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

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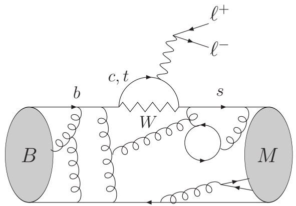
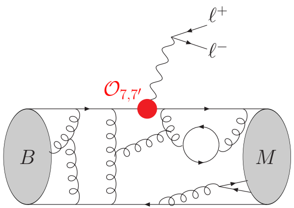
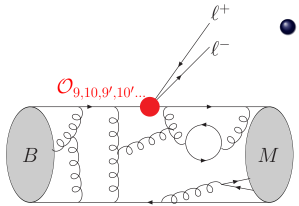
Lyon Workshop

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







$$b \to s\gamma(^*) : \mathcal{H}^{SM}_{\triangle F=1} \propto \sum V^*_{ts} V_{tb} \mathcal{C}_i \mathcal{O}_i + \ldots$$

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

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

$$\mathcal{C}_7^{\rm SM} = -0.29, \; \mathcal{C}_9^{\rm SM} = 4.1, \; \mathcal{C}_{10}^{\rm SM} = -4.3$$

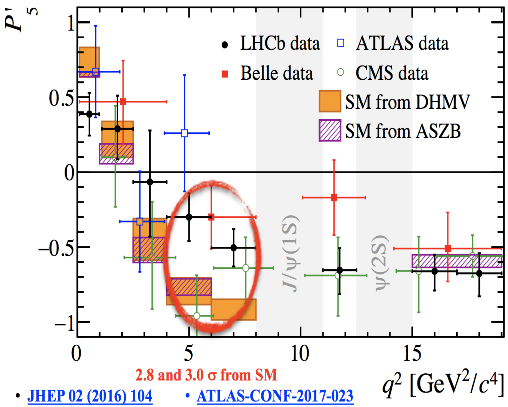
NP changes short-distance $\mathcal{C}_i = \mathcal{C}_i^{\rm SM} + \mathcal{C}_i^{\rm NP}$ for SM or involve additional operators $\mathcal{O}_i$

- Chirally flipped ($W \to W_R$) $\quad \mathcal{O}_{7'} \propto (\bar{s}\sigma^{\mu\nu} P_L \, b) F_{\mu\nu}, \; \mathcal{O}_{9'} \propto (\bar{s}\gamma_\mu P_R \, b)(\bar{\ell}\gamma^\mu \ell)$ ....
- (Pseudo)scalar ($W \to H^+$) $\quad \mathcal{O}_S \propto (\bar{s} P_R b)(\bar{\ell}\ell), \; \mathcal{O}_P \propto (\bar{s} P_R b)(\bar{\ell}\gamma_5 \ell)$
- Tensor operators ($\gamma \to T$) $\quad \mathcal{O}_T \propto \bar{s}\sigma_{\mu\nu}(1-\gamma_5) b \; \bar{\ell}\sigma_{\mu\nu}\ell$

The Anomalies

P_5'.... a closer look to the most tested anomaly (Type-I)

Is this an statistical fluctuation?



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

P_5' was proposed in **DMRV, JHEP 1301(2013)048**

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

Optimized Obs.: Soft form factor ($\xi_\perp$) cancellation at LO.

- 2013: 1fb^{-1} dataset LHCb found 3.7σ.
- 2015: 3fb^{-1} dataset LHCb (**black**) found 3σ in 2 bins.
  $\Rightarrow$ Predictions (**in orange**) from DHMV.
- Belle (**red**) confirmed it in a bin [4,8] few months ago.

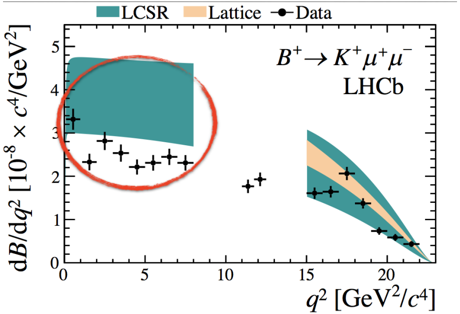
Is there a problem with hadronic uncertainties?: Two robust and independent analysis (same as F_L):

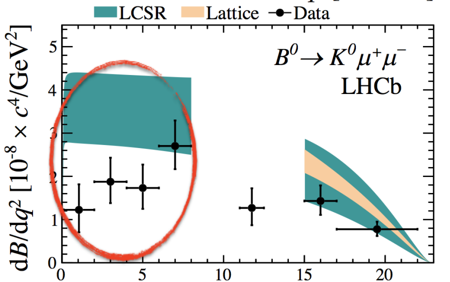
- ORANGE DHMV: using i-QCDF and KMPW FF+ 4 types of corrections.
- MAGENTA ASZB: using full FF from BSZ.

.... are in nice agreement and finds the anomaly.

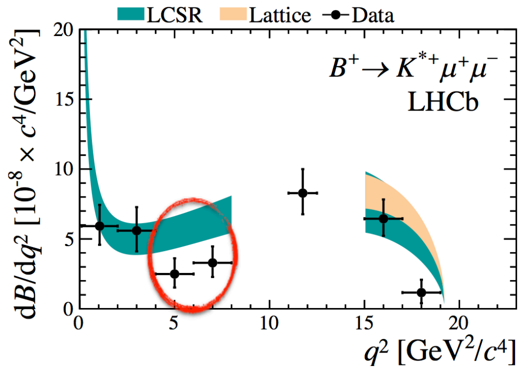
Other $b \to s\mu^+\mu^-$ observables tensions show up: (Coherence II)

Systematic deficit of muons at large-recoil but also at low-recoil:





JHEP 06 (2014) 133

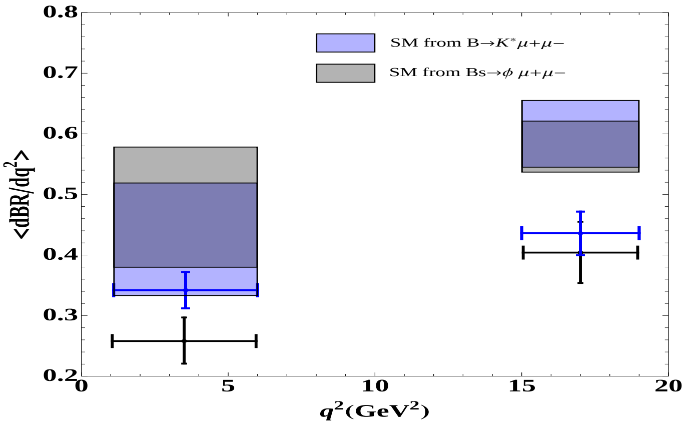


$b \to s\mu^+\mu^-$ $(\times 10^7)$	bin	SM	EXP	Pull
$\mathrm{BR}(B^0 \to K^0\mu^+\mu^-)$	[15,19]	0.91 ± 0.12	0.67 ± 0.12	+1.4
$\mathrm{BR}(B^0 \to K^{*0}\mu^+\mu^-)$	[16,19]	1.66 ± 0.15	1.23 ± 0.20	+1.7
$\mathrm{BR}(B^+ \to K^{*+}\mu^+\mu^-)$	[15,19]	2.59 ± 0.25	1.60 ± 0.32	**+2.5**
$\mathrm{BR}(B_s \to \phi\mu^+\mu^-)$	[15,18.8]	2.20 ± 0.17	1.62 ± 0.20	**+2.2**

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

Systematic low-recoil small tensions:

$10^7 \times \mathrm{BR}(B_s \to \phi\mu^+\mu^-)$	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**



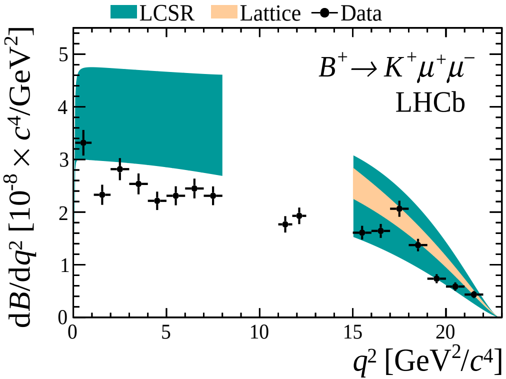
Even if still not statistically significant...

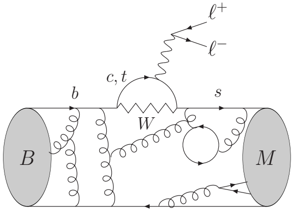
Form factors at low-q^2 for $B_s \to \phi$ (ONLY in BSZ not available in KMPW) are larger than $B \to K^*$, so we would expect at low-q^2 an INVERTED hierarchy with respect to data.
At high-q^2 data and theory (Lattice) seems ok.

... more data required.

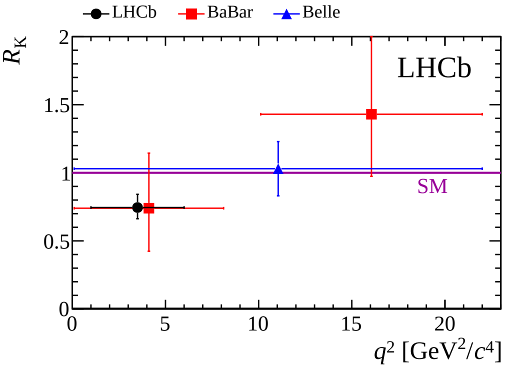
... or a problem of BSZ?

In the meanwhile (2014) new deviations appear...LFUV anomalies





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



⇒ It deviates $\mathbf{2.6\sigma}$ from SM.

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

⇒ NP coupling $\neq$ to μ and e.

