

Flavour anomalies in $b \rightarrow s\ell\ell$ processes, where we are and what's next

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CCDVM (JHEP 1801 (2018) 093) and
M. Alguero, B. Capdevila, S. Descotes-Genon, P. Masjuan, J. Matias (to appear).

State-of-the-art

The framework: $b \rightarrow s\ell\ell$ effective Hamiltonian, **Wilson Coefficients**

$$b \rightarrow s\gamma(^*) : \mathcal{H}_{\Delta F=1}^{SM} \propto \sum V_{ts}^* V_{tb} \mathbf{C}_i \mathcal{O}_i + \dots$$

separate short and long distances ($\mu_b = m_b$)

- $\mathcal{O}_7 = \frac{e}{16\pi^2} m_b (\bar{s} \sigma^{\mu\nu} \mathbf{P}_R b) \mathbf{F}_{\mu\nu}$ [real or soft photon]
- $\mathcal{O}_9 = \frac{e^2}{16\pi^2} (\bar{s} \gamma_\mu \mathbf{P}_L b) (\bar{\ell} \gamma^\mu \ell)$
- $\mathcal{O}_{10} = \frac{e^2}{16\pi^2} (\bar{s} \gamma_\mu \mathbf{P}_L b) (\bar{\ell} \gamma^\mu \gamma_5 \ell)$

At the $\mu_b = 4.8$ GeV scale:

$$\mathbf{C}_7^{\text{SM}} = -0.29, \quad \mathbf{C}_9^{\text{SM}} = 4.1, \quad \mathbf{C}_{10}^{\text{SM}} = -4.3$$

NP changes short-distance $\mathbf{C}_i = \mathbf{C}_i^{\text{SM}} + \mathbf{C}_i^{\text{NP}}$ for SM or involve additional operators \mathcal{O}_i

- Chirally flipped ($W \rightarrow W_R$)
- (Pseudo)scalar ($W \rightarrow H^+$)
- Tensor operators ($\gamma \rightarrow T$)

$$\mathcal{O}_{7'} \propto (\bar{s} \sigma^{\mu\nu} P_L b) F_{\mu\nu}, \quad \mathcal{O}_{9'} \propto (\bar{s} \gamma_\mu P_R b) (\bar{\ell} \gamma^\mu \ell) \dots$$

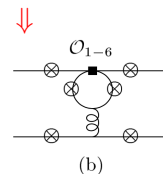
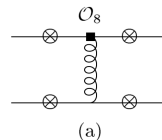
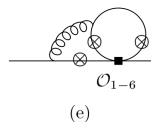
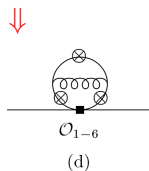
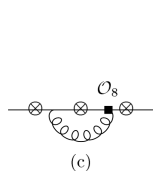
$$\mathcal{O}_S \propto (\bar{s} P_R b) (\bar{\ell} \ell), \quad \mathcal{O}_P \propto (\bar{s} P_R b) (\bar{\ell} \gamma_5 \ell)$$

$$\mathcal{O}_T \propto \bar{s} \sigma_{\mu\nu} (1 - \gamma_5) b \bar{\ell} \sigma_{\mu\nu} \ell$$

$B \rightarrow K^* \mu^+ \mu^-$ in a nutshell: Factorizable & Non-factorizable contributions

Theoretical framework: QCDF/SCET+**robust large-recoil symmetries** +breaking (pert+non-pert)
 \hookrightarrow independent of LCSR details

$$\mathcal{T}_a = \xi_{\mathbf{a}} \left(C_a^{(0)} + \frac{\alpha_s C_F}{4\pi} C_a^{(1)} \right) + \frac{\pi^2}{N_c} \frac{f_B f_{K^*,a}}{M_B} \Sigma_a \sum_{\pm} \int \frac{d\omega}{\omega} \Phi_{B,\pm}(\omega) \int_0^1 du \Phi_{K^*,a}(u) T_{a,\pm}(u, \omega). \quad \mathbf{a} = \perp, \parallel$$



• Diagrams involving the $b \rightarrow s$ transition only

Hard spectator scattering (T_a)

$$C_{9i}^{\text{eff}}(q^2) = \mathbf{C}_9^{\text{SMpert}} + C_9^{\text{NP}} + \mathbf{s}_i \delta \mathbf{C}_{9i}^{\text{ccLD}}(\mathbf{q}^2).$$

Perturbative: $\mathbf{C}_9^{\text{SMpert}} = C_9^{\text{SM}} + \mathbf{Y}(q^2)$

with $Y(q^2)$ stemming from one-loop matrix elements of 4-quark operators O_{1-6} .

... $\mathcal{O}(\alpha_s)$ corrections to $C_{7,9}^{\text{eff}}$ of $Y(q^2)$ included via $C_{\perp,\parallel}^{1(\text{nf})}$ but only $O_{1,2}$ (previous slide)

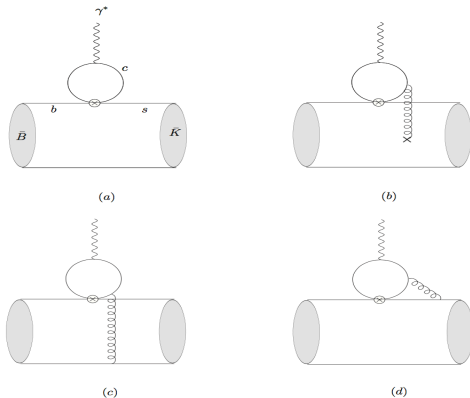
Non-perturbative: $\delta \mathbf{C}_{9i}^{\text{ccLD}}(\mathbf{q}^2)$: Use LCSR to estimate LD contribution + data to try to go beyond LCSR.

THE ONLY REAL COMPUTATION IN LITERATURE (Khodjamirian, Mannel, Pivovarov, Wang).

⇒ long-distance effect by current- current operators $O_{1,2}$ together with the c-quark e.m. current:

$$\mathcal{H}_\mu^{B \rightarrow K^*}(p, q) = i \int d^4x e^{iqx} \langle K^*(p) | T \{ \bar{c}(x) \gamma_\mu c(x) [C_1 O_1 + C_2 O_2] \} | B(p+q) \rangle$$

$$O_1 = (\bar{s}_L \gamma_\rho c_L)(\bar{c}_L \gamma^\rho b_L), \quad O_2 = (\bar{s}_L^j \gamma_\rho c_L^i)(\bar{c}_L^i \gamma^\rho b_L^j)$$



← emission of one soft gluon (with low virtuality but nonvanishing momentum) from the c-quark loop. **Only real part computed!**

- dispersion relation is used to extend it to all region.
- hadronic matrix elements uses LCSR with B-meson DA (we consistently use them for all obs except $B_s \rightarrow \phi$, not available).

Figure 1: Charm-loop effect in $B \rightarrow K^{(*)} \ell^+ \ell^-$: (a)-the leading-order factorizable contribution; (b) nonfactorizable soft-gluon emission, (c),(d)-hard gluon exchange.

