Theoretical review of rare B decays

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Why flavour physics?

Flavour is at the heart of the standard model, with fundamental questions at stake!

- **CP violation:**

  The only CP violating parameter in the SM is the CKM phase. However, we know from baryogenesis that new sources of CP violation are needed.

- **The Standard Model flavour puzzle:**

  Why are the flavour parameters small and hierarchical?

- **The New Physics flavour puzzle:**

  If there is NP at the TeV scale, why are flavour changing neutral current (FCNC) so small?
  If NP has a generic flavour structure, it should contribute to FCNC processes

- **Flavour physics is sensitive to new physics at $\Lambda_{\rm NP} \gg E_{\rm experiments}$**

  Flavour physics can discover new physics or probe it before it is directly observed in experiments

$\rightarrow$ **Probing New Physics at the intensity frontier**

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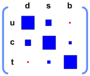

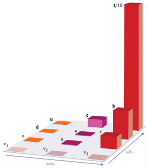

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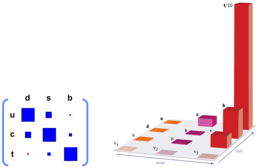

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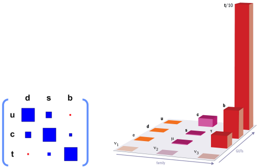

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Why rare B decays?

- Rare B decays are rare!
  They are allowed only at **loop level** in the SM → SM contributions are very small
- New Physics contributions can have similar magnitudes
- QCD corrections are known with high accuracy
- Promissing experimental situation
- Interesting interplay between B physics, collider and dark matter searches (not covered in this talk)
- Indirect hints for new physics: Flavour "anomalies"

  Deviations from the Standard Model predictions in $b \to s\ell\ell$ transitions

Focus of the talk, since there are so few these days and they are still among our best bets!

There are also anomalies in the **tree-level** charged current decays ($b \to c$):

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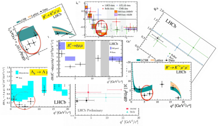

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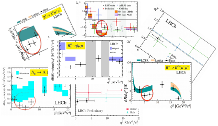

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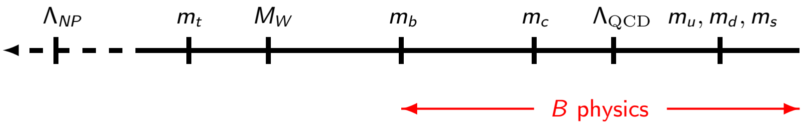
There are two problems due to the mixture of strong and weak interactions:

- Weak Lagrangian in terms of quarks, but hadronic final states
- Multi-scale problem M_W, m_b, $\Lambda_{\rm QCD}$, $m_{\rm light}$



B physics: scales of order m_b, or lower!

So why not integrate out heavier degrees of freedom (t, W, Z)?
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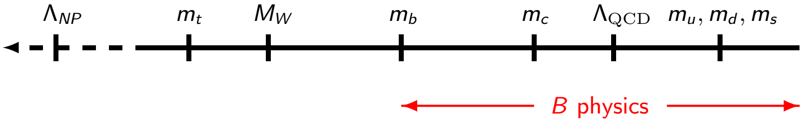

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(with still b, c, s, d, u, g and γ as dynamical particles)

Theoretical framework

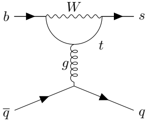
Effective field theory

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1\cdots10} \Big(C_i(\mu) \mathcal{O}_i(\mu) \Big)$$

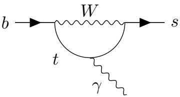
Separation between short distance (Wilson coefficients) and long distance (local operators) effects

Operator set for $b \to s$ transitions:

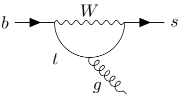
4-quark operators



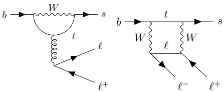
electromagnetic dipole operator



chromomagnetic dipole operator



semileptonic operators



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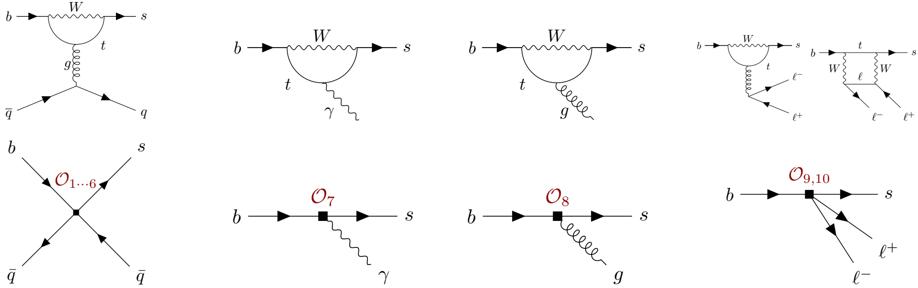