Conceptually R_K very relevant:

1 **Tensions in R_K cannot be explained in the SM by neither factorizable power corrections* nor long-distance charm*.**

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

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

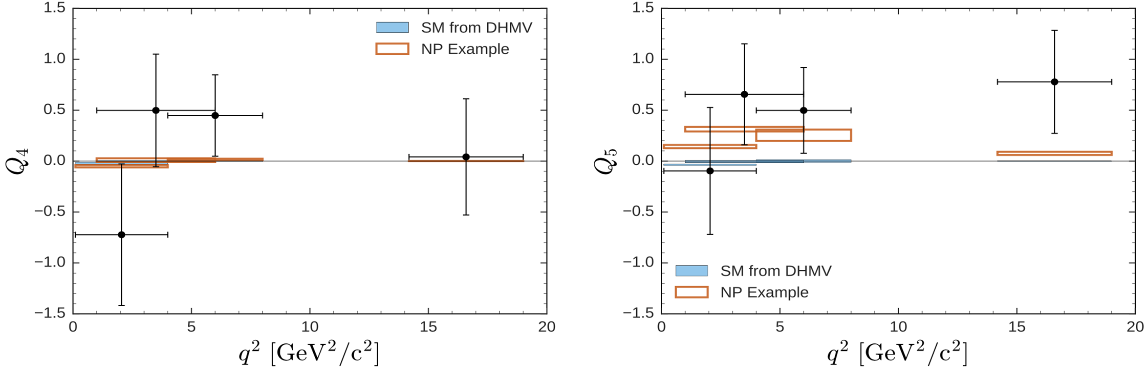


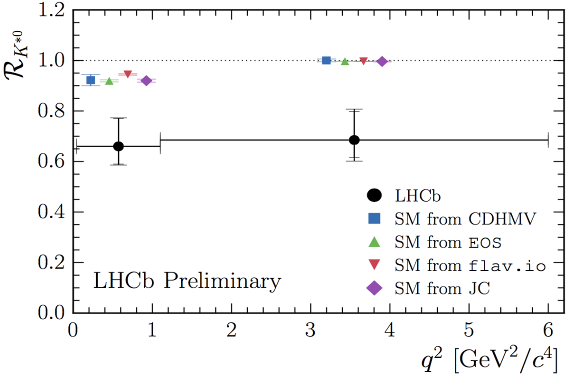
Figure 3: Q_4 and Q_5 observables with SM and favored NP "Scenario 1" from Ref. [6].

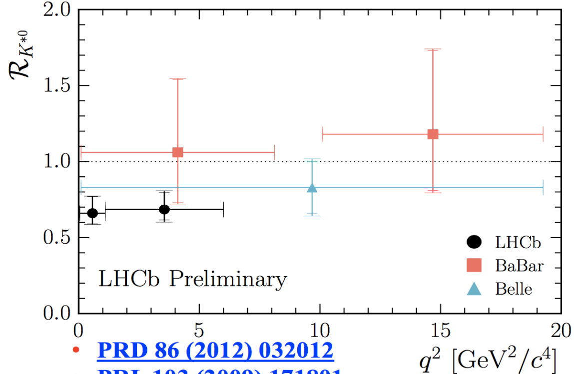
Table 2: Results for the lepton-flavor-universality-violating observables Q_4 and Q_5. The first uncertainty is statistical and the second systematic.

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]	$0.041 \pm 0.565 \pm 0.082$	$0.778 \pm 0.502 \pm 0.065$

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

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





- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

- Both R_K and R_{K^*} are very clean **in the SM and for** $q^2 \geq 1$ **GeV**^{2}.
  - Lepton mass effects even in the SM are important in the first bin.
    $\to$ Our error size in 1st and 2nd bin in agreement with Isidori et al. (including QED $\to 0.03$).
- In presence of New Physics or for $q^2 < 1$ GeV^2 **hadronic uncertainties return.**
  - Typical wrong statement "R_{K^*} is ALWAYS a very clean observable", indeed it is substantially less clean and more FF dependent than any optimized observable.

What is the impact now

on the global fit of the new data?

[Capdevila, Crivellin, Descotes, JM, Virto]

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

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

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

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

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

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

$$P'^{\ell}_i = \sigma_+ \, P'^{\ell}_i(B^+) + (1-\sigma_+)\, P'^{\ell}_i(\bar{B}^0)$$

▶ New ATLAS and CMS measurements on P_i.

Fit 2016: Statistical Approach

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

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

- $\mathbf{Cov} = \mathbf{Cov}^{\rm exp} + \mathbf{Cov}^{\rm th}$.
- Calculate $Cov^{\rm th}$: correlated multigaussian scan over all nuisance parameters
- $Cov^{\rm th}$ depends on $C_i^{\rm NP}$: Must check this dependence

For the Fit:

- Minimise $\chi^2 \to \chi^2_{\rm min} = \chi^2(C_i^{NP\,0})$ (Best Fit Point = $C_i^{NP\,0}$)
- Confidence level regions: $\chi^2(C_i^{NP}) - \chi^2_{\rm min} < \Delta\chi_{\sigma,n}$

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

- Hypotheses "NP in some $\mathcal{C}_i$ only" (1D, 2D, 6D) to be compared with SM **[CCDMV,1704.05340]**

	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.
$\to$ A scenario with a large SM-pull $\Rightarrow$ big improvement over SM and better description of data.

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

* Other groups (Altmannshofer, Straub et al.) do not have updated results for the **All-fit**.
$\to$ They have 5.2σ without including R_{K^*} (1703.09189)

The 1D solution (all) solves many anomalies and alleviates other tensions

Largest pulls	$\langle P_5' \rangle^{[4,6]}$	$\langle P_5' \rangle^{[6,8]}$	$\mathcal{B}^{[2,5]}_{B_s\to\phi\mu^+\mu^-}$	$\mathcal{B}^{[5,8]}_{B_s\to\phi\mu^+\mu^-}$	$\mathcal{B}^{[15,19]}_{B^+\to K^{*+}\mu^+\mu^-}$
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 ± 0.25
Pull (σ)	**-2.9**	**-2.9**	**+2.2**	**+2.2**	**+2.5**
Pred. $\mathcal{C}_{9\mu}^{\rm NP} = -1.1$	-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**

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. $\mathcal{C}_{9\mu}^{\rm NP} = -1.1$	0.79 ± 0.01	0.90 ± 0.05	0.87 ± 0.08
Pull (σ)	**+0.4**	**+1.9**	**+1.2**

.... we will come back to that later on.

Explain or alleviate tension in: P_5' **and large and low-recoil BR,** R_K**,** R_{K^*} **and** Q_5

Largest pulls	$\langle P_5' \rangle^{[4,6]}$	$\langle P_5' \rangle^{[6,8]}$	$\mathcal{B}^{[2,5]}_{B_s\to\phi\mu^+\mu^-}$	$\mathcal{B}^{[5,8]}_{B_s\to\phi\mu^+\mu^-}$	$\mathcal{B}^{[15,19]}_{B^+\to K^{*+}\mu^+\mu^-}$
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 ± 0.25
Pull (σ)	**-2.9**	**-2.9**	**+2.2**	**+2.2**	**+2.5**
Pred. $\mathcal{C}^{\rm NP}_{9\mu} = -1.76$	-0.26 ± 0.12	-0.52 ± 0.15	1.22 ± 0.22	1.37 ± 0.25	1.54 ± 0.10
Pull (σ)	**+0.2**	**-0.1**	**+1.7**	**+1.4**	**-0.3**

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. $\mathcal{C}^{\rm NP}_{9\mu} = -1.76$	0.69 ± 0.01	0.89 ± 0.09	0.83 ± 0.14
Pull (σ)	**-0.7**	**+1.6**	**+0.8**

LFUV implies a value for $\mathcal{C}_{9\mu}$ that even reduces FURTHER the tension.

2D hypothesis

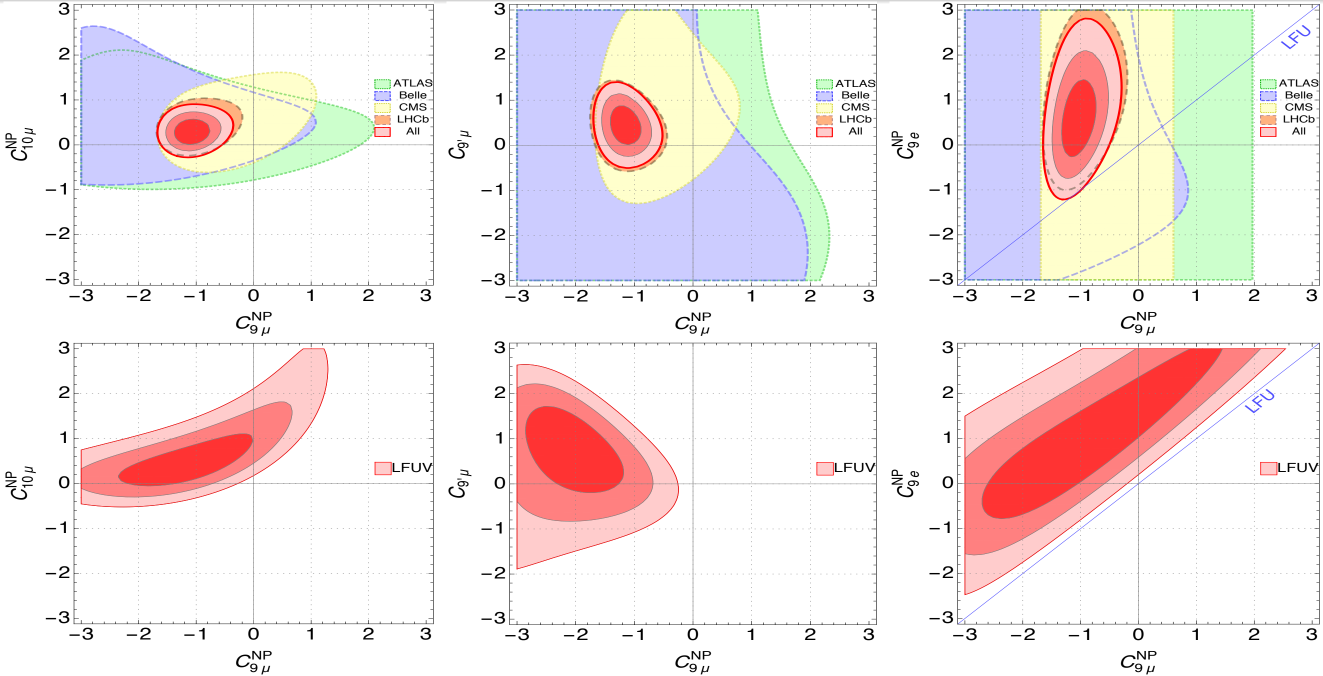
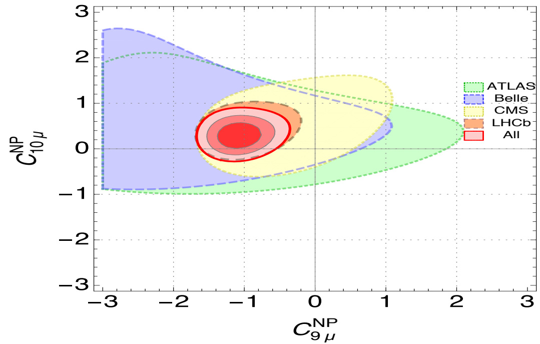
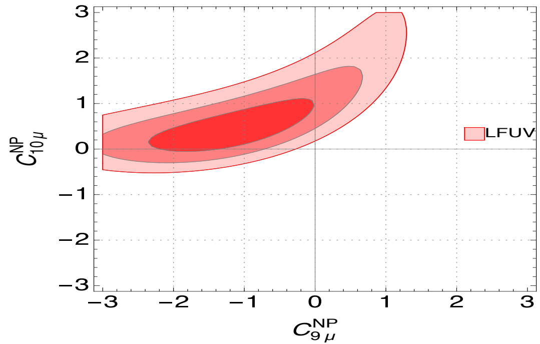


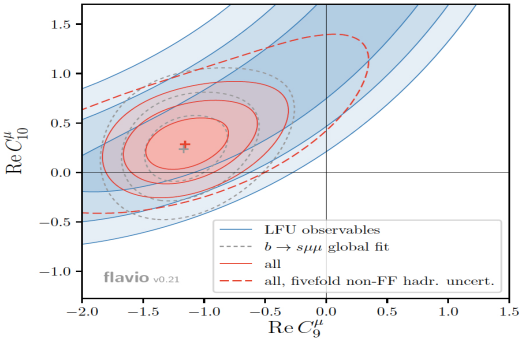
Figure: Allowed regions with all available data (upper) and only LFUV (lower) in good agreement. Constraints from $b \to s\gamma$ observables, $\mathcal{B}(B \to X_s\mu\mu)$ and $\mathcal{B}(B_s \to \mu\mu)$ always included. Experiments at 3σ.

