Model independent analysis for B anomalies

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Lyon University & CERN

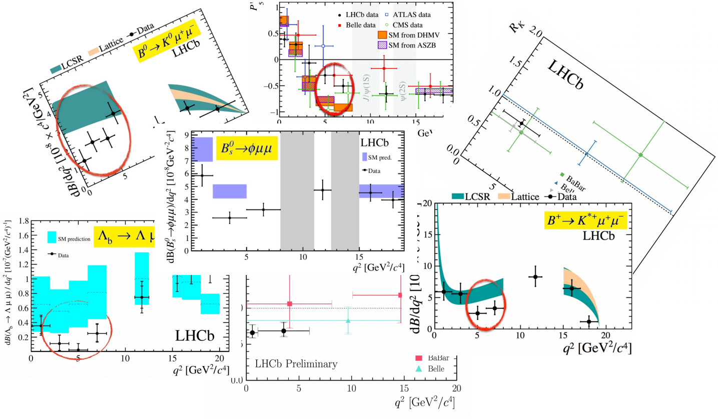
Thanks to T. Hurth, S. Neshatpour and D. Martinez Santos

Workshop on "Flavour Changing and Conserving Processes", Capri, 22-24 Sep. 2022

$b \to s\ell\ell$ measurements

Impressive effort in studying $b \to s\ell\ell$ transitions at LHCb, but also ATLAS, CMS and Belle, with the measurement of a large number of independent branching ratios and angular observables, ratios,...

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



Several small deviations from the SM predictions...

How to make sense of all the data?

Let's make something flavourful!

We are in Capri, so let's prepare Limonchello!

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Model-independent approach

$\downarrow$

gives us the ingredients
C_9, a bit of C_{10},...

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Simplified models

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Z', Lepto quarks, ...

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UV-complete theory

↓

The real model

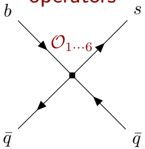
Theoretical framework

Effective field theory

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

Operator set for $b \to s$ transitions:

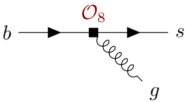
4-quark operators



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

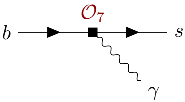
$\mathcal{O}_{3,4} \propto (\bar{s}\Gamma_\mu b)\sum_q(\bar{q}\Gamma^\mu q)$

chromomagnetic dipole operator



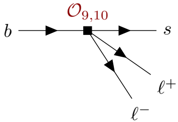
$\mathcal{O}_8 \propto (\bar{s}\sigma^{\mu\nu} T^a P_R) G^a_{\mu\nu}$

electromagnetic dipole operator



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

semileptonic operators



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

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

+ 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,...)**

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

Rare decays

Many observables, with different sensitivities to different Wilson coefficients.

decay	obs	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$
$B \to X_s\gamma$	BR	X		
$B \to K^*\gamma$	BR, $\mathrm{A_I}$	X		
$B \to X_s\ell^+\ell^-$	dBR/dq^2, $A_{\rm FB}$	X	X	X
$B \to K\ell^+\ell^-$	dBR/dq^2	X	X	X
$B \to K^*\ell^+\ell^-$	dBR/dq^2, angular obs.	X	X	X
$B_s \to \phi\ell^+\ell^-$	dBR/dq^2, angular obs.	X	X	X
$B_s \to \mu^+\mu^-$	BR			X

The only reason C_9 is the main player to explain the anomalies is that C_7 and C_{10} are severely constrained!

$$\delta\langle P_5'\rangle_{[4.3,8.68]} \simeq -0.52\,\delta C_7 \quad -0.03\,\delta C_8 \quad -0.08\,\delta C_9 \quad -0.03\,\delta C_{10}$$

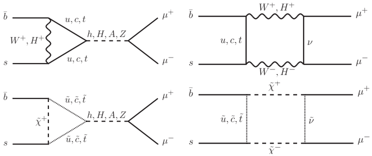
$\mathrm{BR}(B_s \to \mu^+\mu^-)$

Relevant operators:

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

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

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



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

Largest contributions in SM from a Z penguin top loop (75%) and a W box diagram (24%)

Main source of uncertainty:

- f_{B_s} : $\sim 1.5\%$
- CKM : $\sim 2.5\%$
- Other (masses, α_s,...) : $\sim 1\%$

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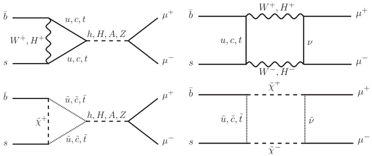

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$\mathrm{BR}(B_s \to \mu^+\mu^-)$

Using the latest FLAG combination: $f_{B_s} = 0.2303(13)$ GeV (arXiv:2111.09849)

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

SuperIso v4.1
Bobeth et al., Phys. Rev. Lett. 112 (2014) 101801, ...