$\mathcal{O}_{1,2} \propto (\bar{s}\Gamma_\mu c)(\bar{c}\Gamma^\mu b)$

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

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

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

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

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

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

Wilson coefficients

The Wilson coefficients are calculated perturbatively and are process independent

Two main steps:

- matching between the effective and full theories → extraction of the $C_i^{eff}(\mu)$ at scale $\mu \sim M_W$

$$C_i^{eff}(\mu) = C_i^{(0)eff}(\mu) + \frac{\alpha_s(\mu)}{4\pi} C_i^{(1)eff}(\mu) + \cdots$$

- Evolving the $C_i^{eff}(\mu)$ to the scale relevant for B decays, $\mu \sim m_b$ using the RGE runnings.

SM contributions known to NNLL **(Bobeth, Misiak, Urban '99; Misiak, Steinhauser '04, Gorbahn, Haisch '04; Gorbahn, Haisch, Misiak '05; Czakon, Haisch, Misiak '06,...)**

$$C_7 = -0.294 \qquad C_9 = 4.20 \qquad C_{10} = -4.16$$

Hadronic quantities

To compute the amplitudes:

$$\mathcal{A}(A \to B) = \langle B|\mathcal{H}_{\rm eff}|A\rangle = \frac{G_F}{\sqrt{2}} \sum_i \lambda_i C_i(\mu) \langle B|\mathcal{O}_i|A\rangle(\mu)$$

$\langle B|\mathcal{O}_i|A\rangle$: hadronic matrix element

How to compute matrix elements?

$\rightarrow$ Model building, Lattice simulations, Light flavour symmetries, Heavy flavour symmetries, ...

$\rightarrow$ Describe hadronic matrix elements in terms of **hadronic quantities**

Two types of hadronic quantities:

- **Decay constants**: Probability amplitude of hadronising quark pair into a given hadron
- **Form factors**: Transition from a meson to another through flavour change

Once the Wilson coefficients and hadronic quantities calculated, the physical observables (branching fractions,...) can be calculated.

$b \to s$ transitions

Inclusive decays $B \to X_s\gamma$ and $B \to X_s\ell^+\ell^-$

- Precise theory calculations
- Heavy mass expansion
- Theoretical description of power corrections available $\to$ they can be calculated or estimated within the theoretical approach
- Require Belle-II for full exploitation (complete angular analysis)

Exclusive decays

- Leptonic: $B_s \to \mu^+\mu^-$
  $\to$ theory errors under control (decay constant with rather good precision)
- Semileptonic: $B \to K^*\ell^+\ell^-$, $B \to K\ell^+\ell^-$ and $B_s \to \phi\mu^+\mu^-$
  $\to$ many experimentally accessible observables

  $\to$ **issue of hadronic uncertainties in exclusive modes**

  no theoretical description of power corrections existing within the theoretical framework of QCD factorisation and SCET

Issue of the hadronic uncertainties

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:

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

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

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

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

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

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

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power corrections $\to$ **unknown**

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

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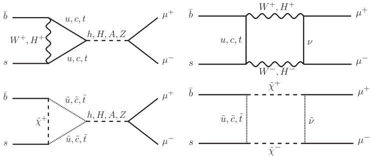
The assumptions on the power corrections can change the theoretical predictions for the branching ratios and angular observables!

Observables and Anomalies

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

Relevant operators:

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



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

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

SM prediction: $\mathrm{BR}(B_s \to \mu^+\mu^-) = (3.60 \pm 0.17) \times 10^{-9}$

SuperIso v4.1
M. Beneke, Ch. Bobeth, R. Szafron, JHEP 10 (2019) 232, ...