Consistency with other analyses





[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])

Other similar works

Similar findings for other fits along same lines (no time to cover)

- Hurth, Mahmoudi, Martinez Santos, Neshatpour
- Ghosh, Nardecchia, Renner
- D'Amico et al. . .

Consistency in the pattern of deviations from

- $b \to s\mu\mu$ branching ratios
- $b \to s\mu\mu$ angular observables
- LFUV ratios

Two types of hadronic uncertainties, but variety of approaches

- Form factors: fit to LCSR and lattice, EFT + power corrections
- $c\bar{c}$ contributions: order of magnitude, LCSR, fit to the data
- all approaches give consistent results (favoured NP scenarios. . .)

(more will be discussed in the rest of the session)

(see also corresponding talks in session)

6D fit the most important one

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

	$\mathcal{C}_7^{\rm NP}$	$\mathcal{C}_{9\mu}^{\rm NP}$	$\mathcal{C}_{10\mu}^{\rm NP}$	$\mathcal{C}_{7'}$	$\mathcal{C}_{9'\mu}$	$\mathcal{C}_{10'\mu}$
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 σ → 5.0 σ (fit “All’ with the latest CMS data at 8 TeV included)

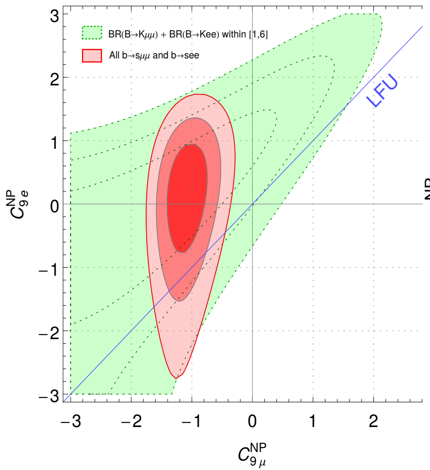
The pattern (very similar to DHMV15):

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

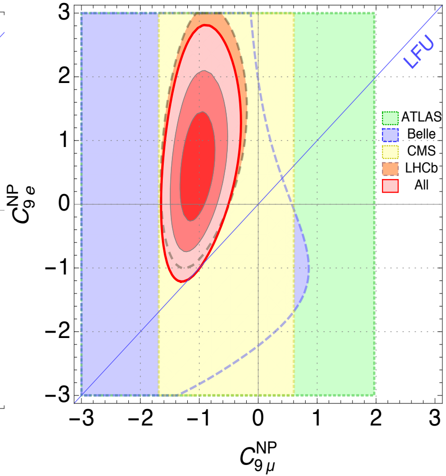
$\mathcal{C}_{9\mu}$ is compatible with the SM much beyond 3 σ, all the other coefficients at 1-2 σ.

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

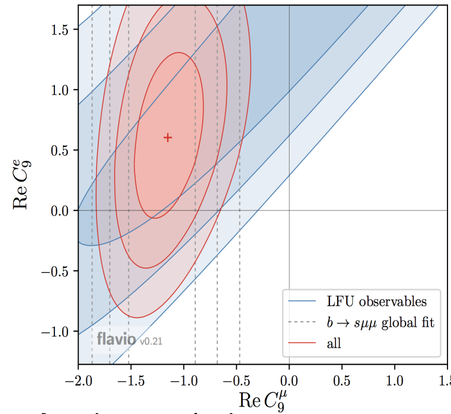
- $C_{9\mu} \sim -\mathcal{O}(1)$
- $C_{9e} \simeq 0$ compatible with SM albeit with large error bars.



2015, with R_K



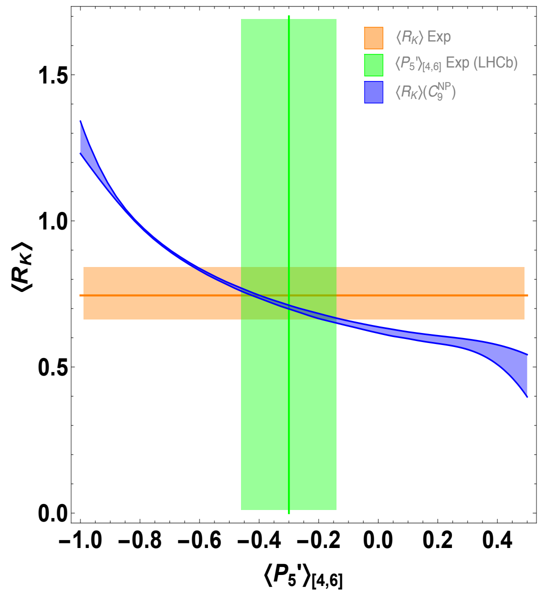
2017, with R_K, R_{K^*}, $Q_{4,5}$

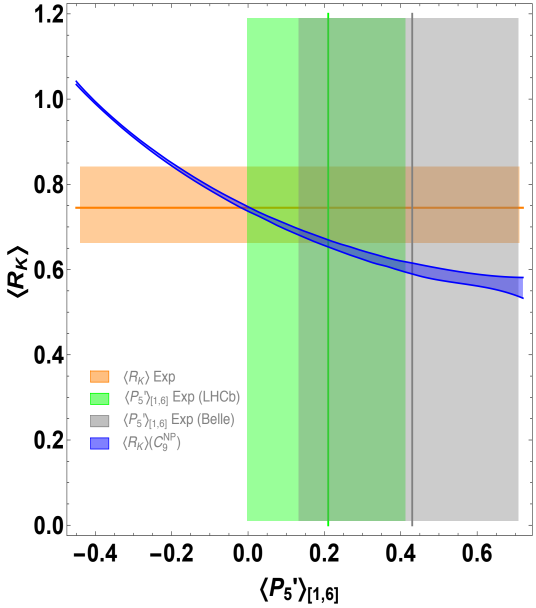


Another analysis [Altmannshofer, Stangl,Straub] using BSZ and different approach finds same results

LFUV (R_K) and $b \to s\mu^+\mu^-$ converges: (Coherence III)

[2] It shares the same explanation than P_5' and other $b \to s\mu\mu$ tensions. [M. Alguero, B. Capdevila, SDG, JM]





Only NP in $C_{9\mu}$ (**BLUE**), Green (LHCb), Gray (Belle).

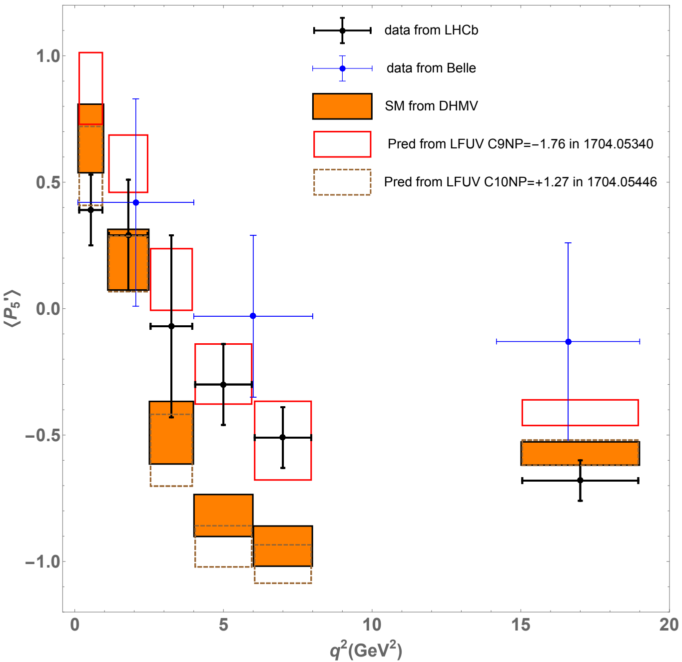
$\Rightarrow$ The attempts of explanation of anomalies in $b \to s\mu^+\mu^-$ based on hadronic arguments enter in crisis...

Experiment: Assume ONLY LFUV observables are measured: R_K, R_{K^*} and $Q_{4,5}$

Question: What they predict for P_5'?

Three cases:

- $C_{9\mu} = -1.76$ (RED) from our paper 1704.05340.
- $C_{10\mu} = +1.27$ (BROWN) from 1704.05446.
- NP in $C_{10e} \Rightarrow$ as bad as SM (ORANGE)



Progress on hadronic uncertainties

How far we can (and it is worth to) go on the theoretical precision for:

- $b \to s\mu\mu$: Optimized observables: P_i

  and non-optimized observables S_i, F_L, $\mathcal{B}$

- LFUV observables: $R_{X=K,K*,\phi}$ and Q_i

Important to find a balance between:

a) Precision / conservative approach for non-perturbative pieces.

b) Parametric and model dependent assumptions of LCSR computation.

... idea behind optimized and SFF treatment is to reduce as much as possible this dependence.

Final Goal: New Physics Discovery should be robust and NOT depend largely on b.

Improvements on $b \to s\mu^+\mu^-$ observables

Two main places where one can do progress:

- Form Factors:
  - Different Theoretical Treatment of Form Factors:

    $\Rightarrow$ Full form factor approach:

    $\boxed{1}$ Particular method specific to the set of Form Factors.

    $\boxed{2}$ All errors and **correlations** depend on inner LCSR assumptions.