Experimental measurement:

HFAG 2017 combination: $\mathrm{BR}(B_s \to \mu^+\mu^-) = (3.1 \pm 0.7) \times 10^{-9}$

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

$\mathrm{BR}(B_s \to \mu^+\mu^-)^{\mathrm{LHCb}} = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$

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$$\mathrm{BR}(B_s \to \mu^+\mu^-) = 3.52^{+0.32}_{-0.30} \times 10^{-9}$$

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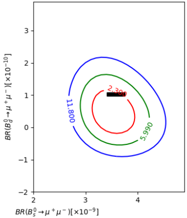

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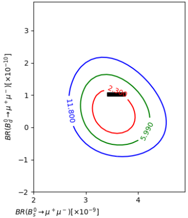

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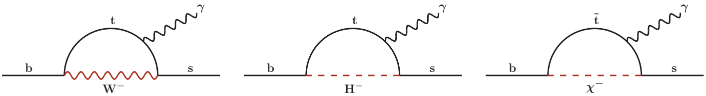
$B \to X_s\gamma$

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)

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

$P(E_0)$ ↓ pert ∼ 96%
$N(E_0)$ ↓ non-pert ∼ 4%

SM prediction: $\mathrm{BR}(\bar{B} \to X_s\gamma) = (3.34 \pm 0.22) \times 10^{-4}$

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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 ±2.6% uncertainty in the world average for $\mathrm{BR}(\bar{B} \to X_s\gamma)_{\mathrm{exp}}$ is expected.

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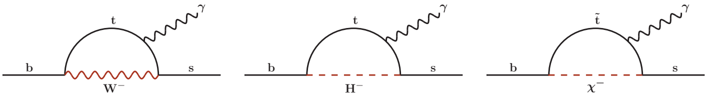

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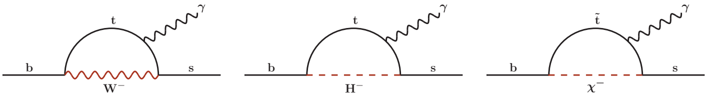

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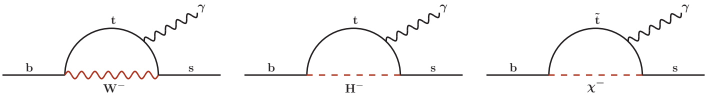

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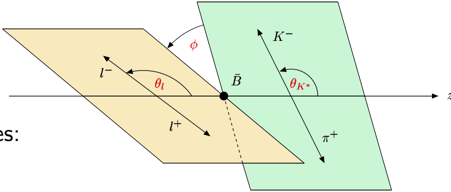
$B \to K^* \mu^+ \mu^-$

Angular distributions



The full angular distribution of the decay $\bar{B}^0 \to \bar{K}^{*0} \ell^+ \ell^-$ ($\bar{K}^{*0} \to K^- \pi^+$) is completely described by four independent kinematic variables: q^2 (dilepton invariant mass squared), θ_ℓ, θ_{K^*}, ϕ

Differential decay distribution:

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

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

↘ angular coefficients J_{1-9}

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

Spin amplitudes: functions of Wilson coefficients and form factors

Main operators:

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

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

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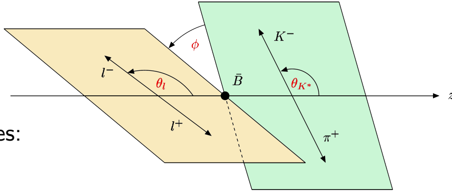

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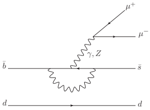