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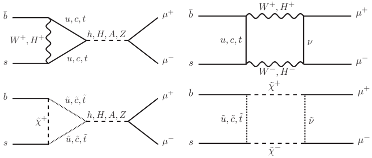

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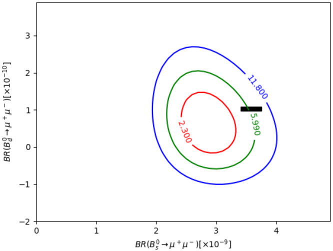
Combination of LHCb, ATLAS and CMS measurements:



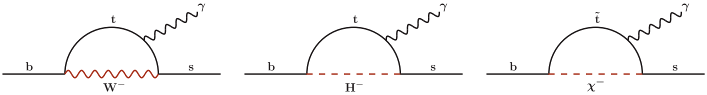
T. Hurth, FM, D. Martinez Santos, S. Neshatpour, PLB 824 (2022) 136838

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

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

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)

Experimental value (HFAG 2017): $\mathrm{BR}(\bar{B} \to X_s\gamma) = (3.32 \pm 0.15) \times 10^{-4}$

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

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M. Misiak et al., Phys. Rev. Lett. 98 (2007) 022002
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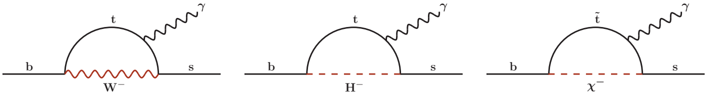

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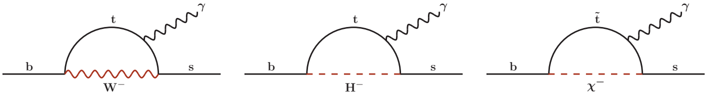

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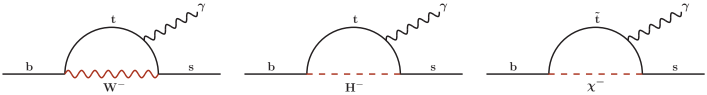

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$b \to s\ell\ell$ Observables

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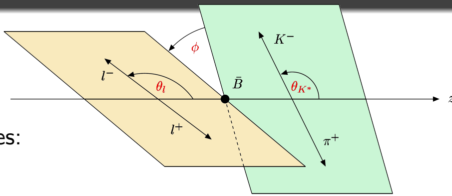
- **Branching fractions**:

$$\begin{array}{l} \mathrm{BR}(B \to K^*\mu^+\mu^-) \\ \mathrm{BR}(B \to K\mu^+\mu^-) \\ \mathrm{BR}(B_s \to \phi\mu^+\mu^-) \\ \mathrm{BR}(\Lambda_b \to \Lambda\mu^+\mu^-) \\ \ldots \end{array}$$

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



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

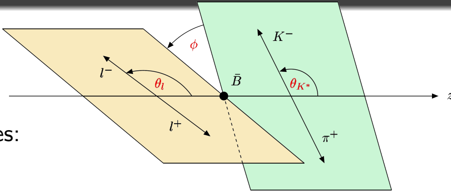
Spin amplitudes: functions of Wilson coefficients and form factors

Main operators:

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

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

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



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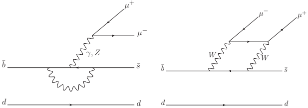
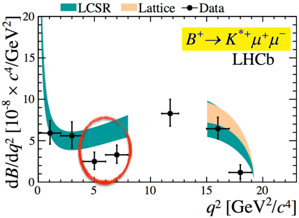


$b \to s\ell\ell$ Branching Ratios



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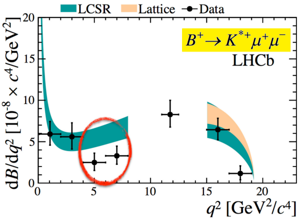
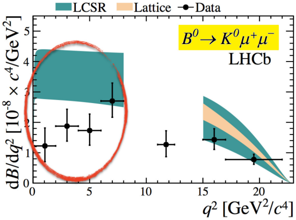
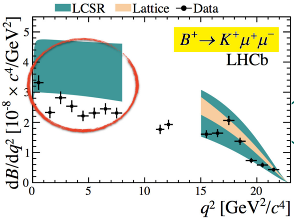
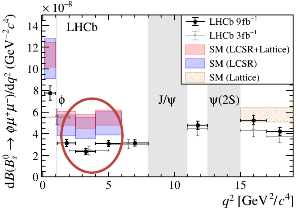