    $\Rightarrow$ **Soft form factor approach**: valid for any FF/flexible, robust and conservative.

    $\boxed{1}$ General method valid for any set of Form Factors.

    $\boxed{2}$ Main **correlations** are encoded via robust large-recoil symmetries, ... independent of LCSR assumptions.

    Natural language for construction of OPTIMIZED observables P_i.

  - Choice of LCSR Form Factor:
    - KMPW: based on LCSR with B meson distribution amplitudes.
    - BSZ: based on LCSR with K^* light-meson distribution amplitudes.
- Non-factorizable perturbative and non-perturbative (i.e. long distance charm contribution)

Form Factors and their Treatment

- Scheme definition:

$$\xi_\perp(q^2) = \tfrac{m_B}{m_B+m_{K^*}} V(q^2) \quad \text{and} \quad \xi_\parallel(q^2) = \tfrac{m_B+m_{K^*}}{2E} A_1(q^2) - \tfrac{m_B-m_{K^*}}{m_B} A_2(q^2)$$

$$\langle \ell^+\ell^- \bar{K}_i^* | \mathrm{H_{eff}} | \bar{B} \rangle = C_i \xi_i + \Phi_B \otimes T_i \otimes \Phi_{K^*} + \mathcal{O}(\Lambda/m_b)$$

$C_i = 1 + \mathcal{O}(\alpha_s)$ hard-vertex renormalization and T_i hard-scattering kernels computed in α_s-expansion. Φ_i light-cone wave functions.

$$F^{full}(q^2) = F^\infty(\xi_\perp, \xi_\parallel) + \triangle F^{\alpha_s}(q^2) + \triangle F^{p.c.}(q^2) \qquad F^{full} = V, A_1, A_2, ...$$

- $F^\infty(\xi_\perp, \xi_\parallel)$ main source of correlations: **robust large-recoil symmetries** independent of LCSR details.

$$\xi_\perp = \frac{m_B}{m_B + m_{K^*}} V = \frac{m_B + m_{K^*}}{2E_{K^*}} A_1 = T_1 = \frac{m_B}{2E_{K^*}} T_2 \qquad +O(\alpha_s, \Lambda/m_b)\ \mathrm{corr}$$

breaking of large-recoil symmetries:

- $\triangle F^{\alpha_s}(q^2)$: α_s scheme-dependent correction (Beneke et al.)

  → Improvement: $\mathcal{O}(\alpha_s^2)$ correction (Beneke et al.) but subleading
- $\triangle F^{p.c.}(q^2)$: expansion in q^2/m_b^2
  - central value obtained from fit to full form factor.
  - Treatment of error: $\mathcal{O}(\Lambda/m_b) \times F$ (model-independent and scheme dependent) as large as cv of p.c. itself or fully correlated (LCSR dependent) and scheme independent

Different Form Factor determinations

B-meson distribution amplitudes.

FF-KMPW	$F^i_{BK^{(*)}}(0)$	b^i_1
f^+_{BK}	$0.34^{+0.05}_{-0.02}$	$-2.1^{+0.9}_{-1.6}$
f^0_{BK}	$0.34^{+0.05}_{-0.02}$	$-4.3^{+0.8}_{-0.9}$
f^T_{BK}	$0.39^{+0.05}_{-0.03}$	$-2.2^{+1.0}_{-2.00}$
V^{BK^*}	$\mathbf{0.36^{+0.23}_{-0.12}}$	$-4.8^{+0.8}_{-0.4}$
$A_1^{BK^*}$	$\mathbf{0.25^{+0.16}_{-0.10}}$	$0.34^{+0.86}_{-0.80}$
$A_2^{BK^*}$	$0.23^{+0.19}_{-0.10}$	$-0.85^{+2.88}_{-1.35}$
$A_0^{BK^*}$	$0.29^{+0.10}_{-0.07}$	$-18.2^{+1.3}_{-3.0}$
$T_1^{BK^*}$	$0.31^{+0.18}_{-0.10}$	$-4.6^{+0.81}_{-0.41}$
$T_2^{BK^*}$	$0.31^{+0.18}_{-0.10}$	$-3.2^{+2.1}_{-2.2}$
$T_3^{BK^*}$	$0.22^{+0.17}_{-0.10}$	$-10.3^{+2.5}_{-3.1}$

Table: The $B \to K^{(*)}$ form factors from LCSR and their z-parameterization.

Light-meson distribution amplitudes+EOM.

- Interestingly in BSZ (update from BZ) some of most relevant FF from BZ moved towards KMPW. For example:

$$V^{BZ}(0) = 0.41 \to 0.34, \quad A_1^{BZ}(0) = 0.29 \to 0.27$$

- The size of uncertainty in BSZ = size of error of p.c.

FF-BSZ	$B \to K^*$	$B_s \to \phi$
$A_0(0)$	0.356 ± 0.046	0.389 ± 0.045
$A_1(0)$	$\mathbf{0.269 \pm 0.029}$	$\mathbf{0.296 \pm 0.027}$
$A_{12}(0)$	0.256 ± 0.033	0.246 ± 0.029
$V(0)$	$\mathbf{0.341 \pm 0.036}$	$\mathbf{0.387 \pm 0.033}$
$T_1(0)$	0.282 ± 0.031	0.309 ± 0.027
$T_2(0)$	0.282 ± 0.031	0.309 ± 0.027
$T_{23}(0)$	0.668 ± 0.083	0.676 ± 0.071

Table: Values of the form factors at $q^2 = 0$ and their uncertainties.

* $6 - 10\%$ shift in one DA affected the error of twist-4

Framework: l-QCDF + SFF + KMPW+ p.c. + conservative estimate of errors of p.c.

What is the impact in the region of the anomaly [4,6] and [6,8] of improving FF error by 50% in:

- Optimized observable P_5' (in percentage present error size)

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

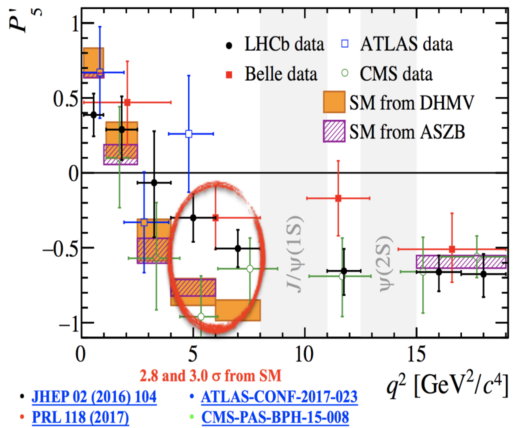
$\longrightarrow$ interestingly BSZ-FF+full-FF approach finds 0.05

$$P'_{5[6,8]} = -0.94 \pm 0.08(\mathbf{9}\%) \rightarrow 0.06(\mathbf{6}\%)$$

- Non-optimized observable S_5

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

$$S_{5[6,8]} = -0.43 \pm 0.10(\mathbf{23}\%) \rightarrow 0.05(\mathbf{11}\%)$$

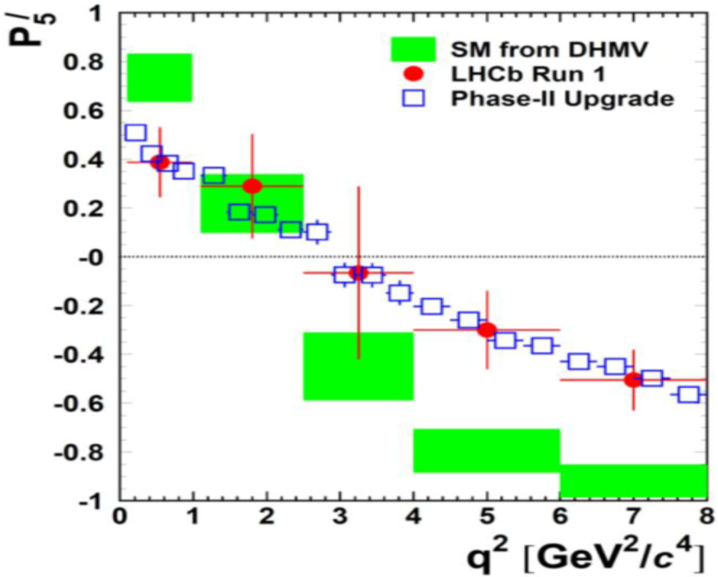


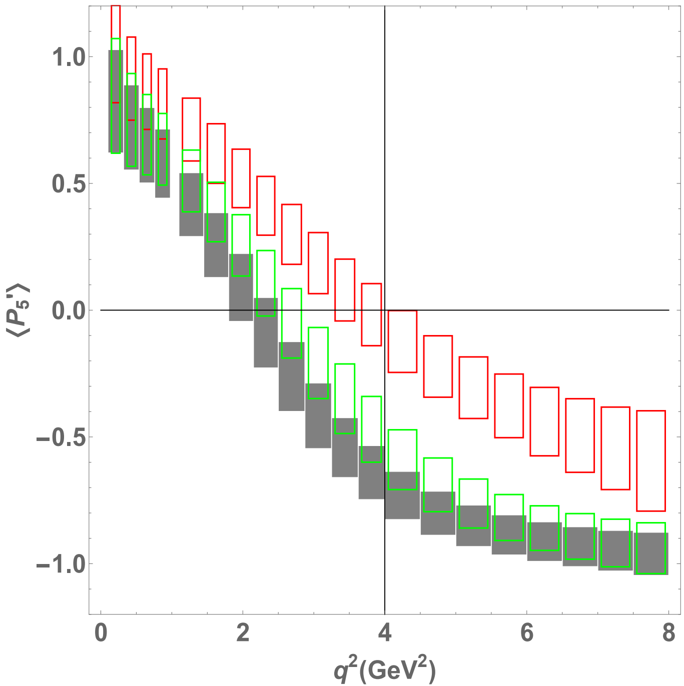
Optimized observables are less sensitive to FF changes (as expected) than non-optimized.

At present our conservative estimate include in general both approaches and FF,

... in the future we may think in averaging them.

Projections from LHCb for P_5' in Phase-II Upgrade. [Taken from LHCb]





A large number of small bins open the window in P_5' for a different observable: zero of P_5'.