175 observables in total (LHCb, Belle, ATLAS and CMS, no CP-violating obs)

- $B \rightarrow K^* \mu \mu$ ($P_{1,2}, P'_{4,5,6,8}, F_L$ in 5 large-recoil bins + 1 low-recoil bin)+available electronic observables.

...April's update of $\text{Br}(B \rightarrow K^* \mu \mu)$ showing now a deficit in muonic channel.

...April's new result from LHCb on R_K^*

- $B_s \rightarrow \phi \mu \mu$ ($P_1, P'_{4,6}, F_L$ in 3 large-recoil bins + 1 low-recoil bin)
- $B^+ \rightarrow K^+ \mu \mu, B^0 \rightarrow K^0 \ell \ell$ (BR) ($\ell = e, \mu$) (R_K is implicit)
- $B \rightarrow X_s \gamma, B \rightarrow X_s \mu \mu, B_s \rightarrow \mu \mu$ (BR).
- Radiative decays: $B^0 \rightarrow K^{*0} \gamma$ (A_I and $S_{K^* \gamma}$), $B^+ \rightarrow K^{*+} \gamma, B_s \rightarrow \phi \gamma$

- New Belle measurements for the isospin-averaged but lepton-flavour dependent ($Q_{4,5} = P'_{4,5}{}^\mu - P'_{4,5}{}^e$):

$$P_i^{\ell} = \sigma_+ P_i^{\ell}(B^+) + (1 - \sigma_+) P_i^{\ell}(\bar{B}^0)$$

- New ATLAS and CMS measurements on P_i .

Frequentist approach: $\mathcal{C}_i = \mathcal{C}_i^{SM} + \mathcal{C}_i^{NP}$, with \mathcal{C}_i^{NP} assumed to be real (no CPV)

$$\chi^2(C_i) = [O_{\text{exp}} - O_{\text{th}}(\mathcal{C}_i^{NP})]_j [Cov^{-1}]_{jk} [O_{\text{exp}} - O_{\text{th}}(\mathcal{C}_i^{NP})]_k$$

Where we stand? Results 1D fits: All $b \rightarrow s\ell\ell$ and LFUV fit

⇒ *Global fits test the **coherence** of a set of deviations with a NP hypothesis versus SM hypothesis*

- Hypotheses “NP in some \mathcal{C}_i only” (1D, 2D, 6D)

All					
1D Hyp.	Best fit	1 σ	2 σ	Pull _{SM}	p-value
$\mathcal{C}_{9\mu}^{\text{NP}}$	-1.11	$[-1.28, -0.94]$	$[-1.45, -0.75]$	5.8	68
$\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}$	-0.62	$[-0.75, -0.49]$	$[-0.88, -0.37]$	5.3	58
$\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}'_{9\mu}$	-1.01	$[-1.18, -0.84]$	$[-1.34, -0.65]$	5.4	61
$\mathcal{C}_{9\mu}^{\text{NP}} = -3\mathcal{C}_{9e}^{\text{NP}}$	-1.07	$[-1.24, -0.90]$	$[-1.40, -0.72]$	5.8	70
LFUV					
1D Hyp.	Best fit	1 σ	2 σ	Pull _{SM}	p-value
$\mathcal{C}_{9\mu}^{\text{NP}}$	-1.76	$[-2.36, -1.23]$	$[-3.04, -0.76]$	3.9	69
$\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}$	-0.66	$[-0.84, -0.48]$	$[-1.04, -0.32]$	4.1	78
$\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}'_{9\mu}$	-1.64	$[-2.13, -1.05]$	$[-2.52, -0.49]$	3.2	32
$\mathcal{C}_{9\mu}^{\text{NP}} = -3\mathcal{C}_{9e}^{\text{NP}}$	-1.35	$[-1.82, -0.95]$	$[-2.38, -0.59]$	4.0	72

Pull_{SM}: how much the SM is disfavoured with respect to a New Physics hypothesis to explain data.

→ A scenario with a large SM-pull ⇒ big improvement over SM and better description of data.

* Other groups (Altmannshofer, Straub et al.) did not updated results for the **All-fit** in tables only plots.

→ They have **5.2 σ** without including R_{K^*} (1703.09189)

2D hypothesis

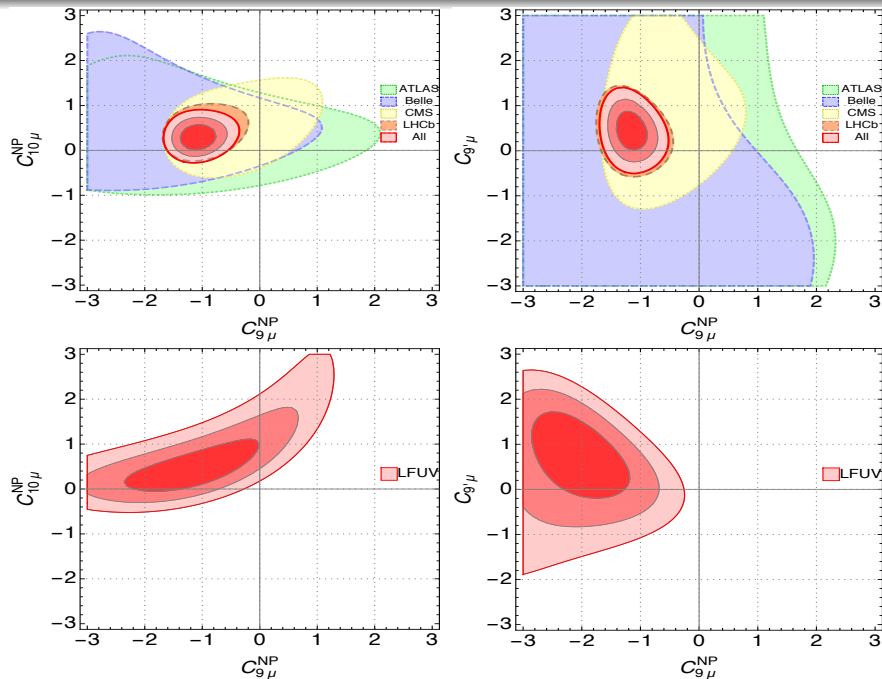
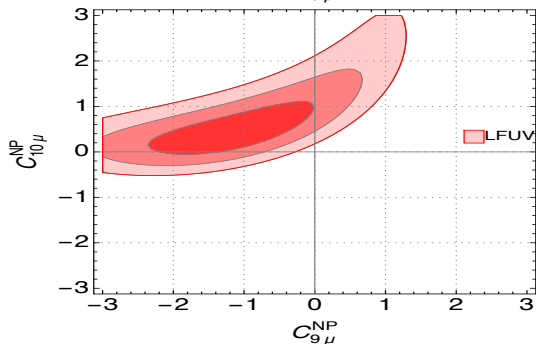
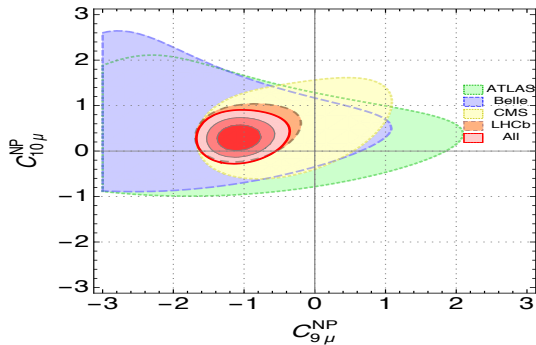
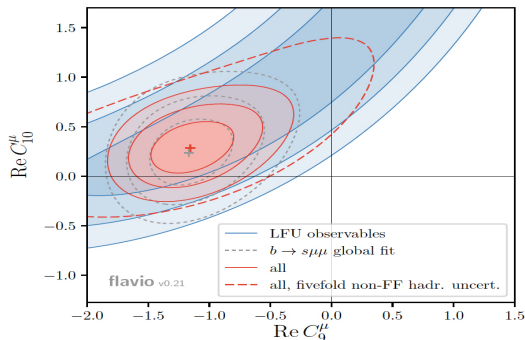