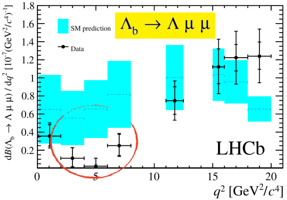




JHEP 06 (2014) 133



PRL 127 (2021) 151801



JHEP 06 (2015) 115

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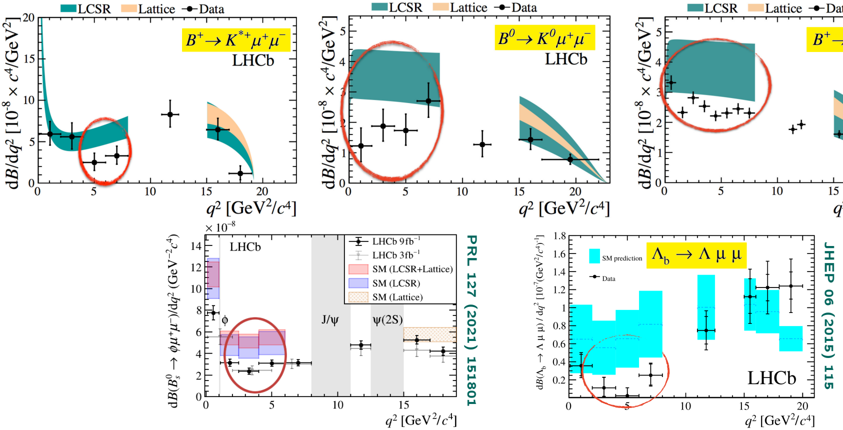

- consistent deviation pattern with the SM predictions
- significance of the deviations between ~ 2 and 3.5 σ
- general trend: EXP < SM in low q^2 regions
- ... but the branching ratios have very large theory uncertainties!

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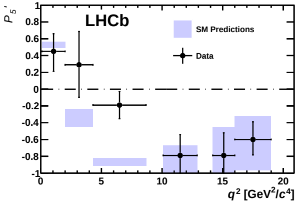

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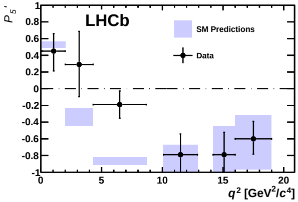

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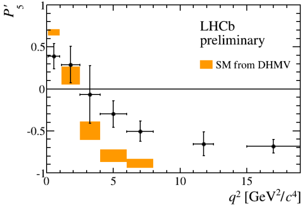

2.9σ in the 4th and 5th bins (3.7σ combined)

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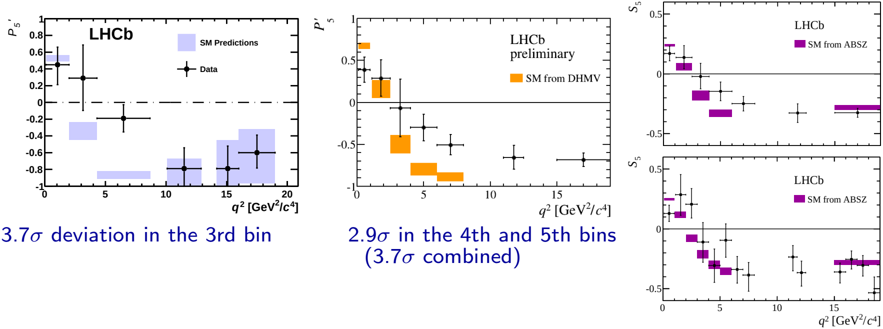

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3.4σ combined fit (likelihood)

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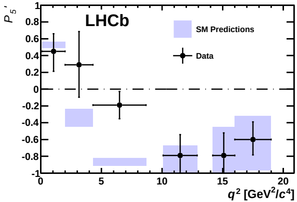

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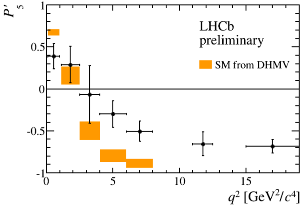

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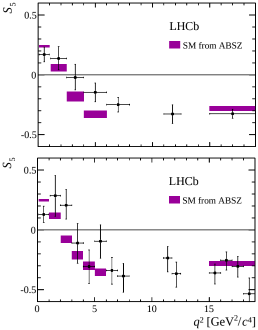
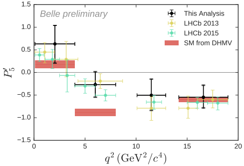


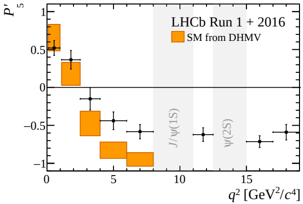
3.4σ combined fit (likelihood)

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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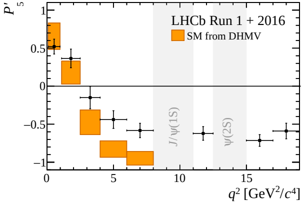
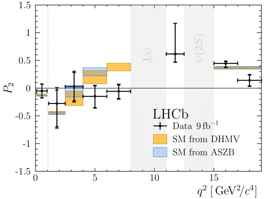
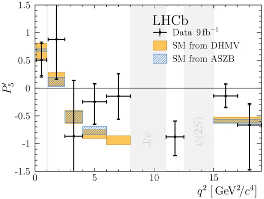


Phys. Rev. Lett. 125, 011802 (2020)

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!