At LO:

$$q_0^2 = -\frac{m_b m_B^2 \mathcal{C}_7^{\rm eff}}{m_b \mathcal{C}_7^{\rm eff} + m_B \mathcal{C}_9^{\rm eff}(q_0^2)}$$

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 $q_0^{C_9^{\rm NP}} \simeq 3.8$ GeV².
- Marginal shift of zero $q_0^{C_9^{\rm NP}=-C_{10}^{\rm NP}} \simeq 2.7$ GeV²

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

Non-factorizable contributions:

Perturbative and from long-distance charm

Non-factorizable perturbative contributions in α_s expansion

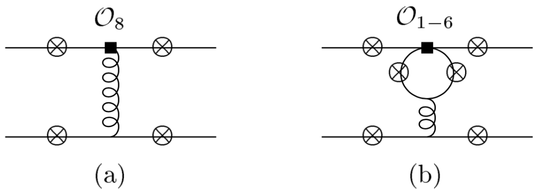
Correction not contained in the definition of the QCD form factors for heavy-to-light transitions:

$\Rightarrow$ they should be added on top of ANY Form Factor computation

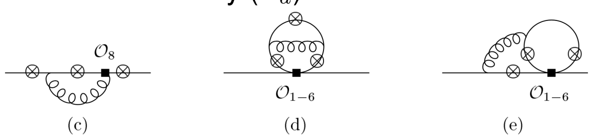
$$\mathcal{T}_a = \xi_a \left(C_a^{(0)} + \frac{\alpha_s C_F}{4\pi} C_a^{(1)} \right) + \frac{\pi^2}{N_c} \frac{f_B f_{K^*,a}}{M_B} \Sigma_a \sum_{\pm} \int \frac{d\omega}{\omega} \Phi_{B,\pm}(\omega) \int_0^1 du \Phi_{K^*,a}(u) T_{a,\pm}(u,\omega)$$

$a = \perp, \parallel$ & $f_{K^*,\perp}$ refers to the transverse decay constant. Two types of non-factorizable contributions:

- Hard spectator scattering (T_a): matrix elements of 4-quark op. and the chromomagnetic O_8 operator



- Diagrams involving the $b \to s$ transition only (C_a)



$\to$ Improvement: $\mathcal{O}(\alpha_s^2)$ correction... probably marginal and not known

Perturbative and non-perturbative charm

Problem: Charm-loop yields q^2- and hadronic-dependent contribution with $O_{7,9}$ structures that may mimic New Physics.

$$C_{9i}^{\rm eff}(q^2) = C_{9\,\rm SMpert} + C_9^{\rm NP} + \mathbf{s_i}\delta\mathbf{C_{9i}^{c\bar{c}LD}(q^2)}. \qquad \mathbf{i} = \perp, \|, \mathbf{0}$$

Perturbative: $C_{9\,\rm SMpert} = C_9^{\rm SM} + Y(q^2)$

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

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

$\rightarrow$ Marginal Perturbative improvement with the 2-loop matrix elements of penguin operators

Non-perturbative: $\delta\mathbf{C_{9i}^{c\bar{c}LD}(q^2)}$

More difficult to make progress here:

1. Use LCSR to try to estimate long-distance contribution with soft-gluon exchange.
2. One can try to ask data:

$\rightarrow$ the proof of existence of a significant long-distance q^2-contribution requires a C_9 dependent on q^2.
(besides the known or included already)

Option 1: Theory approach to long-distance charm

1. THE FIRST 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:

$$\mathcal{H}_\mu^{B\to K^*}(p,q) = i\int d^4x e^{iqx}\langle K^*(p)|T\left\{\bar{c}(x)\gamma_\mu c(x)[C_1O_1 + C_2O_2]\right\}|B(p+q)\rangle$$

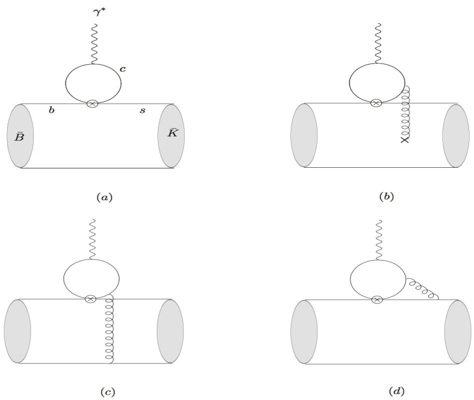
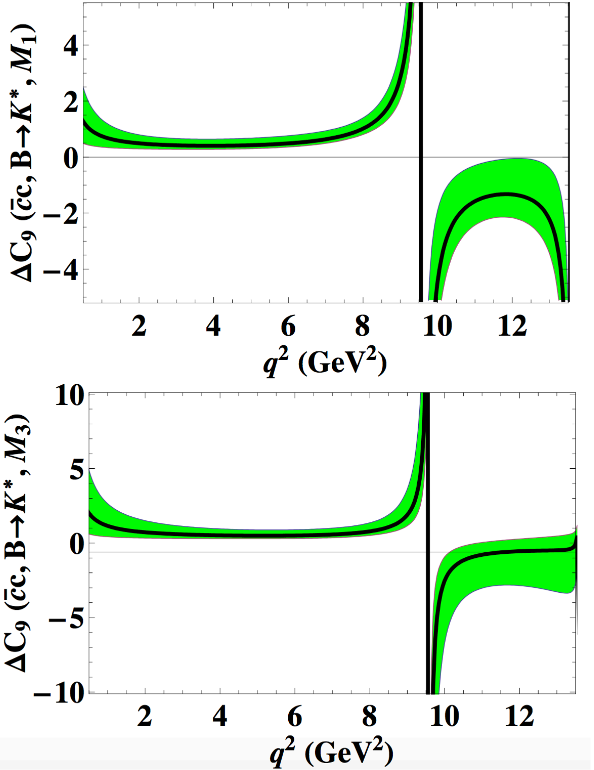


Figure 1: *Charm-loop effect in $B\to K^{(*)}\ell^+\ell^-$: (a)-the leading-order factorizable contribution; (b) nonfactorizale soft-gluon emission, (c),(d)-hard gluon exchange.*

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

- emission of one soft gluon (with low virtuality but nonvanishing momentum) from the c-quark loop.
- dispersion relation is used to extend it to all region.
- hadronic matrix elements uses LCSR with B-meson DA.



- charm-loop effect is represented as a correction to the Wilson coefficient C_9:

$$C_9^{\rm eff\,i} = C_9^{\rm eff}{}_{\rm SM\,pert}(q^2) + C_9^{\rm NP} + s_i \delta C_9^{c\bar{c}(i)LD}{}_{\rm KMPW}(q^2)$$

  $i = \perp, \|, 0$ (where $s_i = 1$ KMPW)

- it is q^2 and helicity dependent result (contrary to a constant universal contribution)

- At face value KMPW long-distance charm computation ($s_i = 1$) implies that the anomaly becomes larger!!!

- How do we treat it? We introduce a parameter $s_i = [-1, 1]$ for each amplitude to include the possibility of a relative phase $\Rightarrow$ our predictions tipically has the largest error from l.d.c.

- **Constructive approach**: Improve this computation within LCSR (more gluons) and/or lattice computation of l.d.c if possible.

Improving on KMPW analysis (Bobeth, Chrzaszcz, van Dyk, Virto' 1707.07305)

Using analytic properties of $\mathcal{H}_\lambda$ function together with experimental information on $B \to K^* J/\psi$ and $B \to K^* \psi(2S)$ and including known QCDF corrections at NLO in α_s write a general parametrization of $\mathcal{H}_\lambda$ in a z-expansion parametrization. ...caveat impact of order of z-truncation.

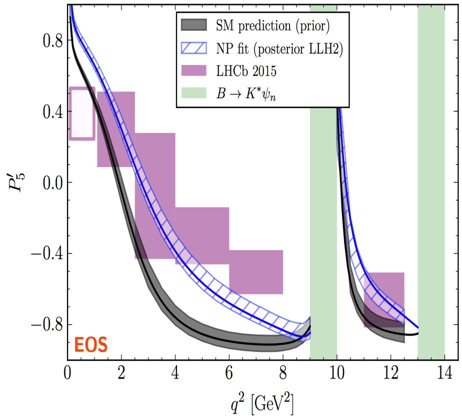
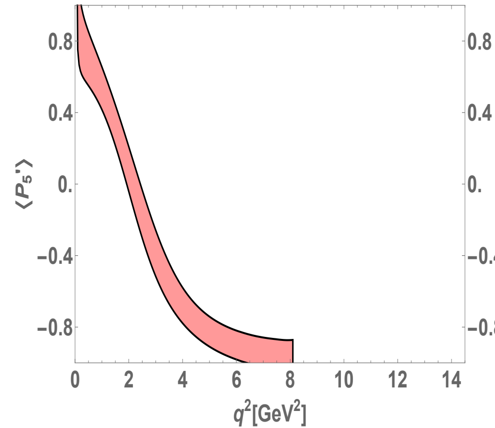


FIG. 2. Prior and posterior predictions for P_5' within the SM and the NP C_9 benchmark, compared to LHCb data.



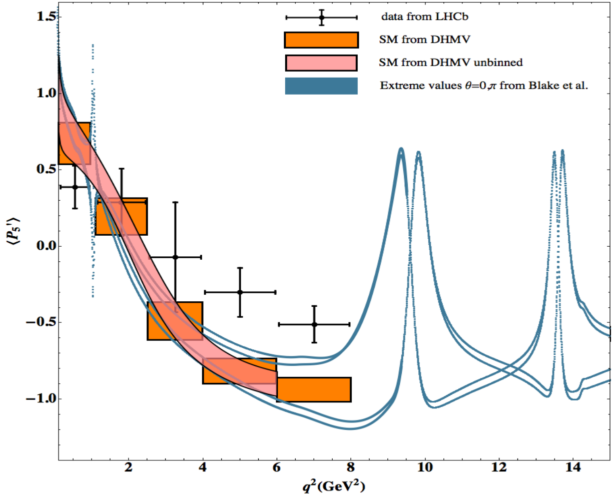
Our prediction for P_5' using KMPW and allowing s_i from $[-1, 1]$.

A comparison between both shows that left prediction fits nicely within our error band but with a clear preference for values pointing to **larger anomaly** in [4,6] if Bobeth et al. is used ($> 3\sigma$).

Long distance charm tests using data II

More arguments to discard long distance charm as a solution.

• Empirical model of long distance contributions based on the use of data on final states involving $J^{\rm PC} = 1^{--}$ resonances [1709.03971]
⇒ Agreement with our error estimate.
⇒ Anomaly cannot be explained.