Figure: Allowed regions with all available data (upper) and only LFUV (lower) in good agreement. Constraints from $b \rightarrow s\gamma$ observables, $\mathcal{B}(B \rightarrow X_s \mu\mu)$ and $\mathcal{B}(B_s \rightarrow \mu\mu)$ always included. Experiments at 3σ .

Other analyses find results in agreement with us



[Capdevila, Crivellin, SDG, Matias, Virto]



[Altmannshofer, Stangl, Straub]

- Different angular observables
- Different form factor inputs (BSZ)
- Different treatment of hadronic corrections (full-FF)
- **No update table of global fit available (only plots)**
- Same NP scenarios favoured (higher significances for [Altmannshofer, Stangl, Straub])

6D fit the most important one

We take all Wilson coefficients SM-like and chirally flipped as free parameters:
(neglect scalars and tensor operators)

	$\mathcal{C}_7^{\text{NP}}$	$\mathcal{C}_{9\mu}^{\text{NP}}$	$\mathcal{C}_{10\mu}^{\text{NP}}$	$\mathcal{C}_{7'}$	$\mathcal{C}_{9'\mu}$	$\mathcal{C}_{10'\mu}$
Best fit	+0.03	-1.12	+0.31	+0.03	+0.38	+0.02
1 σ	$[-0.01, +0.05]$	$[-1.34, -0.88]$	$[+0.10, +0.57]$	$[+0.00, +0.06]$	$[-0.17, +1.04]$	$[-0.28, +0.36]$
2 σ	$[-0.03, +0.07]$	$[-1.54, -0.63]$	$[-0.08, +0.84]$	$[-0.02, +0.08]$	$[-0.59, +1.58]$	$[-0.54, +0.68]$

The SM pull moved from 3.6 $\sigma \rightarrow 5.0 \sigma$ (fit “All” with the latest CMS data at 8 TeV included)

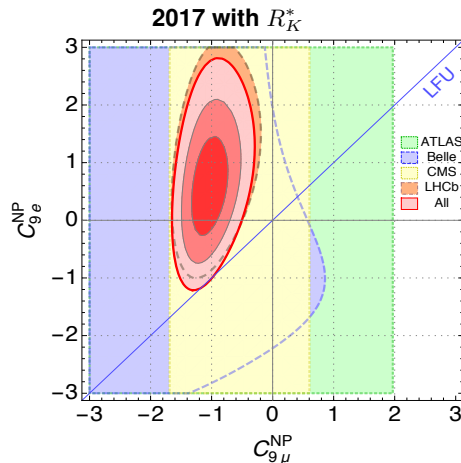
The pattern (very similar to DHMV15):

$$\mathcal{C}_7^{\text{NP}} \gtrsim 0, \mathcal{C}_{9\mu}^{\text{NP}} < 0, \mathcal{C}_{10\mu}^{\text{NP}} > 0, \mathcal{C}'_7 \gtrsim 0, \mathcal{C}'_{9\mu} > 0, \mathcal{C}'_{10\mu} \gtrsim 0$$

$\mathcal{C}_{9\mu}$ is compatible with the SM much beyond 3 σ , all the other coefficients at 1-2 σ .

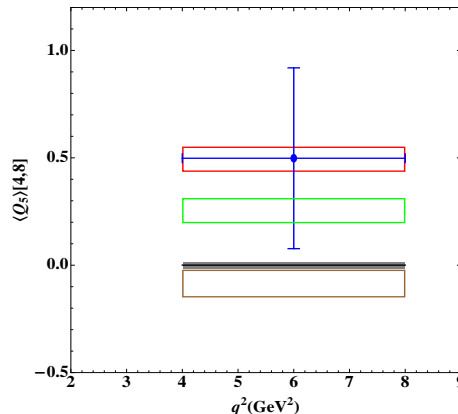
Is there New Physics in electronic or muonic sector?

1 The independent analysis of $b \rightarrow se^+e^-$ and $b \rightarrow s\mu^+\mu^-$ shows:



- $C_{9\mu} \sim -\mathcal{O}(1)$ with higher significance
- $C_{9e} \simeq 0$ compatible with SM albeit with large error bars.

$Q_5 > 0 \Rightarrow$ NP mainly in μ^\pm and marginally in e^\pm
 \hookrightarrow + moderate hadronic pollution



$$Q_5 = P_5'^\mu - P_5'^e$$

- Mainly in μ^\pm sector and marginally in e^\pm sector [DHMV, AS, ...].
- Mainly in e^\pm sector and marginally in μ^\pm sector [Ciuchini et al.]

Hyp: no RHC.

- 1 NP solution of LFUV: only $C_{9\mu} = -1.76$ and $C_{ie} = 0$. $Q_5 \sim 0.49$
- 2 NP solution of all-fit: only $C_{9\mu} = -1.1$ and $C_{ie} = 0$. $Q_5 \sim 0.26$
- 3 NP solution of [Ciuchini et al.]: $C_{10\mu} = -0.12$, $C_{10e} = -1.22$. $Q_5 \sim -0.1$

$Q_5 < 0 \Rightarrow$ NP mainly in e^\pm and marginally in μ^\pm
 \hookrightarrow + huge hadronic pollution

Anatomy of the anomalies (theoretical perspective)

First anomaly of $b \rightarrow s\mu^+\mu^-$ type: P'_5

Framework: I-QCDF + SFF + KMPW+ power corrections

P'_5 was proposed in **DMRV, JHEP 1301(2013)048**

$$P'_5 = \sqrt{2} \frac{\text{Re}(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*})}{\sqrt{|A_0|^2(|A_\perp|^2 + |A_\parallel|^2)}} = P_5^\infty (1 + \mathcal{O}(\alpha_s \xi_\perp) + \text{p.c.})$$

Optimized observables:

SFF sensitivity α_s suppressed compared to non-optimized.