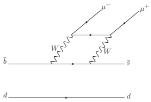

$B \to K^* \mu^+ \mu^-$ – Angular observables

Optimised observables: form factor uncertainties cancel at leading order

$$\langle P_1 \rangle_{\rm bin} = \frac{1}{2} \frac{\int_{\rm bin} dq^2 [J_3 + \bar{J}_3]}{\int_{\rm bin} dq^2 [J_{2s} + \bar{J}_{2s}]} \qquad \langle P_2 \rangle_{\rm bin} = \frac{1}{8} \frac{\int_{\rm bin} dq^2 [J_{6s} + \bar{J}_{6s}]}{\int_{\rm bin} dq^2 [J_{2s} + \bar{J}_{2s}]}$$

$$\langle P'_4 \rangle_{\rm bin} = \frac{1}{\mathcal{N}'_{\rm bin}} \int_{\rm bin} dq^2 [J_4 + \bar{J}_4] \qquad \langle P'_5 \rangle_{\rm bin} = \frac{1}{2\mathcal{N}'_{\rm bin}} \int_{\rm bin} dq^2 [J_5 + \bar{J}_5]$$

$$\langle P'_6 \rangle_{\rm bin} = \frac{-1}{2\mathcal{N}'_{\rm bin}} \int_{\rm bin} dq^2 [J_7 + \bar{J}_7] \qquad \langle P'_8 \rangle_{\rm bin} = \frac{-1}{\mathcal{N}'_{\rm bin}} \int_{\rm bin} dq^2 [J_8 + \bar{J}_8]$$

with

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

+ CP violating clean observables and other combinations

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

Or alternatively:

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

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)
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3.7σ deviation in the 3rd bin

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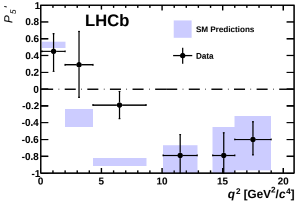

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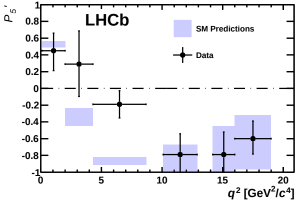

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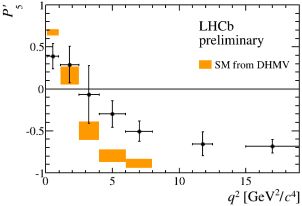

2.9σ in the 4th and 5th bins (3.7σ combined)

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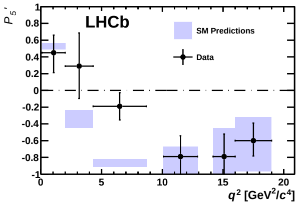

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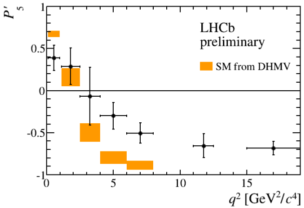

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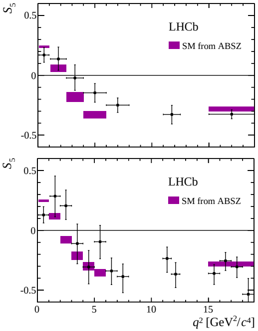

3.4σ combined fit (likelihood)

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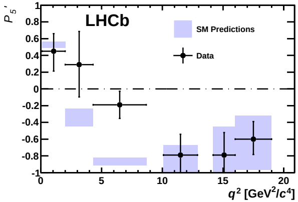

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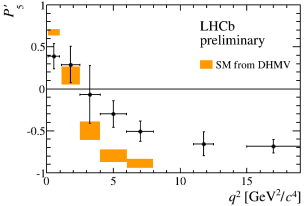

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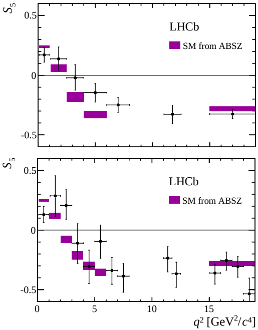

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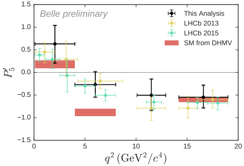
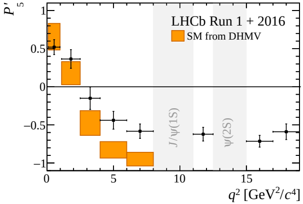
Belle supports LHCb (arXiv:1604.04042) tension at 2.1σ



Tension in the angular observables - 2020 updates

$P_5'(B^0 \to K^{*0}\mu^+\mu^-)$: 2020 LHCb update with 4.7 fb^{-1}: $\sim 2.9\sigma$ local tension



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

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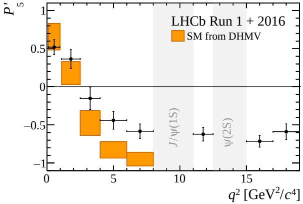
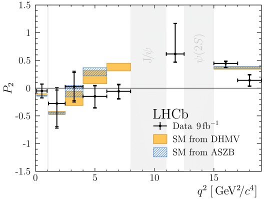
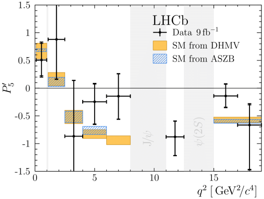


Phys. Rev. Lett. 125, 011802 (2020)

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!