This plot is reevaluated USING KMPW (in the original paper BSZ is used)

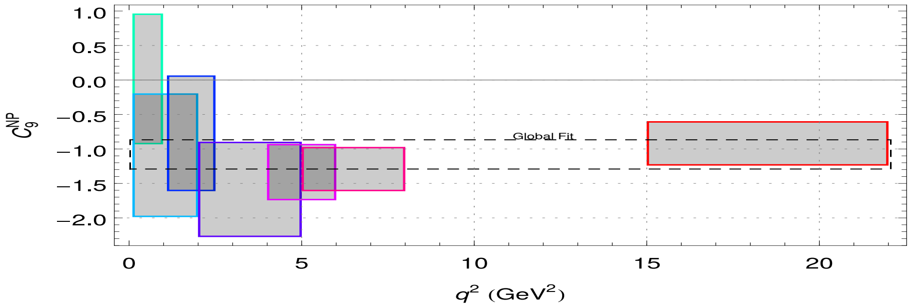
What data can tell us on the existence **or not** of a new and significant q^2 dependence in C_9?

Option 2: What data can tell us on the question charm versus New Physics?

How to disentangle? Is our long-dist $c\bar{c}$ estimate using KMPW as order of magnitude correct?

1 Fit to C_9^{NP} bin-by-bin of $b \to s\mu\mu$ data:

- NP is universal and q^2-independent.
- Hadronic effect associated to $c\bar{c}$ dynamics is (likely) q^2-dependent.



- The excellent agreement of bins [2,5], [4,6], [5,8]: $C_9^{NP\,[2,5]} = -1.6 \pm 0.7$, $C_9^{NP\,[4,6]} = -1.3 \pm 0.4$, $C_9^{NP\,[5,8]} = -1.3 \pm 0.3$ shows **no indication of <u>additional</u> q^2- dependence.**

EXPERIMENT: More precise data will allow to reduce this error between these two bins.

Another approach....now converging with us if no extra hypothesis used

The analysis of [Ciuchini et al.] introduces for each helicity $\lambda = 0, \pm 1$ a second-order polynomial in q^2:

$$h_\lambda = h_\lambda^{(0)} + \frac{q^2}{1\ \mathrm{GeV}^2} h_\lambda^{(1)} + \frac{q^4}{1\ \mathrm{GeV}^4} h_\lambda^{(2)}.$$

then enter the $B \to K^* \mu^+ \mu^-$ transversity amplitudes as follows:

$$\begin{aligned}
A^0_{L,R} &= A^0_{L,R}(s_i = 0) + \frac{N}{q^2}\left(\frac{q^2}{1\ \mathrm{GeV}^2} h_0^{(1)} + \frac{q^4}{1\ \mathrm{GeV}^4} h_0^{(2)}\right), \\
A^{\|}_{L,R} &= A^{\|}_{L,R}(s_i = 0) \\
&\quad + \frac{N}{\sqrt{2} q^2}\left[(h_+^{(0)} + h_-^{(0)}) + \frac{q^2}{1\ \mathrm{GeV}^2}(h_+^{(1)} + h_-^{(1)}) + \frac{q^4}{1\ \mathrm{GeV}^4}(h_+^{(2)} + h_-^{(2)})\right], \\
A^{\perp}_{L,R} &= A^{\perp}_{L,R}(s_i = 0) \\
&\quad + \frac{N}{\sqrt{2} q^2}\left[(h_+^{(0)} - h_-^{(0)}) + \frac{q^2}{1\ \mathrm{GeV}^2}(h_+^{(1)} - h_-^{(1)}) + \frac{q^4}{1\ \mathrm{GeV}^4}(h_+^{(2)} - h_-^{(2)})\right],
\end{aligned}$$

* Be careful one should not include a pole in A_0 (h_0^0 **should be zero**).

$$h_\pm^{(0)} \to C_7,\ h_\lambda^{(1)} \to C_9 \text{ and the question is:}$$

is there any need for $h_\lambda^{(2)}$ that will imply a $C_9(q^2)$ beyond known ones?

• We implemented [JHEP 1704 (2017) 016] different analysis: SM, NP, different FFs,...⇒

Updated table with no h_0^0:

Example:

2 $B \to K^*\mu\mu$ only - $C_{9\mu}^{NP} = -1.1$

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

n	0		1		2		3	
$\chi^{2(n)}_{\min}$	62.10		51.60		50.50		50.00	
$\chi^{2(n-1)}_{\min} - \chi^{2(n)}_{\min}$	1.23	$(0.3\ \sigma)$	10.50	$(2.4\ \sigma)$	1.14	$(0.3\ \sigma)$	0.53	$(0.1\ \sigma)$
$h_+^{(0)}$	$0.66^{+1.06}_{-0.55}$	$(1.2\ \sigma)$	$1.97^{+1.32}_{-0.51}$	$(3.8\ \sigma)$	$1.62^{+1.22}_{-1.00}$	$(1.6\ \sigma)$	$1.43^{+1.13}_{-0.80}$	$(1.8\ \sigma)$
$h_+^{(1)}$			$-1.92^{+0.81}_{-0.76}$	$(2.4\ \sigma)$	$-1.29^{+1.70}_{-1.75}$	$(0.8\ \sigma)$	$-1.45^{+1.40}_{-0.74}$	$(1.0\ \sigma)$
$h_+^{(2)}$					$-0.16^{+0.24}_{-0.09}$	$(0.7\ \sigma)$	$-0.09^{+0.08}_{-0.16}$	$(1.2\ \sigma)$
$h_+^{(3)}$							$0.00^{+0.01}_{-0.00}$	$(0.0\ \sigma)$
$h_-^{(0)}$	$-0.14^{+1.43}_{-0.93}$	$(0.1\ \sigma)$	$1.90^{+1.99}_{-1.64}$	$(1.2\ \sigma)$	$1.87^{+2.71}_{-1.31}$	$(1.4\ \sigma)$	$1.93^{+1.93}_{-0.93}$	$(2.1\ \sigma)$
$h_-^{(1)}$			$-0.81^{+0.68}_{-0.43}$	$(1.2\ \sigma)$	$-0.56^{+0.48}_{-1.32}$	$(1.2\ \sigma)$	$-0.65^{+0.59}_{-0.82}$	$(1.1\ \sigma)$
$h_-^{(2)}$					$-0.04^{+0.22}_{-0.07}$	$(0.2\ \sigma)$	$-0.02^{+0.14}_{-0.10}$	$(0.1\ \sigma)$
$h_-^{(3)}$							$-0.00^{+0.00}_{-0.00}$	$(0.2\ \sigma)$
$h_0^{(0)}$								
$h_0^{(1)}$			$-1.28^{+1.17}_{-1.24}$	$(1.1\ \sigma)$	$-2.24^{+1.64}_{-1.43}$	$(1.4\ \sigma)$	$-2.08^{+0.90}_{-1.38}$	$(2.3\ \sigma)$
$h_0^{(2)}$					$0.08^{+0.17}_{-0.07}$	$(1.1\ \sigma)$	$0.16^{+0.17}_{-0.12}$	$(1.3\ \sigma)$
$h_0^{(3)}$							$-0.00^{+0.01}_{-0.00}$	$(0.5\ \sigma)$

n refers to h_λ^n

No significant improvement in the quality of the fit that require to go beyond the $h_\lambda^{(1)}$ term.

(Ciuchini et al.) paper (next talk) also converges now in this direction

In the frame where only data is used PMD (no controversial enforced constraints at very low-q^2):

→ A comparison between 2015 and 2017 analysis quite interesting.

Parameter	Absolute value	Phase (rad)
$h_0^{(0)}$	$(5.8 \pm 2.1) \cdot 10^{-4}$	3.54 ± 0.56
$h_0^{(1)}$	$(2.9 \pm 2.1) \cdot 10^{-4}$	0.2 ± 1.1
$h_0^{(2)}$	$(3.4 \pm 2.8) \cdot 10^{-5}$	-0.4 ± 1.7
$h_+^{(0)}$	$(4.0 \pm 4.0) \cdot 10^{-5}$	0.2 ± 1.5
$h_+^{(1)}$	$(1.4 \pm 1.1) \cdot 10^{-4}$	0.1 ± 1.7
$h_+^{(2)}$	$(2.6 \pm 2.0) \cdot 10^{-5}$	3.8 ± 1.3
$h_-^{(0)}$	$(2.5 \pm 1.5) \cdot 10^{-4}$	$1.85 \pm 0.45 \cup 4.75 \pm 0.75$
$h_-^{(1)}$	$(1.2 \pm 0.9) \cdot 10^{-4}$	$-0.90 \pm 0.70 \cup 0.80 \pm 0.80$
$h_-^{(2)}$	$(2.2 \pm 1.4) \cdot 10^{-5}$	0.0 ± 1.2

Table 5. *Results for the parameters defining the nonfactorizable power corrections h_λ obt without using the numerical information from ref. [47].*

Par.	(I)	(II)	(III)	(IV)	(V)	(VI)
C_7^{NP}	–	–	0.015 ± 0.014	-0.011 ± 0.013	0.003 ± 0.013	0.015 ± 0.014
$C_{9,\mu}^{NP}$	-1.58 ± 0.28	-1.53 ± 0.25	-1.66 ± 0.29	–	-0.54 ± 0.17	-1.64 ± 0.29
$C_{9,e}^{NP}$	-0.10 ± 0.45	–	-0.18 ± 0.46	–	0.09 ± 0.25	-1.6 ± 1.0
$C_{10,\mu}^{NP}$	–	0.03 ± 0.16	–	-0.12 ± 0.22	0.54 ± 0.17	0.009 ± 0.200
$C_{10,e}^{NP}$	–	–	–	-1.22 ± 0.37	-0.09 ± 0.25	-0.91 ± 0.76
$\lvert h_0^{(0)}\rvert \cdot 10^4$	2.1 ± 1.2	2.0 ± 1.2	2.2 ± 1.3	1.8 ± 1.2	1.3 ± 1.0	2.0 ± 1.3
$\lvert h_+^{(0)}\rvert \cdot 10^4$	0.079 ± 0.067	0.079 ± 0.067	0.076 ± 0.065	0.083 ± 0.069	0.086 ± 0.072	0.076 ± 0.064
$\lvert h_-^{(0)}\rvert \cdot 10^4$	0.53 ± 0.19	0.54 ± 0.19	0.52 ± 0.19	0.56 ± 0.20	0.60 ± 0.21	0.52 ± 0.19
$\lvert h_0^{(1)}\rvert \cdot 10^4$	0.30 ± 0.23	0.30 ± 0.22	0.30 ± 0.23	0.45 ± 0.26	0.32 ± 0.24	0.28 ± 0.22
$\lvert h_+^{(1)}\rvert \cdot 10^4$	0.22 ± 0.20	0.22 ± 0.19	0.22 ± 0.19	0.21 ± 0.19	0.26 ± 0.22	0.22 ± 0.19
$\lvert h_-^{(1)}\rvert \cdot 10^4$	0.23 ± 0.19	0.23 ± 0.19	0.23 ± 0.20	0.30 ± 0.21	0.32 ± 0.22	0.23 ± 0.19
$\lvert h_+^{(2)}\rvert \cdot 10^4$	0.052 ± 0.045	0.053 ± 0.045	0.052 ± 0.044	0.046 ± 0.042	0.064 ± 0.053	0.050 ± 0.044
$\lvert h_-^{(2)}\rvert \cdot 10^4$	0.046 ± 0.038	0.046 ± 0.039	0.046 ± 0.039	0.092 ± 0.050	0.070 ± 0.047	0.045 ± 0.038

Table 2 *Results from the fit for WCs and hadronic contributions in the PMD approach. See Sec. 2.1 for details on the six NP scenarios.*

LEFT (2015): ONLY large-recoil $B \to K^* \mu^+ \mu^-$ data, $\mathbf{h}_\lambda^{\mathbf{i}}$ **large** with NO New Physics assuming that there is an unknown **large** long-distance charm with emphasis on $\mathbf{h}_-^{(\mathbf{2})} \neq \mathbf{0}$.