Impact of an improvement on KMPW-FF errors (50%):

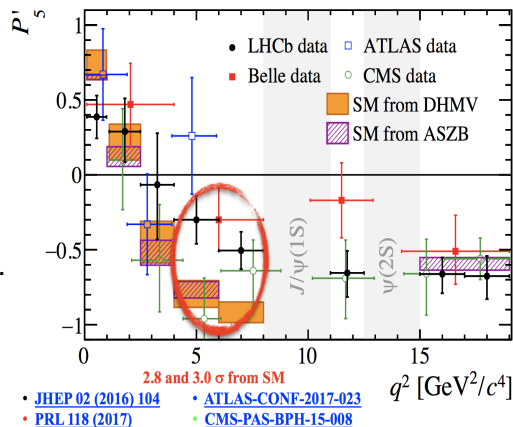
- Optimized observable P'_5 (% present error size)

$$P'_{5[4,6]} = -0.82 \pm 0.08(\mathbf{10\%}) \rightarrow \mathbf{0.06(8\%)}$$

→ interestingly BSZ-FF+full-FF approach finds 0.05

- Non-optimized observable S_5

$$S_{5[4,6]} = -0.35 \pm 0.12(\mathbf{34\%}) \rightarrow \mathbf{0.06(17\%)}$$



Experimentally: LHCb (1fb^{-1} 3.7σ and 3fb^{-1} 2 bins 3σ), Belle confirmed [4,8]. ATLAS and CMS first measurement.

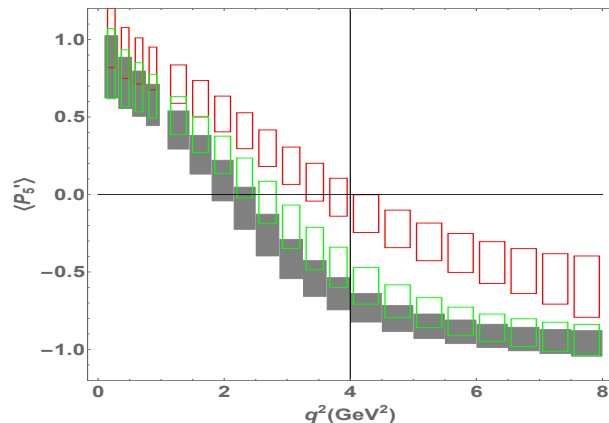
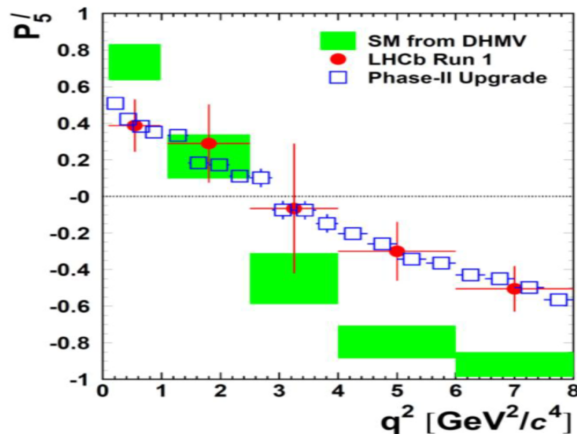
Orange: our th. framework with conserv. KMPW
Magenta: full-FF using BSZ (+dep. LCSR details)

At present our conservative estimate contains both approaches and FF

A bright future: LHCb ultimate precision expected in RUN II

Projections from LHCb for P'_5 in Phase-II Upgrade.

Green (Sc1): $C_9^{\text{NP}} = -C_{10}^{\text{NP}} = -0.66$,
Red (Sc2): $C_9^{\text{NP}} = -1.76$



A large number of small bins open the window in P'_5 for another observable: zero of P'_5 .

At LO:

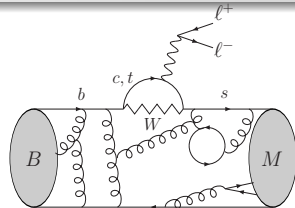
$$q_0^2 = -\frac{m_b m_B^2 C_7^{\text{eff}}}{m_b C_7^{\text{eff}} + m_B C_9^{\text{eff}}(q_0^2)}$$

zero not sensitive to C_{10} (at LO).

At NLO:

- Large shift of zero of P'_5 from $q_0^{2SM} \simeq 2$ GeV² to $q_0^{C_9^{\text{NP}}=-1.76} \simeq 3.8$ GeV².

First anomaly of LFUV type: R_K



$$R_K = \frac{\text{Br}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\text{Br}(B^+ \rightarrow K^+ e^+ e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

⇒ It deviates **2.6 σ** from SM.

⇒ equals to 1 in SM (universality of lepton coupling).

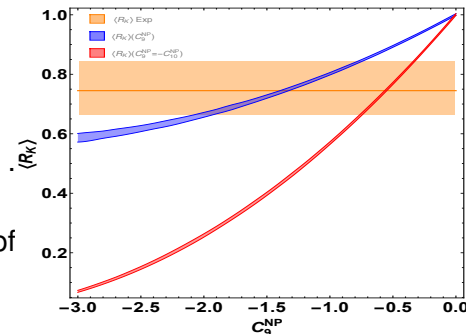
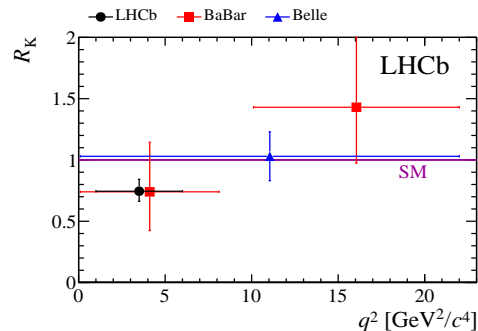
⇒ NP coupling \neq to μ and e .

1 First signal of LFUV.

If experimental error reduces by 40% LFUV-fit $> 5\sigma$

2 Simple structure: $f_{+,0,T} \rightarrow$ one SFF (f_+) at large-recoil.
 $\rightarrow f_0$ lepton mass suppressed or arises in the presence of (pseudo)scalar while f_T suppressed by C_7^{eff} .

3 Tensions cannot be explained inside the SM by neither factorizable power corrections* nor long-distance charm*. • In presence of NP also clean prediction



R_{K^*} plays a different league

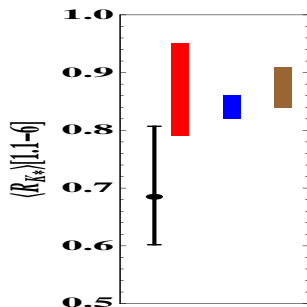
$$R_{K^*} = \frac{Br(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{Br(B^0 \rightarrow K^{*0} e^+ e^-)}$$

pulls	$R_{K^*}^{[0.045, 1.1]}$	$R_{K^*}^{[1.1, 6]}$
Exp.	$0.66^{+0.113}_{-0.074}$	$0.685^{+0.122}_{-0.083}$
SM	0.92 ± 0.02	1.00 ± 0.01

R_{K^*} : More complex structure, 6-8 Amplitudes and 7 form factors.