Issue of the hadronic power corrections

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

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

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

Transversity amplitudes:

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

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

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

The significance of the anomalies depends on the assumptions made for the unknown power corrections!

This does not affect LFUV ratios, but does affect the combined fits!

Lepton flavour universality tests

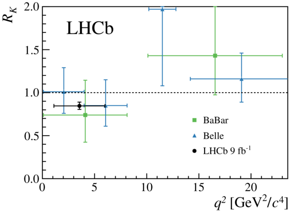
Lepton flavour universality in $B^+ \to K^+ \ell^+ \ell^-$

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

- 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}

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

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



Nature Phys. 18 (2022) 3, 277

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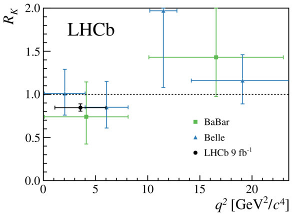


Nature Phys. 18 (2022) 3, 277

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

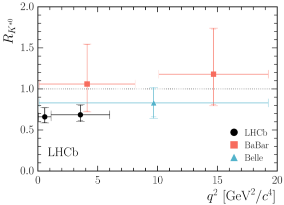
$$R_{K^*} = BR(B^0 \to K^{*0} \mu^+ \mu^-)/BR(B^0 \to K^{*0} e^+ e^-)$$

- 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

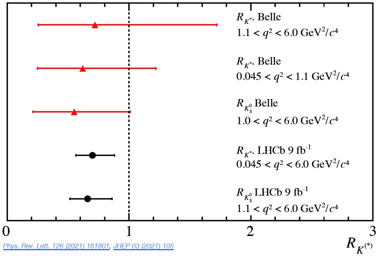
Lepton flavour universality tests

Two more recent 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



Phys. Rev. Lett. 126 (2021) 161801, JHEP 03 (2021) 105

More measurements to come:

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

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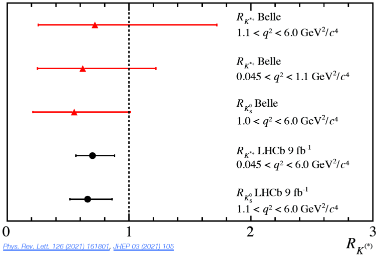

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Global fits

New Physics interpretation?

IF the deviations are from New Physics...

we need to find the Ingredients first!

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

Relevant $\mathcal{O}$perators:

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

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

→ Constraints on the Wilson coefficients C_i

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Theoretical uncertainties

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

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:

- $\text{BR}(B \to X_s \gamma)$
- $\text{BR}(B \to X_d \gamma)$
- $\text{BR}(B \to K^* \gamma)$
- $\Delta_0(B \to K^* \gamma)$
- $\text{BR}^{\text{low}}(B \to X_s \mu^+ \mu^-)$
- $\text{BR}^{\text{high}}(B \to X_s \mu^+ \mu^-)$
- $\text{BR}^{\text{low}}(B \to X_s e^+ e^-)$
- $\text{BR}^{\text{high}}(B \to X_s e^+ e^-)$
- $\text{BR}(B_s \to \mu^+ \mu^-)$
- $\text{BR}(B_s \to e^+ e^-)$
- $\text{BR}(B_d \to \mu^+ \mu^-)$
- R_K in the low q^2 bin
- R_{K^*} in 2 low q^2 bins
- $\text{BR}(B \to K^0 \mu^+ \mu^-)$
- $B \to K^+ \mu^+ \mu^-$: 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

Single operator fits

Comparison of one-operator NP fits:

