Patterns of New Physics in $b \to s\ell^+\ell^-$ transitions in the light of recent data

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May 24, 2017

Flavour Physics at LHC run II (Benasque)

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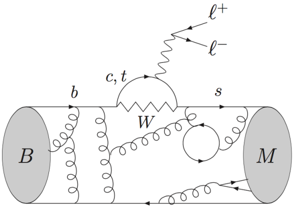
Based on **1605.03156 JHEP (2016)**, **1701.08672 JHEP (2017)** & **1704.05340 (2017)**

Outline

1. Review of the theoretical framework
2. New global fit results
3. Future opportunities for LFUV
4. Conclusions

Review of the theoretical framework

Effective Hamiltonian Approach



$\mathcal{A} \sim C_i$ (short dist.)

$\times$ Hadronic Matrix Elements (long dist.)

$b \to s\gamma^{(*)}$ Effective Hamiltonian

$$\mathcal{H}^{\text{SM}}_{\Delta F=1} \propto V^*_{ts} V_{tb} \sum_i C_i \mathcal{O}_i$$

- $\mathcal{O}_7 = \frac{\alpha}{4\pi} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu}$
- $\mathcal{O}_9 = \frac{\alpha}{4\pi} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$
- $\mathcal{O}_{10} = \frac{\alpha}{16\pi} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$

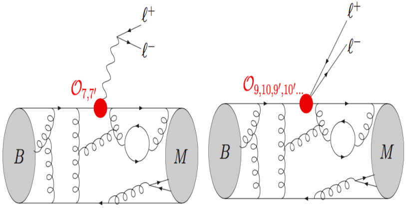
$C_7^{\text{SM}}(\mu_b) = -0.29 \qquad C_9^{\text{SM}}(\mu_b) = 4.1$

$C_{10}^{\text{SM}}(\mu_b) = -4.3 \qquad (\mu_b = m_b)$

$\Rightarrow$ In this picture, New Physics (NP) effects can enter through two mechanisms:

- Extra contributions to the WCs.
- Additional effective operators: $\mathcal{O}'_i$, $\mathcal{O}_S$, $\mathcal{O}_P$, $\mathcal{O}_T$,...

Effective Hamiltonian Approach



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Form Factors $B \to K^* \ell^+ \ell^-$

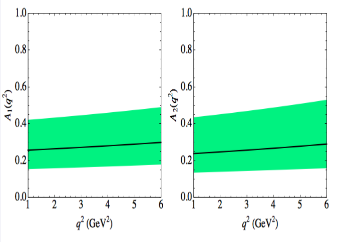
The matrix elements of the effective operators are written in terms of (seven) form factors (FF),

$$\langle K^* | \mathcal{O}_i | B \rangle \sim F(q^2) \quad (i = 7, 9, 10)$$

Two parametrizations available in the market,

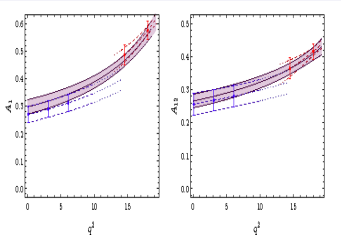
Khodjamirian et al (KMPW)

$\Rightarrow$ LCSRs with B distribution amplitudes.



Bharucha et al (BSZ)

$\Rightarrow$ LCSRs with K^* distribution amplitudes.



Clean Observables

- HQET/LEET ($m_B \to \infty$ and $E_{K^*} \to \infty$ = large-recoil):

$$\frac{m_B}{m_B + m_V} V(q^2) = \frac{m_B + m_V}{2E} A_1(q^2) = T_1(q^2) = \frac{m_B}{2E} T_2(q^2) = \xi_\perp(E)$$

$$\frac{m_V}{E} A_0(q^2) = \frac{m_B + m_V}{2E} A_1(q^2) - \frac{m_B - m_V}{m_B} A_2(q^2) = \frac{m_B}{2E} T_2(q^2) - T_3(q^2) = \xi_\|(E)$$

$\Rightarrow$ In this limit, we can build ratios where the FF cancel (at LO),

$$\frac{\epsilon^{*\mu} q^\nu \langle K^* | \bar{s}\sigma_{\mu\nu} P_R b | B \rangle}{i m_B \langle K^* | \bar{s} \not\epsilon^* P_L b | B \rangle} = 1 + \mathcal{O}(\alpha_s, \Lambda/m_b)$$

- Following this idea one can build a basis of observables with this property [Matias, Mescia, Ramon 2012 & Descotes-Genon, Matias, Ramon, Virto 2013]