Impact of long-distance charm from KMPW on $B \rightarrow K^*$ larger than on $B \rightarrow K$.

- In presence of NP or for $q^2 < 1 \text{ GeV}^2$ **hadronic uncertainties return**.
- Two surces: $(C_i^\mu - C_i^e)\delta FF$ and interf. in quadr. $(C_i^\mu = C_i^{SM} + C_i^{NP} + C_i^h)^2 - (C_i^e = C_i^{SM} + C_i^h)^2$.



Bins	Predictions R_{K^*}		
	[0.045, 1.1]	[1.1, 6.]	[15., 19.]
Standard Model	0.916 ± 0.025	1.000 ± 0.006	0.998 ± 0.001
$\Leftarrow C_{9\mu}^{NP} = -1.11$	0.897 ± 0.049	0.867 ± 0.080	0.788 ± 0.005
$C_{9\mu}^{NP} = -1.76$	0.895 ± 0.084	0.827 ± 0.137	0.698 ± 0.009
$C_{9\mu}^{NP} = -C_{10\mu}^{NP} = -0.62$	0.866 ± 0.057	0.751 ± 0.027	0.714 ± 0.006

- 1st bin is expected to be SM-like.
- $C_9 < 0$ gets near saturation at large-recoil.

KMPW-sch.1:

$$\xi_{\perp} = 0.31^{+0.20}_{-0.10}, \xi_{\parallel} = 0.10^{+0.03}_{-0.02}$$

BSZ-sch.1

$$\xi_{\perp} = 0.32 \pm 0.03, \xi_{\parallel} = 0.12 \pm 0.02$$

JC-sch.2

$$\xi_{\perp} = 0.31 \pm 0.04, \xi_{\parallel} = 0.10 \pm 0.02$$

New category of LFUV observables: $Q_{4,5} = P_{4,5}'^\mu - P_{4,5}'^e$ (BELLE)

[S. Wehle et al. PRL118 (2017)]

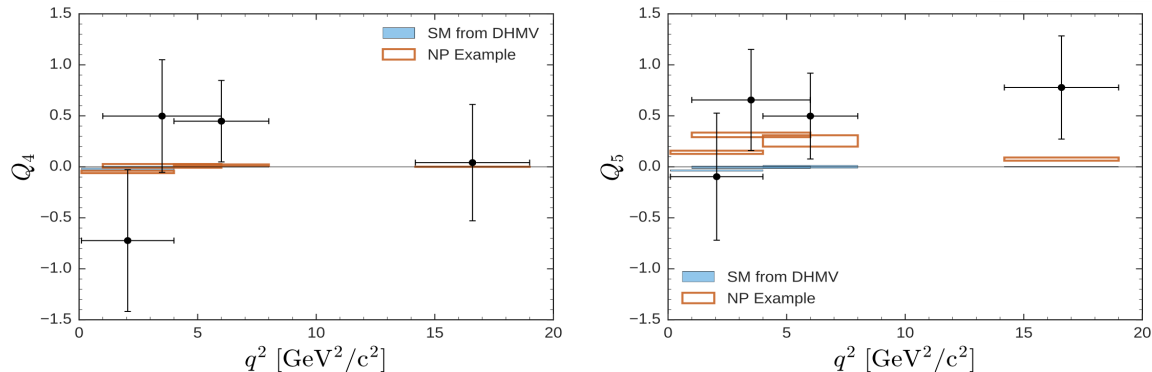


Figure 3: Q_4 and Q_5 observables with SM and favored NP “Scenario 1” from Ref. [6].

Table 2: Results for the lepton-flavor-universality-violating observables Q_4 and Q_5 . The first uncertainty is statistical and the second systematic.

q^2 in GeV ² /c ²	Q_4	Q_5
[1.00, 6.00]	$0.498 \pm 0.527 \pm 0.166$	$0.656 \pm 0.485 \pm 0.103$
[0.10, 4.00]	$-0.723 \pm 0.676 \pm 0.163$	$-0.097 \pm 0.601 \pm 0.164$
[4.00, 8.00]	$0.448 \pm 0.392 \pm 0.076$	$0.498 \pm 0.410 \pm 0.095$
[14.18, 19.00]	$0.041 \pm 0.565 \pm 0.082$	$0.778 \pm 0.502 \pm 0.065$

Anatomy of the fit: coherence and tension

Improving on the main anomalies \rightarrow Coherence

The 1D solution solves many anomalies and alleviates other tensions

Largest pulls	$\langle P_5' \rangle^{[4,6]}$	$\langle P_5' \rangle^{[6,8]}$	$\mathcal{B}_{B_s \rightarrow \phi \mu^+ \mu^-}^{[2,5]}$	$\mathcal{B}_{B_s \rightarrow \phi \mu^+ \mu^-}^{[5,8]}$	$\mathcal{B}_{B \rightarrow K^* + \mu^+ \mu^-}^{[15,19]}$
Experiment	-0.30 ± 0.16	-0.51 ± 0.12	0.77 ± 0.14	0.96 ± 0.15	1.60 ± 0.32
SM pred.	-0.82 ± 0.08	-0.94 ± 0.08	1.55 ± 0.33	1.88 ± 0.39	2.59 ± 0.24
Pull (σ)	-2.9	-2.9	+2.2	+2.2	+2.5
Pred. $C_{9\mu}^{\text{NP}} = -1.1$	-0.50 ± 0.11	-0.73 ± 0.12	1.30 ± 0.26	1.51 ± 0.30	2.05 ± 0.18
Pull (σ)	-1.0	-1.3	+1.8	+1.6	+1.2
Pred. LFUV $C_{9\mu}^{\text{NP}} = -1.76$	-0.26 ± 0.12	-0.52 ± 0.15	1.22 ± 0.22	1.37 ± 0.25	1.82 ± 0.16
Pull (σ)	+0.2	-0.1	+1.7	+1.4	+0.6
Pred. LFUV $C_{9\mu}^{\text{NP}} = -C_{10\mu}^{\text{NP}} = -0.66$	-0.72 ± 0.10	-0.91 ± 0.10	1.10 ± 0.24	1.30 ± 0.29	1.81 ± 0.18
Pull (σ)	-2.2	-2.5	+1.2	+1.0	+0.6