Lepton flavour universality tests

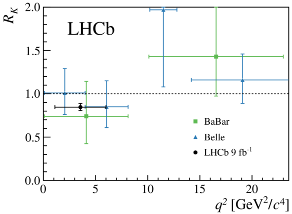
Lepton flavour universality in $B^+ \to K^+ \ell^+ \ell^-$

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

- 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}

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

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



Nature Phys. 18 (2022) 3, 277

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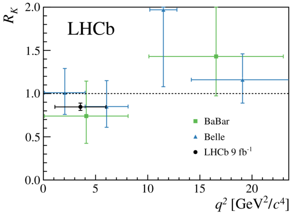


Nature Phys. 18 (2022) 3, 277

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

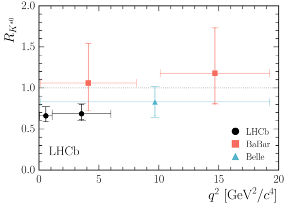
$$R_{K^*} = BR(B^0 \to K^{*0} \mu^+ \mu^-)/BR(B^0 \to K^{*0} e^+ e^-)$$

- 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

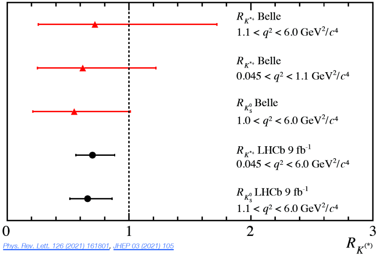
Lepton flavour universality tests

Two new 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:

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

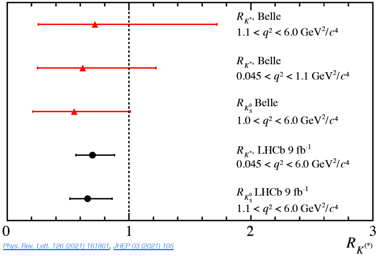
Lepton flavour universality tests

Two new 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

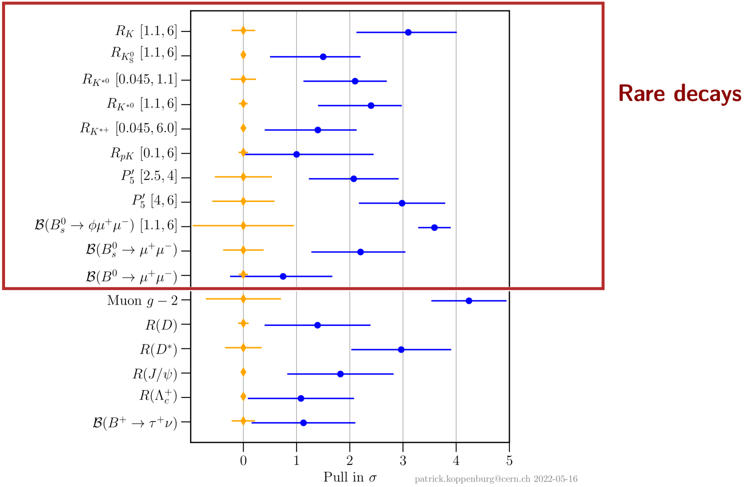


Phys. Rev. Lett. 126 (2021) 161801, JHEP 03 (2021) 105

More measurements to come:

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

Summary of anomalies



Sensitivity to Wilson coefficients

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_{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

C_9 is the main player to explain the anomalies because C_7 and C_{10} are severely constrained!

Global fits

What the data tell us?