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

Only $R_{K^{(*)}}, B_{s,d} \to \mu^+\mu^-$ ($\chi^2_{\rm SM} = 34.25$)			
	b.f. value	$\chi^2_{\rm min}$	$\mathrm{Pull}_{\rm SM}$
δC_9	-2.00 ± 5.00	30.5	0.4σ
δC_9^e	0.83 ± 0.21	10.8	4.4σ
δC_9^μ	-0.80 ± 0.21	11.8	4.3σ
δC_{10}	0.03 ± 0.20	30.6	0.1σ
δC_{10}^e	-0.81 ± 0.19	8.7	4.7σ
δC_{10}^μ	0.50 ± 0.14	16.2	3.8σ
$\delta C_{\rm LL}^e$	0.43 ± 0.11	9.7	4.6σ
$\delta C_{\rm LL}^\mu$	-0.33 ± 0.08	12.4	4.3σ

↓

clean

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

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clean

All observables except $R_{K^{(*)}}, B_{s,d} \to \mu^+\mu^-$ ($\chi^2_{\rm SM} = 221.8$)			
	b.f. value	$\chi^2_{\rm min}$	${\rm Pull}_{\rm SM}$
δC_9	-0.95 ± 0.13	185.1	6.1σ
δC_9^e	0.70 ± 0.60	220.5	1.1σ
δC_9^μ	-0.96 ± 0.13	182.8	6.2σ
δC_{10}	0.29 ± 0.21	219.8	1.4σ
δC_{10}^e	-0.60 ± 0.50	220.6	1.1σ
δC_{10}^μ	0.35 ± 0.20	218.7	1.8σ
$\delta C_{\rm LL}^e$	0.34 ± 0.29	220.6	1.1σ
$\delta C_{\rm LL}^\mu$	-0.64 ± 0.13	195.0	5.2σ

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

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

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All observables ($\chi^2_{\rm SM} = 253.3$)			
	b.f. value	$\chi^2_{\rm min}$	${\rm Pull}_{\rm SM}$
δC_9	-0.95 ± 0.13	215.8	6.1σ
δC_9^e	0.82 ± 0.19	232.4	4.6σ
δC_9^μ	-0.92 ± 0.11	195.2	7.6σ
δC_{10}	0.08 ± 0.16	253.2	0.5σ
δC_{10}^e	-0.77 ± 0.18	230.6	4.8σ
δC_{10}^μ	0.43 ± 0.12	238.9	3.8σ
$\delta C_{\rm LL}^e$	0.42 ± 0.10	231.4	4.7σ
$\delta C_{\rm LL}^\mu$	-0.43 ± 0.07	213.6	6.3σ

↓ clean

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

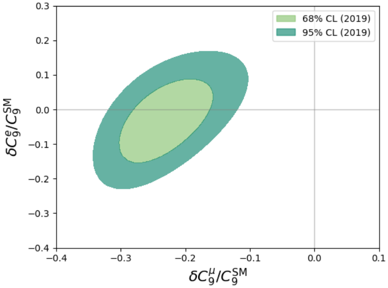
$\delta C_{\rm LL}^\ell$ basis corresponds to $\delta C_9^\ell = -\delta C_{10}^\ell$.

- 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

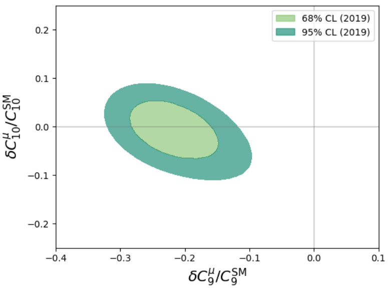
Fit results for two operators

2D fits to all available data:

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



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



2019: Run I results

Fit results for two operators

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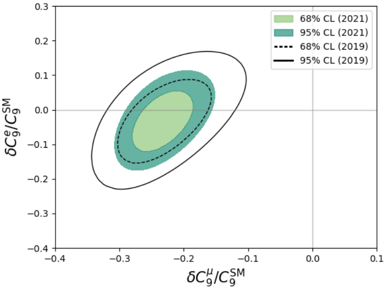
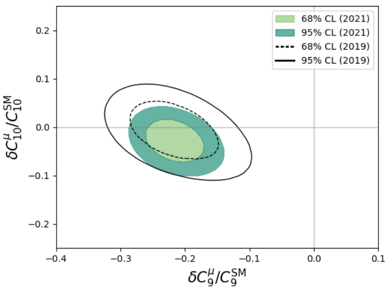