Optimized Observables

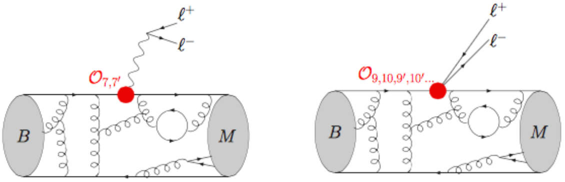
$$P_1 = \frac{J_3}{2J_{2s}} \qquad P_2 = \frac{J_{6s}}{8J_{2s}} \qquad P_4' = \frac{J_4}{\sqrt{-J_{2s}J_{2c}}}$$

$$P_5' = \frac{J_5}{2\sqrt{-J_{2s}J_{2c}}} \qquad P_6' = \frac{-J_7}{2\sqrt{-J_{2s}J_{2c}}} \qquad P_8' = \frac{-J_8}{\sqrt{-J_{2s}J_{2c}}}$$

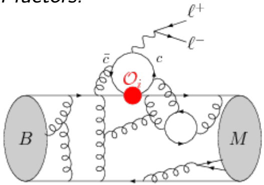
Hadronic corrections: factorisable and non-factorisable

Theory predictions receive different types of QCD corrections.

- Factorisable Corrections: *corrections that **can** be absorbed into the definition of the (full) form factors.*



- Non-factorisable Corrections: *corrections that **cannot** be absorbed into the definition of the (full) form factors.*



Improved QCDF

Improved QCDF (iQCDF) Approach: General decomposition of a full form factor (FF)

$$F^{\text{Full}}(q^2) = F^{\infty}(\xi_\perp(q^2), \xi_\parallel(q^2)) + \Delta F^{\alpha_s}(q^2) + \Delta F^{\Lambda}(q^2)$$

where F stands for any form factor, either from the helicity or transversity basis.

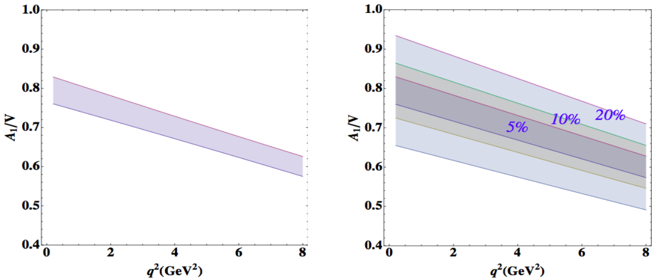
- Large recoil symmetries: low-q^2 and at LO in α_s and Λ/m_B
  $\Rightarrow$ **Dominant correlations** automatically taken into account (important for a maximal cancellation of errors).
- $\mathcal{O}(\alpha_s)$ corrections $\Rightarrow$ QCDF
- $\mathcal{O}(\Lambda/m_B)$ corrections $\Rightarrow$ **cannot** be explicitly computed within QCDF

Parametrization of ΔF^{Λ} [Jäger & Camalich 2012]

$$\Delta F^{\Lambda}(q^2) = a_F + b_F \frac{q^2}{m_B^2} + c_F \frac{q^4}{m_B^4} + \ldots$$

Improved QCDF (vs full FF approach)

- How to estimate ΔF^{Λ}?
  $\Rightarrow$ Central values for a_F, b_F, c_F from **fit to full LCSR FF**.
  $\Rightarrow$ Error estimate: assign **uncorrelated** $\sim 100\%$ errors to $a_F, b_F, c_F = \mathcal{O}(\Lambda/m_B) \times F = 10\% \times F$
- Is our estimation of errors conservative?
  FF ratio A_1/V (that controls P_5'): BSZ (including correlations) vs iQCDF for different size of power corrections.

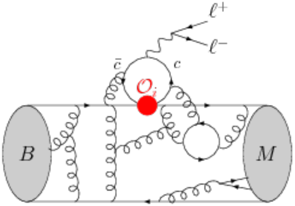


Already a 5% power corrections (right) reproduces the BSZ full FF approach errors (left).

Non-factorisable hadronic corrections

There are two different types of non-factorisable hadronic corrections

- α_s-corrections from hard gluon exchange ($\mathcal{O}_{1-6}$, $\mathcal{O}_8$ topologies) $\Rightarrow$ QCDF.
- $\mathcal{O}(\Lambda/m_B)$ corrections involving $c\bar{c}$ loops,
  - $\Rightarrow$ LCSR + dispersion relations (only th. calculation) [KMPW 2010]
  - $\Rightarrow$ Non-factorisable $\mathcal{O}(\Lambda/m_B)$ power corrections (charm loops) yield q^2- and helicity-dependent contributions to C_7 and C_9.



