fits by other groups:
Geng et al., arXiv:2103.12738, Alok et al., arXiv:1903.09617, Datta et al., arXiv:1903.10086, Kowalska et al., arXiv:1903.10932, D'Amico et al., arXiv:1704.05438, Hiller et al., arXiv:1704.05444, ...

2D fits to angular observables and branching ratios (No LFU ratios):

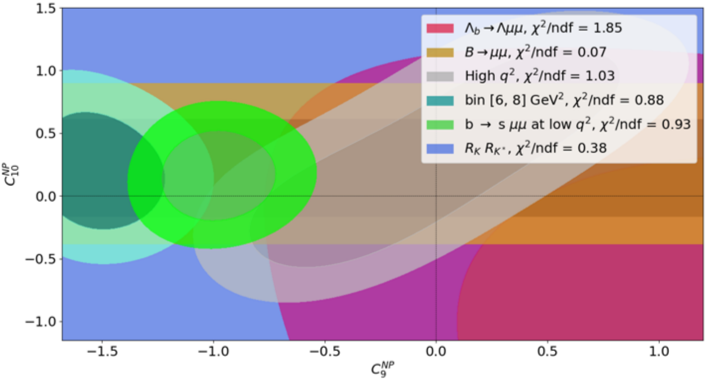
with the assumption of 10% power corrections



GAMBIT, J. Bhom et al., Eur.Phys.J.C 81 (2021) 12, 1076

- Contour lines: 1, 2 and 3σ confidence regions.
- SM prediction: yellow cross.
- Grey contours: when the theory covariance is approximated by its value in the SM, across the entire parameter space.

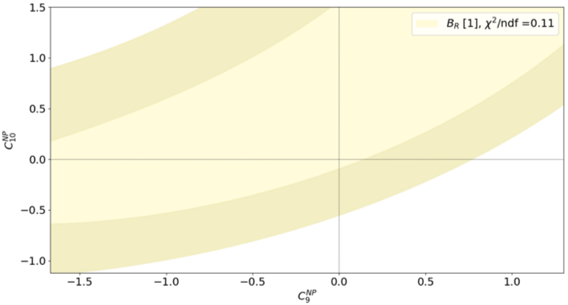
Current situation



Main theoretical uncertainties:

- Local Form Factors
- Non-local Form Factors

Fit to $B \to K^* \mu\mu$ branching ratios at low q^2



[1] 1503.05534: Bharucha, Straub and Zwicky
[2] 1811.00983: Gubernari, Kokulu and van Dyk

Large sensitivity to local form factors
Significant impacts on the fits!

See also N. Gubernari, M. Reboud, D. van Dyk, J. Virto, arXiv:2305.06301

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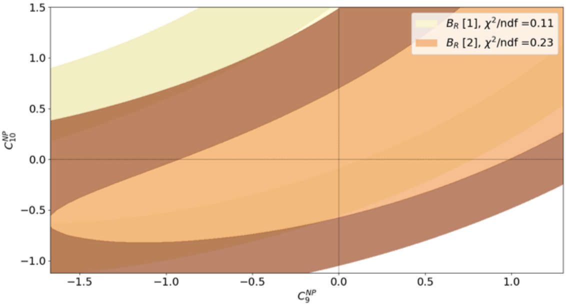

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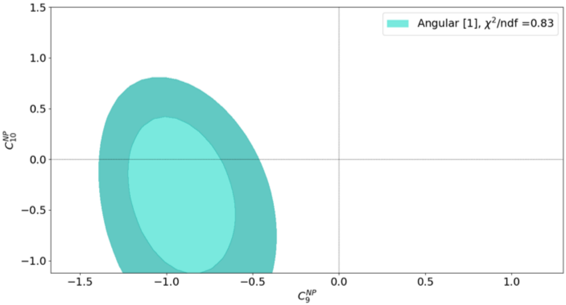

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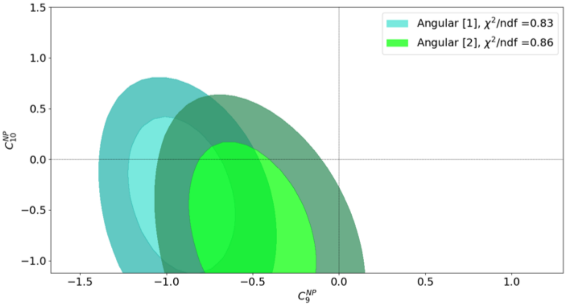

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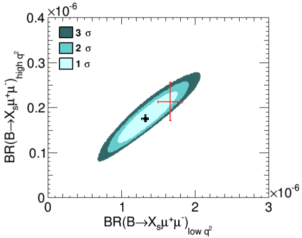
At Belle-II, for inclusive $b \to s\ell\ell$:



T. Hurth, FM, JHEP 1404 (2014) 097

T. Hurth, FM, S. Neshatpour, JHEP 1412 (2014) 053

Predictions based on our model-independent analysis

black cross: future measurements at Belle-II assuming the best fit solution

red cross: SM predictions

$\rightarrow$ Belle-II will check the NP interpretation with theoretically clean modes

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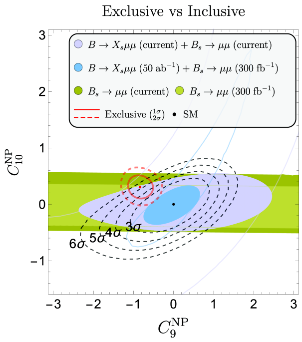

T. Hurth talk at FPCP 2023

→ Belle-II will check the NP interpretation with theoretically clean modes

Conclusion

- Reduction of the significance of the most preferred NP scenarios
- C_9 continues to be the Wilson coeffcient which includes most of the NP effects
- LFUV components are mostly suppressed
- High significances for scenarios with universal NP in C_9
- Some tensions in the inner structure of the fit:
  - LFU ratios are SM-like
  - $B \to K^{(*)}\mu\mu$ observables and in particular branching ratio of $B \to K\mu\mu$ continue to deviate with high significance

New Physics or Not New Physics?