$(C_9^\mu - C_{10}^\mu)$



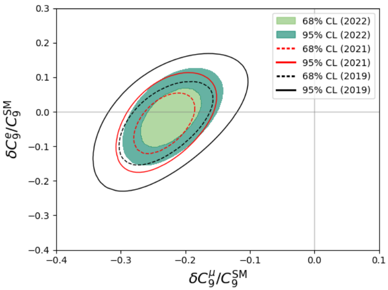
2019: Run I results

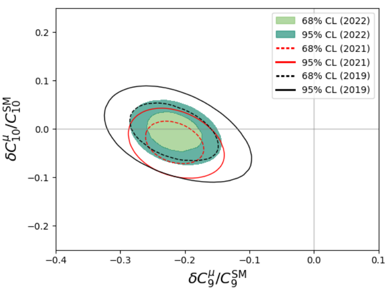
2021: (partial) Run II updates, mainly for $B \to K^* \mu^+\mu^-$, R_K and $B_s \to \mu^+\mu^-$ (LHCb)

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

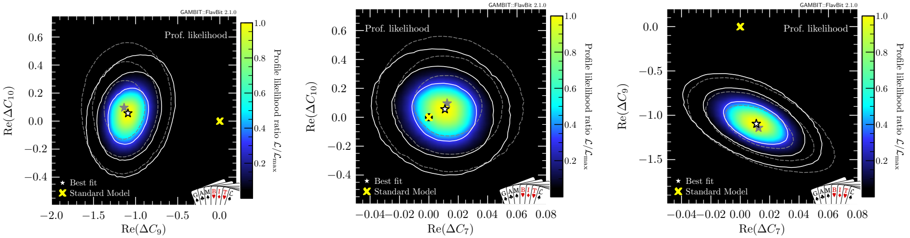
2021: (partial) Run II updates, mainly for $B \to K^* \mu^+\mu^-$, R_K and $B_s \to \mu^+\mu^-$ (LHCb)

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

Two operator fits

2D fits to angular observables and branching ratios (No LFUV 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.

Large negative contributions to C_9 are favoured

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 $\chi^2_{\rm SM} = 253.5$ $\chi^2_{\rm min} = 179.1$; $\mathrm{Pull}_{\rm SM} = 5.5\sigma$			
δC_7 0.06 ± 0.03		δC_8 -0.80 ± 0.40	
$\delta C_7'$ -0.01 ± 0.01		$\delta C_8'$ -0.30 ± 1.30	
δC_9^μ -1.14 ± 0.19	δC_9^e -6.50 ± 1.90	δC_{10}^μ 0.21 ± 0.20	δC_{10}^e 2.60 ± 3.1
$\delta C_9'^\mu$ 0.05 ± 0.32	$\delta C_9'^e$ 1.40 ± 2.30	$\delta C_{10}'^\mu$ -0.03 ± 0.19	$\delta C_{10}'^e$ 1.30 ± 3.2
$C_{Q_1}^\mu$ 0.04 ± 0.20	$C_{Q_1}^e$ -1.60 ± 1.70	$C_{Q_2}^\mu$ -0.15 ± 0.08	$C_{Q_2}^e$ -4.10 ± 0.9
$C_{Q_1}'^\mu$ -0.03 ± 0.20	$C_{Q_1}'^e$ -1.50 ± 2.10	$C_{Q_2}'^\mu$ -0.16 ± 0.08	$C_{Q_2}'^e$ -4.00 ± 1.2

- No real improvement in the fits when going beyond the C_9^μ case
- Many parameters are weakly constrained at the moment
- The global tension is at the level of 5.5σ (assuming 10% uncertainty for the power corrections)

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	$5.5\,(5.6)\sigma$	$0.2\,(0.3)\sigma$

T. Hurth, FM, D. Martinez Santos, S. Neshatpour, PLB 824 (2022) 136838

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).

Conclusion

→ Several deviations from the SM predictions in $b \to s\ell\ell$ transitions since 2013

→ We learned from model-independent analysis that $\sim 25\%$ reduction in C_9 can consistently explain the data

→ Possible to build concrete (simplified) NP models to accommodate this (see next talks)

How to interpret the anomalies?

- They cannot be explained by Statistical fluctuations
- They cannot be explained by experimental issues
- They cannot be explained by unknown pieces in the theoretical calculations
- They cannot be explained by underestimated theoretical uncertainties

Possible explanations:

- Combination of above!!
- New Physics

The next round of experimental results will hopefully give us the verdict!

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