Many observables → **Global fits**

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

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

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

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 (1411.3161, 1503.05534), including all the correlations
- Parameterisation of uncertainties from power corrections:

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

$|a_k|$ between 10 to 60%, $b_k \sim 2.5 a_k$
Low recoil: $b_k = 0$

⇒ Computation of a (theory + exp) correlation matrix

Global fits

Global fits of the observables obtained by minimisation of

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

$(\Sigma_{\rm th} + \Sigma_{\rm exp})^{-1}$ 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

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	34.1	0.4σ
δC_9^e	0.83 ± 0.21	14.5	4.4σ
δC_9^μ	-0.80 ± 0.21	15.4	4.3σ
δC_{10}	0.43 ± 0.24	30.6	1.9σ
δC_{10}^e	-0.81 ± 0.19	12.3	4.7σ
δC_{10}^μ	0.66 ± 0.15	10.3	4.9σ
$\delta C_{\rm LL}^e$	0.43 ± 0.11	13.3	4.6σ
$\delta C_{\rm LL}^\mu$	-0.39 ± 0.08	10.1	4.9σ

↓

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

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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	220.9	0.9σ
$\delta C_{\rm LL}^\mu$	-0.64 ± 0.13	195.0	5.2σ

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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	-0.93 ± 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
$\delta C_{\rm LL}^e$	0.42 ± 0.10	231.2	4.7σ
$\delta C_{\rm LL}^\mu$	-0.46 ± 0.07	208.2	6.7σ

$\downarrow$

$\downarrow$ $\downarrow$

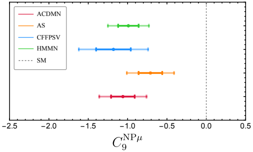
Dependent on the assumptions on the non-factorisable power corrections

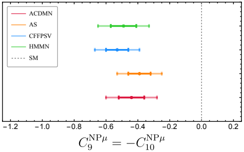
$\delta C^\ell_{\rm LL}$ basis corresponds to $\delta C^\ell_9 = -\delta C^\ell_{10}$.

- 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

Comparison between the groups

One dimensional fits:





ACDMN: M. Algueró, B. Capdevila, S. Descotes-Genon, J. Matias, M. Novoa-Brunet arXiv:2104.08921
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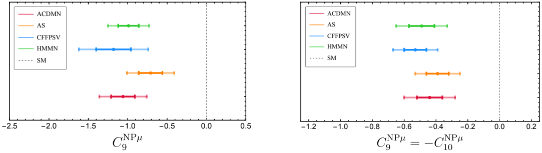

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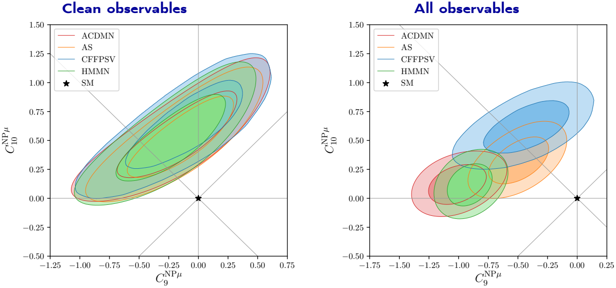

NP scenarios

New physics scenarios

Global fits: New physics is likely to appear in C_9:

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

It can also affect C_9' and C_{10} in a much lesser extent.

However, difficult to generate $\delta C_9 \sim -1$ at loop level...

$\rightarrow$ Need for tree level diagrams...

Mainstream scenarios:

- Z' bosons
- leptoquarks
- composite models

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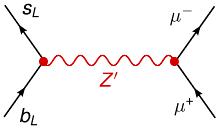
Mainstream scenarios

Z' obvious candidate to generate the O_9 operator:

- Flavour-changing couplings to left-handed quarks
- Vector-like couplings to leptons
- Flavour violation or non-universality in the lepton sector



Leptoquarks:

- t-channel diagrams
- Different possible representations, can be scalar (spin 0) or vector (spin 1)
- Cannot alter only C_9, but both C_9 and C_{10} $(= -C_9)$
- Cannot be lepton flavour non-universal and conserve lepton number simultaneously

Composite models:

- Neutral resonance ρ_μ coupling to the muons via composite elementary mixing
- requires some compositeness for the muons
- can allow for lepton flavour violating couplings
- constrained by the LEP Z-width measurements and $B_s - \bar{B}_s$ mixing

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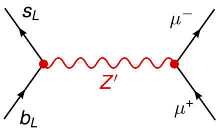

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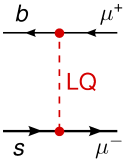

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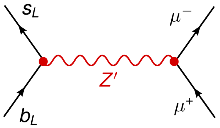

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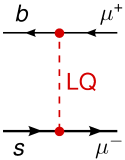