- More work is needed to assess the hadronic uncertainties
- The measurement of the electron modes will be very important
- Cross-check with other ratios, and also inclusive modes will be very useful
- Interplay with the charged current mode and $b \to s\tau\tau$ can also be interesting

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Backup

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:

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

Comparison between the groups

- Different experimental inputs, e.g.
  - $q^2 \in [6, 8]$ GeV^2 data (ABCDMN, CFFPSV, HMMN)
  - High-q^2 data (AS / GSSS, ABCDMN, HMMN)
  - Radiative decays (ABCDMN, CFFPSV, HMMN)
  - $\Lambda_b \to \Lambda\mu^+\mu^-$ (AS / GSSS, HMMN)
- Different form factor inputs
  - Low-q^2: form factors from LCSR, reduced with heavy-quark & large-energy symmetries + (uncorrelated) power corrections. High-q^2: lattice form factors ($B \to V\ell\ell$ ABCDMN)
  - Full q^2 region: form factors from HPQCD lattice fit across all q^2, with full correlations ($B \to P\ell\ell$ ABCDMN)
  - Full q^2 region: form factors from combined LCSR + lattice fit, with full correlations (AS / GSSS, HMMN)
  - Low q^2 region: form factors from combined LCSR + lattice fit, with full correlations (CFFPSV)
- Different assumptions about non-local matrix elements
  - Order of magnitude estimates based on theory calculations from continuum methods, with different parameterisations (ABCDMN, AS / GSSS, HMMN)
  - Direct fit to data in each scenario, relying on continuum methods only for $q^2 \leq 1$ GeV^2 while allowing them to freely grow for larger q^2 (CFFPSV)
- Different statistical frameworks

20-D fits

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

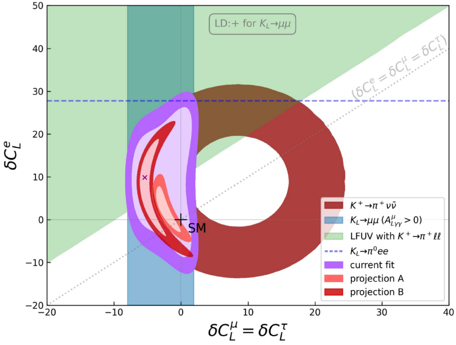
All observables with $\chi^2_{\rm SM} = 231.3$			
July 2023 ($\chi^2_{\rm min} = 184.6$; ${\rm Pull_{SM}} = 3.4(3.5)\sigma$)			
δC_7		δC_8	
0.06 ± 0.03		-0.70 ± 0.40	
$\delta C_7'$		$\delta C_8'$	
-0.01 ± 0.01		-0.60 ± 0.90	
δC_9^μ	δC_9^e	δC_{10}^μ	δC_{10}^e
-1.16 ± 0.18	-2.00 ± 0.80	0.21 ± 0.21	1.20 ± 2.2
$\delta C_9'^\mu$	$\delta C_9'^e$	$\delta C_{10}'^\mu$	$\delta C_{10}'^e$
0.05 ± 0.31	-2.60 ± 1.40	-0.02 ± 0.19	-1.90 ± 1.9
$C_{Q_1}^\mu$	$C_{Q_1}^e$	$C_{Q_2}^\mu$	$C_{Q_2}^e$
-0.25 ± 0.14	-0.30 ± 0.40	-0.04 ± 0.02	1.40 ± 0.7
$C_{Q_1}'^\mu$	$C_{Q_1}'^e$	$C_{Q_2}'^\mu$	$C_{Q_2}'^e$
-0.13 ± 0.13	-0.25 ± 0.30	-0.09 ± 0.02	1.30 ± 0.7

- Many parameters are weakly constrained at the moment
- The global tension is at the level of 3.5σ (assuming 10% uncertainty for the power corrections)

From B physics to kaons

It is natural to expect that the NP effects in B-meson decays would also impact operators contributing to kaon decays. [1705.10729, 1802.00786, 2005.03734, 2206.14748]...

Global picture: [2206.14748]



Relevant operators:

$$O_9^\ell = (\bar{s}\gamma_\mu P_L d)\,(\bar{\ell}\gamma^\mu \ell)$$

$$O_{10}^\ell = (\bar{s}\gamma_\mu P_L d)\,(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

$$O_L^\ell = (\bar{s}\gamma_\mu P_L d)\,(\bar{\nu}_\ell\, \gamma^\mu (1-\gamma_5)\,\nu_\ell)$$

Projection A: Assuming SM as the central values

Projection B: Assuming the best-fit values from the current fits as the central values

→ **Effective probe of NP in the muon sector!**

Need to achieve a better accuracy in the theoretical computation of $K_L \to \mu\mu$

G. D'Ambrosio, A. Iyer, FM, S. Neshatpour, JHEP 09 (2022) 148