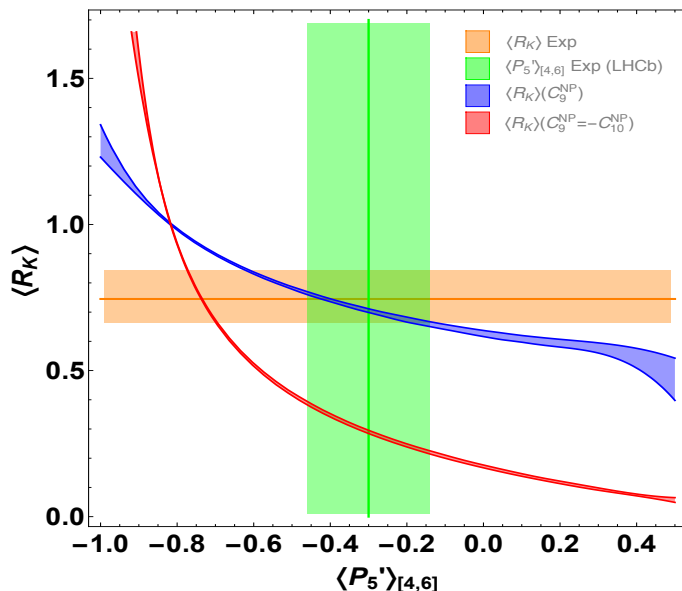
Largest pulls	$R_K^{[1,6]}$	$R_{K^*}^{[0.045,1.1]}$	$R_{K^*}^{[1.1,6]}$
Experiment	$0.745^{+0.097}_{-0.082}$	$0.66^{+0.113}_{-0.074}$	$0.685^{+0.122}_{-0.083}$
SM pred.	1.00 ± 0.01	0.92 ± 0.02	1.00 ± 0.01
Pull (σ)	+2.6	+2.3	+2.6
Pred. $C_{9\mu}^{\text{NP}} = -1.1$	0.79 ± 0.01	0.90 ± 0.05	0.87 ± 0.08
Pull (σ)	+0.4	+1.9	+1.2
Pred. LFUV $C_{9\mu}^{\text{NP}} = -1.76$	0.69 ± 0.01	0.89 ± 0.09	0.83 ± 0.14
Pull (σ)	-0.7	+1.6	+0.8
Pred. LFUV $C_{9\mu}^{\text{NP}} = -C_{10\mu}^{\text{NP}} = -0.66$	0.70 ± 0.01	0.86 ± 0.06	0.74 ± 0.03
Pull (σ)	-0.5	+1.6	+0.4

- C_9^{NP} (LFUV) fixes completely most of the anomalies... but generates some other tensions.
- $C_9^{\text{NP}} = -C_{10}^{\text{NP}}$ nicely fixes many anomalies but fails in others.
- Can we disentangle them.... ? yes with Q_5 .

An explicit example to see the coherence: LFUV (R_K) versus $b \rightarrow s\mu^+\mu^-$

[M. Alguero, B. Capdevila, SDG, JM'18]

- $R_{K[1,6]}$ shares the same explanation than $P'_{5[4,6]}$ and other $b \rightarrow s\mu\mu$ tensions **if NP only in C_9** .



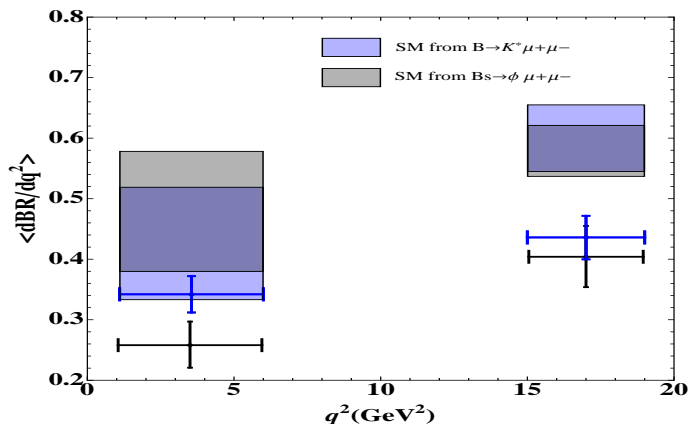
- Variation of NP ONLY in $C_{9\mu}$ (**BLUE**), Green and Orange (LHCb data)
no extra hadronic contribution besides all those included in our computation is required at low- q^2 looking only at $R_K - P_5$.
- Variation of NP in $C_{9\mu} = -C_{10\mu}$ (**RED**), **do require extra hadronic contributions besides all those known ones looking only at $R_K - P_5$.**

\Rightarrow The need or not of extra unknown contributions is clearly scenario dependent.

Tension: Let's take a closer look to the case of $B_s \rightarrow \phi \mu^+ \mu^-$

Systematic low-recoil small tensions:

$10^7 \times \text{BR}(B_s \rightarrow \phi \mu^+ \mu^-)$	SM	EXP	Pull
[0.1,2]	1.56 ± 0.35	1.11 ± 0.16	+1.1
[2,5]	1.55 ± 0.33	0.77 ± 0.14	+2.2
[5,8]	1.89 ± 0.40	0.96 ± 0.15	+2.2



Even if still not statistically significant...

Form factors at low- q^2 for $B_s \rightarrow \phi$ (ONLY in BSZ not available in KMPW) are larger than $B \rightarrow K^*$, so we would expect at low- q^2 an INVERTED hierarchy with respect to data.

At high- q^2 data and theory (Lattice) seems ok.

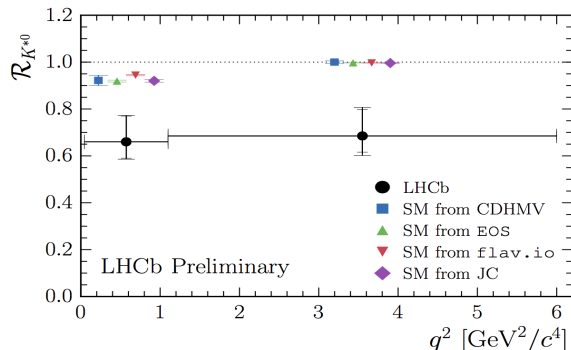
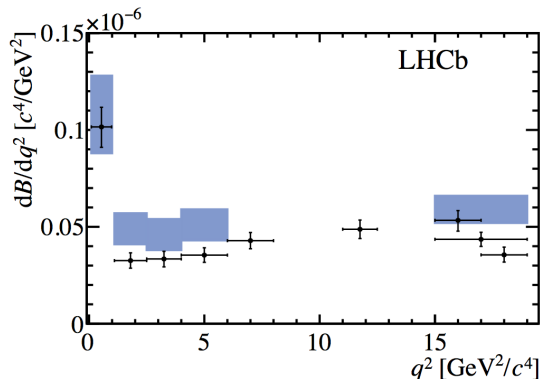
... more data required.

... or a problem of BSZ?

A comparison between the 1st bin of R_{K^*} and the 2nd has to be done NOT only looking at:

R_{K^*} but also to the $\mathcal{B}_{B \rightarrow K^* \mu \mu}$.

pulls	$R_{K^*}^{[0.045, 1.1]}$	$R_{K^*}^{[1.1, 6]}$
Exp.	$0.66^{+0.113}_{-0.074}$	$0.685^{+0.122}_{-0.083}$
SM	0.92 ± 0.02	1.00 ± 0.01



1 The mechanism to explain the 1st bin is opposite to the mechanism of the 2nd bin and of all \mathcal{B} tensions: $\mathcal{B}_{B \rightarrow K^* \mu \mu}$ 1st bin is SM-like \Rightarrow to get $R_{K^*} < 1$ you need an **excess of electrons!** while in all \mathcal{B} we observe a **deficit in muons**.