Estimating the $c\bar{c}$-loop contribution at large-recoil

- Introduce a shift in the C_9 coefficient at the amplitude level:

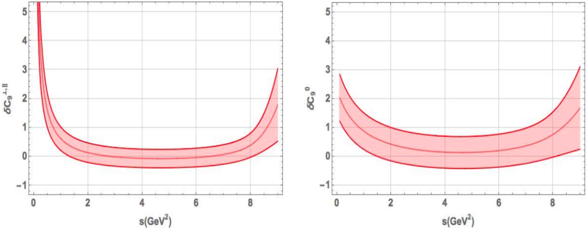
$$C_9^{\text{eff}}(q^2) \to C_9^{\text{eff}}(q^2) + s_i \delta C_9^{\text{LD},i}(q^2) \quad (i = \perp, \|, 0 \text{ no summation})$$

- The "charm-loop functions" are parametrized in the following way,

$$\delta C9^{\text{LD},\perp}(q^2) = \frac{a^\perp + b^\perp q^2(c^\perp - q^2)}{q^2(c^\perp - q^2)} \qquad \delta C9^{\text{LD},\|}(q^2) = \frac{a^{||} + b^{||} q^2(c^{||} - q^2)}{q^2(c^{||} - q^2)}$$

$$\delta C9^{\text{LD},0}(q^2) = \frac{a^0 + b^0(q^2 + s_0)(c^0 - q^2)}{(q^2 + s_0)(c^0 - q^2)}$$

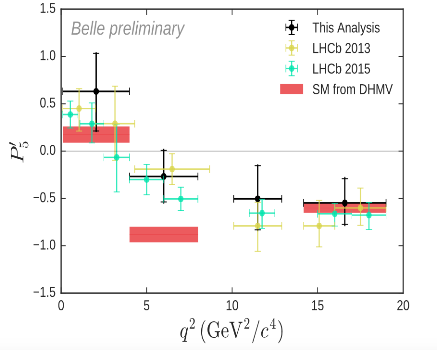
⇒ We vary s_i in the range $[-1, 1]$.
⇒ a, b, c parameters are fixed so that our parametrization covers the results from KMPW.



New global fit results

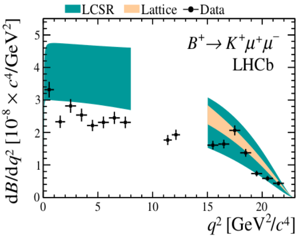
The P_5' anomaly

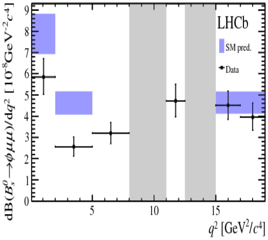
$b \to s\ell\ell$ driven processes have provided some interesting anomalies during the recent years.

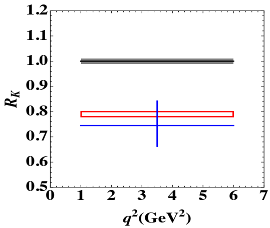


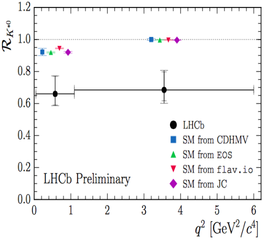
- 2013: 1fb^{-1} dataset LHCb found 3.7σ.
- 2015: 3fb^{-1} dataset LHCb found 3σ in 2 bins.
- Belle confirmed it in a bin [4,8] few months ago.

Other tensions beyond P'_5









- $BR(B \to K\mu\mu)$ small compared to SM predictions.
- Deviations in $BR(B_s \to \phi\mu\mu)$.
- Several systematic low-recoil small tensions in BR_μ.
- LFUV ratios R_K & R_{K^*}.

Summary of anomalies

Currently available $b \to s\ell\ell$ data comprises up to ~ 170 observables. The main anomalies observed are:

Observable	Experiment	SM Prediction	Pull
$\langle P_5' \rangle^{[4,6]}$	-0.30 ± 0.16	-0.82 ± 0.08	-2.9σ
$\langle P_5' \rangle^{[6,8]}$	-0.51 ± 0.12	-0.94 ± 0.08	-2.9σ
$R_K^{[1,6]}$	$0.745^{+0.097}_{-0.082}$	1.00 ± 0.01	$+2.6\sigma$
$R_{K^*}^{[0.045,1.1]}$	$0.660^{+0.113}_{-0.074}$	0.92 ± 0.02	$+2.3\sigma$
$R_{K^*}^{[1.1,6]}$	$0.685^{+0.122}_{-0.083}$	1.00 ± 0.01	$+2.6\sigma$
$\mathcal{B}^{[2,5]}_{B_s \to \phi\mu^+\mu^-}$	0.77 ± 0.14	1.55 ± 0.33	$+2.2\sigma$
$\mathcal{B}^{[5,8]}_{B_s \to \phi\mu^+\mu^-}$	0.96 ± 0.15	1.88 ± 0.39	$+2.2\sigma$

$\Rightarrow$ To assess all theses deviations consistently, we need **global fits**.