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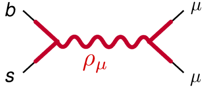
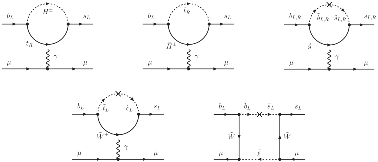


MSSM and C_9

Contributions to C_9 can come from Z and photon penguins, and box diagrams



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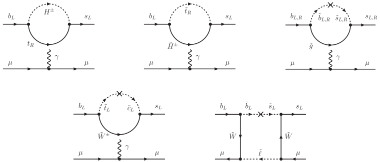
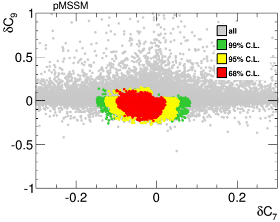


PMSSM:



FM, S. Neshatpour, J. Virto, Eur. Phys. J. C74 (2014) no.6, 2927

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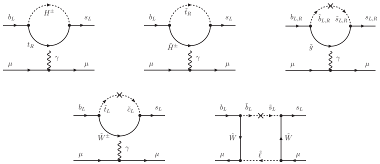
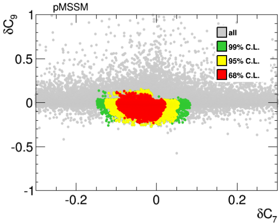
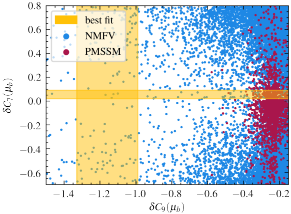


PMSSM:

PMSSM with non-minimal flavour violation:

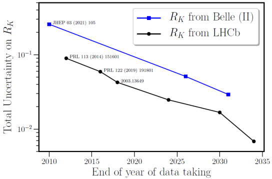


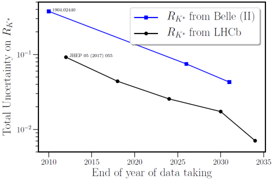


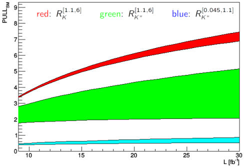
FM, S. Neshatpour, J. Virto, Eur. Phys. J. C74 (2014) no.6, 2927

M.A. Boussejra, FM, G. Uhlrich, arXiv:2201.04659

Future prospects







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

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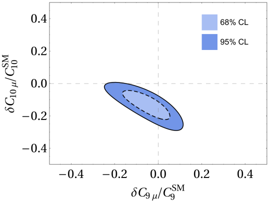
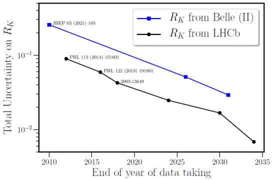
For all three scenarios, NP significance will be larger than 6σ already with 18 fb^{-1}!

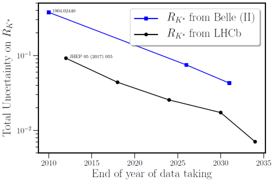


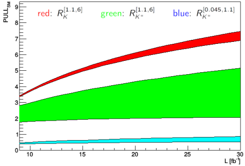
Current data

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

Future prospects







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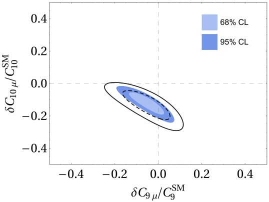

Projections for 18 fb^{-1}

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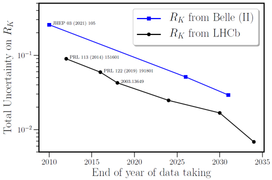
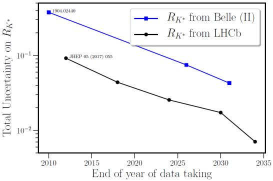
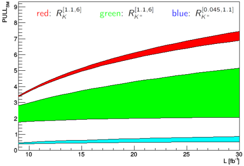
Future prospects



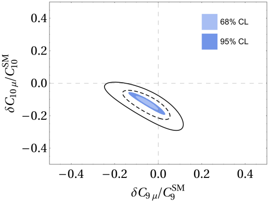




Predictions of $\mathrm{Pull}_{\mathrm{SM}}$ for the fit to δC_9^μ, δC_{10}^μ and δC_{LL}^μ:

$\mathrm{Pull}_{\mathrm{SM}}$ 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

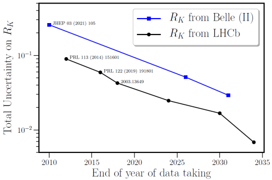
For all three scenarios, NP significance will be larger than 6σ already with 18 fb^{-1}!