2 A scan to semileptonic and electromagnetic NP coefficients shows that a too large C_7^{NP} contribution is required to explain 1st bin of R_{K^*} . [CCDMV'18]

It is customary in all rare B decay experimental talks to include the question:

*Are the anomalies due to New Physics or to unknown charmed hadronic uncertainties that **mimics** New Physics?*

Is the question well posed?

Let's scrutinize the question

Q1: Are the anomalies an evidence of NP or an experimental issue (statistical fluctuation or systematics?)

- The answer depends on more data from LHCb and few new observables (Q_5).
- The answer depends crucially on BELLE II, a different experimental setup.

Q2: Are the $b \rightarrow s\mu\mu$ anomalies due to NP or unknown charmed hadronic uncertainties **mimicking** NP?

Mimic: It plays same role than NP, i.e., it has to be **universal** (in μ^\pm) and constant and **same sign**.

a) Is $\delta C_9^{had}(q^2)$ (including anything beyond KMPW-LD + contrib. of different origin) significantly q^2 -dependent?

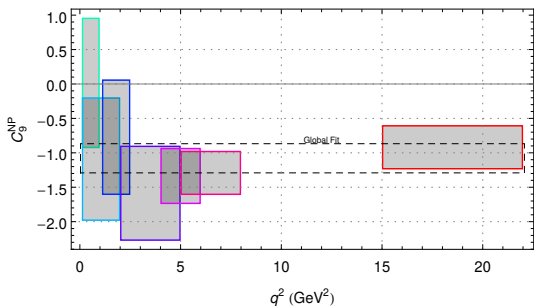
$$C_{9i}^{\text{eff}}(q^2) = C_{9\text{SMpert}} + C_9^{\text{NP}} + C_{9i}^{c\bar{c}K\text{MPW-LD}}(q^2) + \delta C_9^{\text{had}}(q^2)$$

b) If not, is δC_9^{had} a **universal** hadronic contribution **mimicking** New Physics (in muons)?

$\delta C_9^{had}(q^2)$ has a significant q^2 -dependence? NO

There are different ways to test it, all pointing in same direction:

1. Bin-by-bin Fit



Excellent agreement of $C_9^{\text{NP}} [4,6] = -1.3 \pm 0.4$, $C_9^{\text{NP}} [5,8] = -1.3 \pm 0.3$, i.e., no indication of additional q^2 -dependence.

3. Experimental analysis

Empirical model of long distance based on data on final states involving $J^{\text{PC}} = 1^{--}$ resonances: agreement with us.

2. Introduce for each helicity amplitude $\lambda = 0, \pm$:

$$h_\lambda = h_\lambda^{(0)} + \left(\frac{q^2}{1\text{GeV}^2} \right) h_\lambda^{(1)} + \left(\frac{q^2}{1\text{GeV}^2} \right)^2 h_\lambda^{(2)} \quad h_0^{(0)} = 0$$

Notation of [Ciuchini et al.]

$$h_\pm^{(0)} \rightarrow C_7, h_\lambda^{(1)} \rightarrow C_9$$

is there any need for $h_\lambda^{(2)}$ that will imply a q^2 -dependent in C_9^{eff} ?

$$\chi_{\min; h=0}^2 = 63.30$$

n	0	1	2	3
$\chi_{\min}^{2(n)}$	62.10	51.60	50.50	50.00
$\chi_{\min}^{2(n-1)} - \chi_{\min}^{2(n)}$	1.23	10.50	1.14	0.53
	(0.3 σ)	(2.4 σ)	(0.3 σ)	(0.1 σ)

We found that there is **no improvement in the fit's quality beyond $n = 1$** .

Also [Ciuchini et al.] using data+KMPW with dispersion relations finds **$h_-^{(2)} = (0.4 \pm 0.4) \times 10^{-5}$** (in 4 out 6 NP scenarios of PMD analysis) in agreement with us.

\hookrightarrow A controversial ““conservative”” approach (PDD) imposing $\text{Re}[C_9^{\text{KMPW}}]^2 + \text{Im}[C_9^{\text{KMPW}}]^2 = |C_9^{\text{exp}}|^2$ at $q^2 < 1 \text{ GeV}^2$ but **$\text{Im}[C_9^{\text{KMPW}}]$ is totally unknown**. Why BSZ and not KMPW?

Is there a universal C_9^h constant that mimics New Physics?

What is C_9^h ? can this mimic a destructive (negative) New Physics contribution?

1. SM: Pure two-loop electroweak perturbative contributions to the Wilson coefficient $C_9^{\text{SM}}(\mu_b)$ (**small**)
2. SM: Non-perturbative **constant unknown** charmed long-distance contribution. (?)
 \hookrightarrow is charm physics program not reliable then?
3. NP: or a **a lepton flavour New Physics universal (electrons and muons) contribution!**

Hypothesis: Let's assume for a moment that C_9^h exists... different from all other existing contributions:

$$C_{9\text{SMpert}} + C_9^{\text{NP}} + C_{9i}^{c\bar{c}KMPW-LD}(q^2)$$

Instead of performing a fit with a long list of nuisance hadronic parameters we prefer:

A global fit allowing besides C_9^{NP} **and** a universal extra parameter C_9^h : (**preliminary**)

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A global fit allowing besides C_9^{NP} **and** a universal extra parameter C_9^h : (**preliminary**)

	Best-fit point	1 σ CI	2 σ CI
$C_{9\mu}^{\text{NP}}$	-1.5291	[-2.1407, -0.9682]	[-2.7364, -0.4810]
C_9^h	0.6339	[0.0433, 1.2886]	[-0.4776, 1.9674]

Notice: The C_9^h parameter **does not compete** with New Physics LFV instead being **positive** requires a **larger New Physics deviation than $C_9^{\text{NP}} = -1.1$** than in absence of it!!!

However be careful RANGES are very WIDE now.

What happens if we allow for non-universal contributions?

A global fit allowing different hadronic parameters @low/high q^2 to test universality: (**preliminary**)

$$C_9^{\text{NP}}, C_{10}^{\text{NP}}, C_9^L, C_9^H$$

	Best-fit point	1 σ CI	2 σ CI
$C_{9\mu}^{\text{NP}}$	-1.5049	[-2.0607, -0.9680]	[-2.5963, -0.4764]
C_9^L	0.5762	[-0.1021, 1.1042]	[-0.7330, 1.5113]
C_9^H	0.9064	[0.2785, 1.5858]	[-0.2922, 2.2925]

- Again NP increases w.r.t. $C_9^{L,H} = 0$!
- Even if $C_9^{L,H}$ same sign **cannot** mimic NP due to opposite sign to NP.