RIGHT (2017): MORE data (low-recoil missing) and now they NEED New Physics and in 4 out of 6 scenarios: $h_-^{(2)}$ is **one order of magnitude smaller and more consistent with zero!**

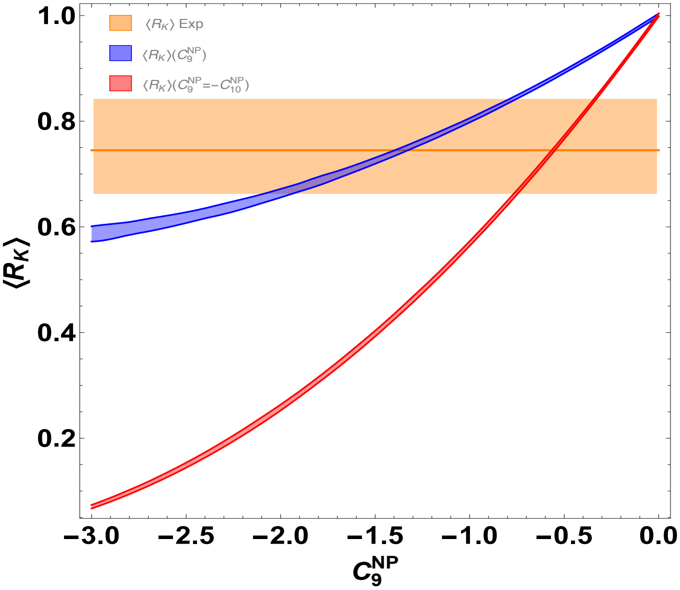
$$h_-^{(2)2015} = (2.2 \pm 1.4) \times 10^{-5} \to h_-^{(2)2017} = (0.4 \pm 0.4) \times 10^{-5}$$

→ **in good agreement with our previous result (except Sc4 and partly Sc5)**

What about LFUV observables?

Classification according to sensitivity to hadronic uncertainties in presence of New Physics: Ratios of BR, R_K

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



BLUE $C_9^{\rm NP}$, RED $C_9^{\rm NP} = -C_{10}^{\rm NP}$

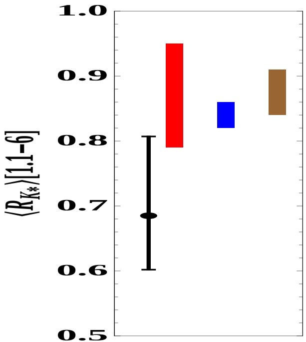
- $C_9^{\rm NP} < 0$ and $C_{10}^{\rm NP} > 0$ same weight adds coherently.
- Central value of R_K prefers a large negative contrib. to $C_9^{\rm NP}$ in excellent agreement with P_5' anomaly.

Classification according to sensitivity to hadronic uncertainties in presence of New Physics: Ratios of BR, R_{K^*}

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

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

- In presence of NP or for $q^2 < 1$ GeV^2 **hadronic uncertainties return.**
- Two surces: $\delta R_{K^*} \propto (C_i^\mu - C_i^e)\delta FF$ and interference in quadratic $(C_i^\mu - C_i^e)^2$ terms.



Predictions R_{K^*}			
Bins	$[0.045, 1.1]$	$[1.1, 6.]$	$[15., 19.]$
Standard Model	0.916 ± 0.025	1.000 ± 0.006	0.998 ± 0.001
$C_{9\mu}^{\text{NP}} = -1.11$	0.897 ± 0.049	0.867 ± 0.080	0.788 ± 0.005
$C_{9\mu}^{\text{NP}} = -1.76$	0.895 ± 0.084	0.827 ± 0.137	0.698 ± 0.009
$C_{9\mu}^{\text{NP}} = -C_{10\mu}^{\text{NP}} = -0.62$	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 and $C_9 < 0$ $C_{10} > 0$ adds coherently.

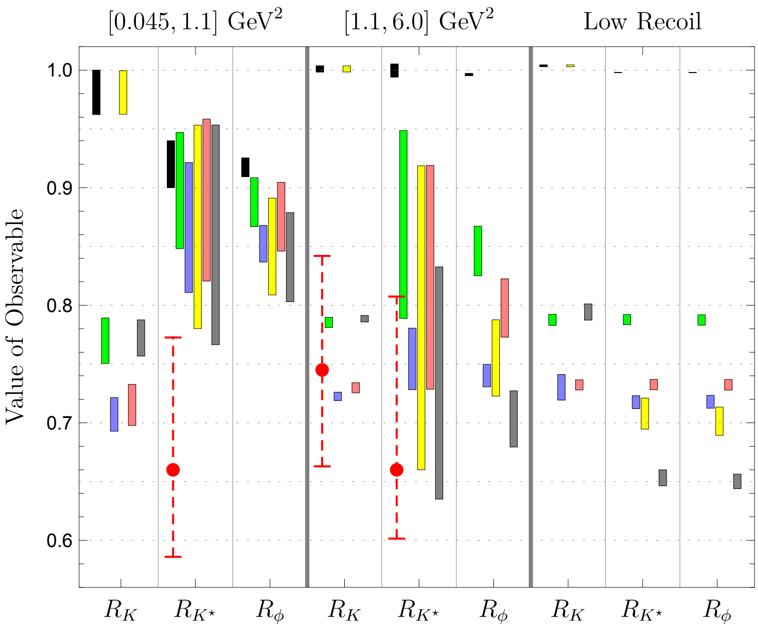
At the point $C_{9\mu}^{\text{NP}} = -1.1$, $C_{9e}^{\text{NP}} = 0$:

KMPW-sch.1: $\xi_\perp = \mathbf{0.31^{+0.20}_{-0.10}}, \xi_\| = \mathbf{0.10^{+0.03}_{-0.02}}$

BSZ-sch.1 $\xi_\perp = \mathbf{0.32 \pm 0.03}, \xi_\| = 0.12 \pm 0.02$

JC-sch.2 $\xi_\perp = \mathbf{0.31 \pm 0.04}, \xi_\| = 0.10 \pm 0.02$

Disentangling New Physics: Ratios of Branching Ratios



SM-[BLACK]

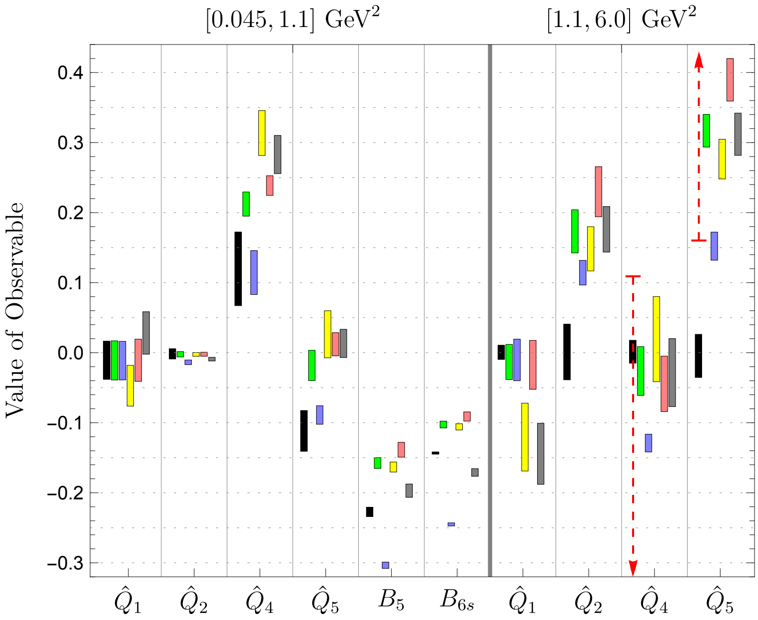
Five "good" scenarios:

- Sc. 1 [GREEN]: $C_{9\mu}^{\rm NP} = -1.1$,
- Sc. 2 [BLUE]: $C_{9\mu}^{\rm NP} = -C_{10\mu}^{\rm NP} = -0.61$,
- Sc. 3 [YELLOW]: $C_{9\mu}^{\rm NP} = -C'_{9\mu} = -1.01$,
- Sc. 4 [ORANGE]: $C_{9\mu}^{\rm NP} = -3C_{9e}^{\rm NP} = -1.06$,
- Sc. 5:[GRAY]: The best fit point in the six-dimensional fit.

R_{K^*} is computed using very conservative KMPW-FF but R_ϕ using BSZ-FF (only available).

ATTENTION: In presence of NP $R_{K^*,\phi}$ are largely sensitive to FF choices

Q_i observables are better to disentangle NP: Q_i inheritates the properties of optimized observables.



$$Q_i = P_i^\mu - P_i^e$$

SM-[BLACK] and dashed-red [BELLE data]

Five "good" scenarios:

- Sc. 1 [GREEN]: $C_{9\mu}^{\rm NP} = -1.1$,
- Sc. 2 [BLUE]: $C_{9\mu}^{\rm NP} = -C_{10\mu}^{\rm NP} = -0.61$,
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- Sc. 4 [ORANGE]: $C_{9\mu}^{\rm NP} = -3C_{9e}^{\rm NP} = -1.06$,
- Sc. 5:[GRAY]: The best fit point in the six-dimensional fit.

A precise measurement of Q_5 in [1,6] can discard the solution $C_9 = -C_{10}$ in front of all other sols.

What is the impact of LFUV observables in presence of New Physics of reducing FF error by 50%?