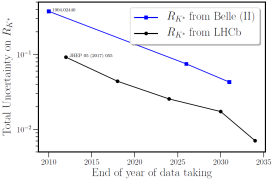


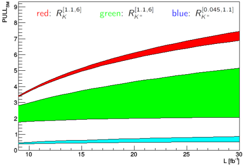
Projections for 50 fb^{-1}

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

Future prospects







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

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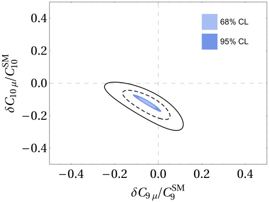
For all three scenarios, NP significance will be larger than 6σ already with 18 fb^{-1}!



Projections for 300 fb^{-1}

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

Concluding remarks

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

$\to$ growing with time both in **statistical significance** and in internal **consistency**

Could they be explained by:

- Statistical fluctuations alone?
- Experimental issues alone?
- Underestimated theoretical uncertainties alone?
- Unknown pieces in the theoretical calculations alone?

  - Combination of above?

  - New Physics option?

Concluding remarks

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

$\to$ growing with time both in **statistical significance** and in internal **consistency**

Could they be explained by:

- Statistical fluctuations alone?
- Experimental issues alone?
- Underestimated theoretical uncertainties alone?
- Unknown pieces in the theoretical calculations alone?

  - Combination of above?

  - New Physics option?

Concluding remarks

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

$\to$ growing with time both in **statistical significance** and in internal **consistency**

Could they be explained by:

- Statistical fluctuations alone? × NO!
- Experimental issues alone?
- Underestimated theoretical uncertainties alone?
- Unknown pieces in the theoretical calculations alone?

  - Combination of above?

  - New Physics option?

Concluding remarks

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

$\to$ growing with time both in **statistical significance** and in internal **consistency**

Could they be explained by:

- Statistical fluctuations alone? ✕ **NO!**
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- Underestimated theoretical uncertainties alone?
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Concluding remarks

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

$\to$ growing with time both in **statistical significance** and in internal **consistency**

Could they be explained by:

- Statistical fluctuations alone? ✕ **NO!**
- Experimental issues alone? ✕ **NO!**
- Underestimated theoretical uncertainties alone?
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Concluding remarks

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

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- Unknown pieces in the theoretical calculations alone?

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Concluding remarks

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

$\to$ growing with time both in **statistical significance** and in internal **consistency**

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Concluding remarks

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    - Combination of above? ✓ **POSSIBLE**
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  - New Physics option? ✓ **POSSIBLE**

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  - New Physics option? ✓ **POSSIBLE**

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  - Combination of above? ✓ **POSSIBLE**

    Is Nature teasing us?

  - New Physics option? ✓ **POSSIBLE**

    Or teaching us?

Concluding remarks

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

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    - Combination of above? ✓ **POSSIBLE**

      Is Nature teasing us?

    - New Physics option? ✓ **POSSIBLE**

      Or teaching us?

The next round of data will hopefully give us the verdict!

Thank you for your attention!

Backup

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 $\chi^2_{\rm SM} = 225.8$ $\chi^2_{\rm min} = 151.6$; $\text{Pull}_{\rm SM} = 5.5(5.6)\sigma$			
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/ $C_{10}^{\prime e}$
$\delta C_9^{\prime\mu}$ 0.09 ± 0.34	$\delta C_9^{\prime e}$ 1.90 ± 1.50	$\delta C_{10}^{\prime\mu}$ -0.12 ± 0.20	$\delta C_{10}^{\prime e}$ 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 $[4.50 \pm 1.5]$
$C_{Q_1}^{\prime\mu}$ 0.15 ± 0.10 $[0.02 \pm 0.12]$	$C_{Q_1}^{\prime e}$ -1.70 ± 1.20 $[-0.30 \pm 1.10]$	$C_{Q_2}^{\prime\mu}$ -0.14 ± 0.11 $[-0.16 \pm 0.10]$	$C_{Q_2}^{\prime e}$ -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

Pull$_{\rm SM}$ of 1, 2, 6, 10 and 20 dimensional fit:

Set of WC	param.	$\chi^2_{\rm min}$	Pull$_{\rm SM}$	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	$5.5\,(5.6)\sigma$	$0.2\,(0.3)\sigma$

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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).