	Best-fit point	1 σ CI	2 σ CI
$C_{9\mu}^{\text{NP}}$	-0.4908	[-1.3060, 0.0940]	[-2.0078, 0.5260]
$C_{10\mu}^{\text{NP}}$	0.6104	[0.2948, 0.8819]	[0.0369, 1.0878]
C_9^L	-0.7766	[-1.2569, 0.0516]	[-1.6141, 0.9159]
C_9^H	0.1631	[-0.4669, 1.0200]	[-0.9141, 1.6633]

- $C_9^{L,H}$ seems to prefer rather different values (so no universal) but all ranges are wide. Interestingly tends to $C_9 \sim -C_{10}$ and there is a interplay $C_{9\mu} \leftrightarrow C_9^L$.

In summary:

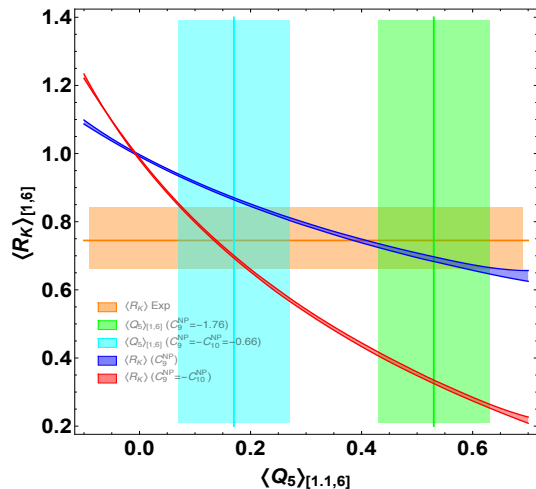
- 1 THERE IS NOT a **universal** hadronic contribution entering $C_{9\ell}^{\text{eff}}$ **mimicking NP (wrong sign)**.
and **non-universal** hypothetical hadronic parameters are **highly scenario-dependent**.
- 2 Ranges for C_9^h are too large (and consistent or near zero) to extract definite conclusions,
more LFUV data required to break degeneracies.

Our proposal to disentangle among different
NP scenarios and hypothetical unknown hadronics
using LFUV observables

[M. Alguero, B. Capdevila, SDG, JM'18]

- a** Assuming LFUV is explained by NP in μ^\pm , $b \rightarrow s\mu\mu$ contain NP+hadronic parameters:
 \hookrightarrow h.p.'s size depends on scenario and region in q^2

...how to disentangle between C_9 and $C_9 = -C_{10}$ scenario? R_K and Q_5



SM	$C_9^{\text{NP}} = -1.76$	$C_9^{\text{NP}} = -C_{10}^{\text{NP}} = -0.66$
-0.007 ± 0.001	$+0.535 \pm 0.033$	$+0.166 \pm 0.019$

The two LFUV theory scenarios differ by 10σ

- Blue curve $C_{9\mu}$ NP scenario.
- Red curve $C_{9\mu} = -C_{10}$ NP scenario.
- Orange band: R_K DATA.
- Hypothetical data**

- Green Band value of $C_9^{\text{NP}} = -1.76$ with ± 0.1 error band.
- Blue Band value of $C_9^{\text{NP}} = -C_{10}^{\text{NP}} = -0.66$ with ± 0.1 error.

\Rightarrow It is possible to disentangle between the two scenarios only if $Q_5 \gtrsim 0.3$. This in turn fixes the hypothetical hadronic parameters.

- For the first time, we observe in particle physics a large set of **coherent deviations** in observables:

1 in $b \rightarrow s\mu^+\mu^-$: $P'_5, \mathcal{B}_{B^+ \rightarrow K^{*+}\mu^+\mu^-}, \mathcal{B}_{B_s \rightarrow \phi\mu^+\mu^-}$ (low and large-recoil).

2 in LFUV observables: $R_K, R_{K^*}, Q_{4,5}$

pointing **in a global fit** to different patterns/scenarios of NP:

- $\mathcal{C}_{9\mu} = -1.1, \mathcal{C}_{9e} = 0$ with **pull-SM 5.8 σ** • $\mathcal{C}_{9\mu} = -\mathcal{C}_{10\mu} = -0.62, \mathcal{C}_{9e} = 0$ with pull-SM 5.3 σ

- The fit using **only LFUV observables** finds **Violations of LFU** at the 3-4 σ level.
- We have shown, using the fit, that the answer to the naïve question:
"Are the $b \rightarrow s\mu\mu$ anomalies due to NP or unknown charmed hadronic contributions mimicking NP?"
 \hookrightarrow is that there seems **not to exist a universal hypothetical hadronic contribution** mimicking NP
 \hookrightarrow still **non-universal scenario-dependent** hypothetical hadronic contributions are allowed and can complement New Physics, but more data is required...
- We discussed a procedure based on $R_K - Q_5$ that provides an excellent method to disentangle $\mu^\pm e^\pm$ and **NP scenarios**. Belle-II and LHCb will play a leading role.
- We have identified a link between disentangling scenarios of NP and hypothetical **non-universal hadronic unknown contributions** that can help to solve both.

Flavour observables are sensitive to higher scales than direct searches at colliders

... if NP affects flavour it is not surprising that we detect it first.

What is the scale of NP for $b \rightarrow s\ell\ell$? Rescaling the Hamiltonian by $H_{eff}^{\text{NP}} = \sum \frac{\mathcal{O}_i}{\Lambda_i^2}$

- Tree-level induced (semi-leptonic) with $\mathcal{O}(1)$ couplings ($\times \sqrt{g_{bs} g_{\mu\mu}}$):

$$\Lambda_i^{\text{Tree}} = \frac{4\pi v}{s_w g} \frac{1}{\sqrt{2|V_{tb}V_{ts}^*|}} \frac{1}{|C_i^{\text{NP}}|^{1/2}} \sim \frac{35\text{TeV}}{|C_i^{\text{NP}}|^{1/2}}$$

- Loop level-induced (semi-leptonic) with $\mathcal{O}(1)$ couplings:

$$\Lambda_i^{\text{Loop}} \sim \frac{35\text{TeV}}{4\pi |C_i^{\text{NP}}|^{1/2}} = \frac{2.8\text{TeV}}{|C_i^{\text{NP}}|^{1/2}}$$

- MFV with CKM-SM, extra suppression $\sqrt{|V_{tb}V_{ts}^*|} \sim 1/5$

Solution $C_9^{\text{NP}} \sim -1.1$ (scale is \sim numerator) or $C_9^{\text{NP}} = -C_{10}^{\text{NP}} \sim -0.6$ (30 % higher scale).

Similar exercise for $b \rightarrow c\tau\nu$ taking a 10% (in amplitude) enhancement over SM:

$$\Lambda^{\text{NP}} \sim 1/(\sqrt{2}G_F|V_{cb}|0.10)^{1/2} \sim 3.9\text{ TeV}$$