$R_{K^*[1.1,6]}$	SM	$C_9^{\rm NP} = -1.76$ (sc1)	$C_9^{\rm NP} = -C_{10}^{\rm NP} = -0.66$ (sc2)	6D (sc3)
ref.	$+1.000 \pm 0.006$	$+0.827 \pm 0.137$	$+0.736 \pm 0.029$	$+0.737 \pm 0.080$
FF-50%	$+1.000 \pm 0.003$	$+0.827 \pm 0.073$	$+0.736 \pm 0.015$	$+0.737 \pm 0.044$

$Q_{5[1.1,6]}$	SM	$C_9^{\rm NP} = -1.76$ (sc1)	$C_9^{\rm NP} = -C_{10}^{\rm NP} = -0.66$ (sc2)	6D (sc3)
ref.	-0.007 ± 0.001	$+0.535 \pm 0.033$	$+0.166 \pm 0.019$	$+0.304 \pm 0.029$
FF-50%	-0.007 ± 0.001	$+0.535 \pm 0.028$	$+0.167 \pm 0.016$	$+0.304 \pm 0.027$

- Marginal improvement on the very robust Q_5 observable compared to R_{K^*}.
- R_{K^*}: even after a 50% improvement sc1 and sc2 only differ by 1σ and sc2-sc3 are indistinguishable.
- Q_5: after a 50% improvement sc1 and sc2 differ by 10σ and sc2-sc3 differ by $> 4\sigma$.

What about experimental improvement from LFUV?
Two key observables: R_K and Q_5

- R_K: Doubling (or a bit more) the statistics and reducing the systematics beyond 50%
  $\to$ combined error on R_K reduces by $\sim 40\%$ to +0.6 assuming same CV.

The LFUV fit will find:

Coefficient $\mathcal{C}_i^{NP} = \mathcal{C}_i - \mathcal{C}_i^{SM}$	Best fit	1σ	3σ	Pull_{SM}
$\mathcal{C}_{\mathbf{9}}^{\text{NP}}$	-1.56	$[-1.99, -1.19]$	$[-3.16, -0.56]$	**5.1** $\Leftarrow$
$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{10}^{\text{NP}}$	-0.61	$[-0.73, -0.48]$	$[-1.01, -0.25]$	**5.3** $\Leftarrow$

This will lead to 5σ only with LFUV

The all fit will find:

Coefficient $\mathcal{C}_i^{NP} = \mathcal{C}_i - \mathcal{C}_i^{SM}$	Best fit	1σ	3σ	Pull_{SM}
$\mathcal{C}_{\mathbf{9}}^{\text{NP}}$	-1.13	$[-1.28, -0.97]$	$[-1.58, -0.64]$	**6.8** $\Leftarrow$
$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{10}^{\text{NP}}$	-0.61	$[-0.71, -0.51]$	$[-0.93, -0.31]$	**6.5** $\Leftarrow$

- Q_5 will be able to disentangle the right scenario together with R_K

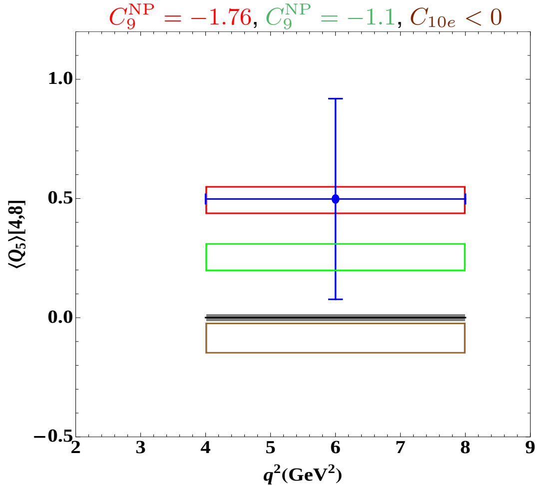
Q_5 can disentangle if $h_\lambda \simeq 0$ and marginal or relevant: Scenario IV

All started from the large P_5' anomaly and can be solved with Q_5.

Assume three scenarios to close a discussion:

- Q_5 is negative in the range [4,8] then:
  - a solution like $C_{10e} < 0$ proposed by [Ciuchini et al.] will be preferred.
  - all $b \to s\ell\ell$ anomalies at large and low-recoil would be of hadronic origin and one would need $\mathcal{O}(40)$ **large new unknown parameters** to fix it...
- Q_5 is positive but very small < 0.1 in [4,8] then:
  - a solution like $C_9 = -C_{10} = -0.6$ is preferred (also $C_9^{\rm NP}$ is possible) and h^λ **are small/medium but not negligible**.
- Q_5 is positive but large $0.5 - 0.2$ in [4,8] then:
  - a solution like $C_9 < 0$ is preferred.
  - a large value around $0.5 - 0.4$ would imply a **negligibly small non-factorizable long distance charm** $\mathbf{h}^\lambda \simeq \mathbf{0}$.

Belle data in blue



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

In summary the larger and positive Q_5 is the more marginal the long distance charm.

Conclusions

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

  1. in $b \to s\mu^+\mu^-$: P_5', $\mathcal{B}_{B^+\to K^{*+}\mu^+\mu^-}$, $\mathcal{B}_{B_s\to\phi\mu^+\mu^-}$ (low and large-recoil).
  2. in LFUV observables: R_K,R_{K^*}, $Q_{4,5}$

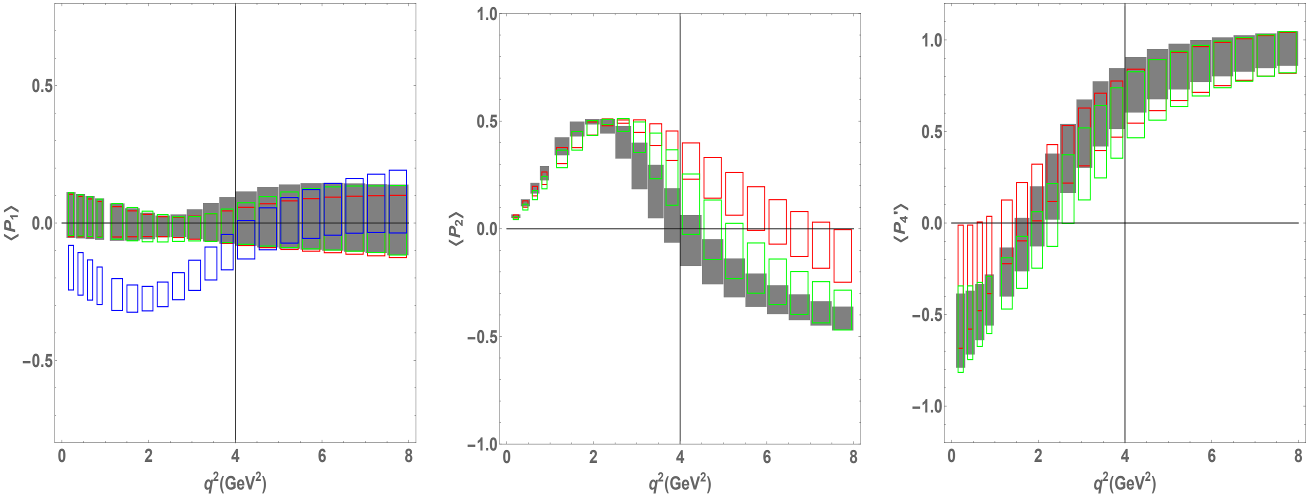
  pointing **in a global fit** to different patterns/scenarios of NP:

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

- The fit using **only LFUV observables** finds **Violations of LFU** at the 3-4σ level.
- Crucial to follow different theoretical treatments (SFF or FF) and FF LCSR approaches.
- Disentangling scenarios with LFUV observables:
  - R_{K^*} very sensitive to hadronic uncertainties in presence of NP in particular to changes in FF.
  - R_K excellent probe in SM but also in NP due to simple structure.
  - Q_5 unique capacity to disentangle $C_9 = -C_{10}$ and C_9, but also size of possible hadronic contributions.
- An experimental improvement on R_K error by 40% assuming same cv:

  A fit with only LFUV will move above 5σ and near 7σ of complete fit.

Information that could be extracted with present theory precision



Similar information than the Amplitude analysis. Shape information is new and crucial.

- Predictions of $P_{1,2,4'}$ in smaller bins:

Green (Sc1): $C_9^{\rm NP} = -C_{10}^{\rm NP} = -0.66$ Red (Sc2): $C_9^{\rm NP} = -1.76$
Blue: 6D fit (Sc3) $C_7^{\rm NP} = +0.03$, $C_9^{\rm NP} = -1.12$, $C_{10}^{\rm NP} = +0.31$, $C_{7'} = +0.03$, $C_{9'} = +0.38$, $C_{10'} = +0.02$

• $P_1 \neq 0$ only 6D with RHC • P_2 in Sc2 zero shifted from 4 to 6 GeV^2 • P_4' is SM-like.

Impact of correlations: two types of correlations

We include the most robust correlations:

$\rightarrow$ coming from **large-recoil symmetries** and correct for their breaking.

We tested the impact of including also "**inner LCSR correlations**" in BSZ for P_5'.

$\rightarrow$ increases your sensitivity to LCSR hypothesis.

$P_5'[4.0, 6.0]$	scheme 1 [CDHM]
$\boxed{1}$	$-0.72 \pm \mathbf{0.05}$
$\boxed{2}$	-0.72 ± 0.03
$\boxed{3}$	-0.72 ± 0.03
full BSZ	$-0.72 \pm \mathbf{0.03}$

errors only from pc with BSZ form factors
[Capdevila, Descotes, Hofer, JM]

$\boxed{1}$ $\triangle F^{\rm PC} = F \times \mathcal{O}(\Lambda/m_B)$
correl. from large-recoil sym. $\rightarrow \xi_{\perp,\parallel}, \triangle F^{\rm PC}$ unc.
(minimal input from LCSR on correlations)

$\boxed{2}$ $\triangle F^{\rm PC}$ from fit to LCSR
correl. from large-recoil sym. $\rightarrow \xi_{\perp,\parallel}, \triangle F^{\rm PC}$ unc.

$\boxed{3}$ $\triangle F^{\rm PC}$from fully correlated fit to LCSR
+ **correl.** from LCSR between $\xi_{\perp,\parallel}, \triangle F^{\rm PC}$
(maximal input from LCSR correlations)

Difference dominated by our conservative assumption $\mathcal{O}(\Lambda/m_b)\times$ FF $\sim 10\%$ while BSZ ($\sim 5\%$)

$\rightarrow$ including all or part of the inner correlations will impact on the size of conservative assumption

Unprotected observables like S_i much more sensitive to inner LCSR correlations than P_i.