List of observables in the fit

We perform a fit to all available data (except CPV obs.) $\Rightarrow$ 175 observables.

- Inclusive decays

  $\Rightarrow B \to X_s\gamma$ (BR).

  $\Rightarrow B \to X_s\mu^+\mu^-$ (BR).

- Exclusive leptonic decays

  $\Rightarrow B_s \to \mu^+\mu^-$ (BR).

- Exclusive radiative/semileptonic decays

  $\Rightarrow B \to K^*\gamma$ (BR, $S_{K^*\gamma}$, A_I).

  $\Rightarrow B \to K\ell^+\ell^-$ (BR_μ, R_K).

  $\Rightarrow B \to K^*\ell^+\ell^-$ (BR_μ, $P^{(\prime)\,\mu}_{1,2,4,5,6,8}$, F_L^μ, available electronic angular obs).

  $\Rightarrow B_s \to \phi\mu^+\mu^-$ (BR, $P^{(\prime}_{1,4,6}$), F_L).

List of observables in the fit (2017 update)

- Updates
  - ⇒ $\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)$ **(LHCb)**.
  - ⇒ Isospin-averaged $P'^{\,e\mu}_{4,5}(B \to K^*\ell\ell)$ **(Belle)**.
  - ⇒ $P^{(\prime)}_{1,4,5,6,8}, F_L(B^0 \to K^{*0}\mu^+\mu^-)$ in the large-recoil region **(ATLAS)**.
  - ⇒ $P^{(\prime)}_{1,5}(B^0 \to K^{*0}\mu^+\mu^-)$ at large-recoil plus $[16, 19]$ GeV^2 bin **(CMS)**.
  - ⇒ F_L, A_{FB} from 2015 and F_L, A_{FB}, BR from 2013 at 7 TeV **(CMS)**.
  - ⇒ R_{K^*} in the bins $[0.045, 1.1]$, $[1.1, 6]$ GeV^2 **(LHCb)**.

Statistical framework

We parametrize the Wilson coefficients as

$$C_i = C_i^{\text{SM}} + C_i^{\text{NP}} \quad (i = 7, 9, 10,\ C_i^{\text{NP}} \in \mathbb{R} \Rightarrow \text{no CPV})$$

Standard frequentist fit to the NP contributions to the Wilson coefficients,

$$\chi^2(C_i^{\text{NP}}) = \left(\mathcal{O}^{\text{th}}(C_i^{\text{NP}}) - \mathcal{O}^{\text{exp}}\right)_i Cov_{ij}^{-1} \left(\mathcal{O}^{\text{th}}(C_i^{\text{NP}}) - \mathcal{O}^{\text{exp}}\right)_j$$

- Both **theory and experiment** contribute to the covariance matrix, $\Rightarrow Cov = Cov^{\text{th}} + Cov^{\text{exp}}$
- Experimental covariance, $\Rightarrow$ **Experimental correlations** between observables (if not provided, assumed uncorrelated). Assume guassian errors (symmetrize if needed).
- Theoretical covariance, $\Rightarrow$ Compute the **theoretical correlations** by performing a multivariate gaussian scan over all nuisance parameters.
- In principle $Cov = Cov(C_i)$, $\Rightarrow$ Very **mild** dependency $\Rightarrow Cov = Cov_{\text{SM}} \equiv Cov(C_i = 0)$.

Statistical framework

- Fit procedure:
  - $\Rightarrow$ **Best fit points** (bfp): $\chi^2(C_i^{\rm NP}) \to \chi^2_{\rm min} = \chi^2(\hat{C}_i^{\rm NP})$.
  - $\Rightarrow$ **Confidence intervals** (gaussian approximation): $\chi^2(C_i^{\rm NP}) - \chi^2_{\rm min} \leq Q^2$ $(1\sigma \to Q^2 = 1,\ 2\sigma \to Q^2 = 4,\ \ldots)$.
  - $\Rightarrow$ Compute **pulls** (σ) by inversion of the above formula.
  - $\Rightarrow$ Calculate *p*-**values** as usual $p = \int_{\chi^2_{\rm min}}^{\infty} d\chi^2 f(\chi^2; n_{\rm dof})$.
- Two types of fits
  - $\Rightarrow$ *Canonical* fit: fit to **all data** (175 data points).
  - $\Rightarrow$ LFUV fit: R_K, R_{K^*}, $P'^{\,e\mu}_{4,5}(B \to K^*\ell\ell)$ plus $b \to s\gamma$ (17 data points)
- Testing different **hypothesis**
  - $\Rightarrow$ Hypothesis with NP only in one Wilson coefficient (**1D fits**).
  - $\Rightarrow$ Hypothesis with NP in two Wilson coefficients (**2D fits**).
  - $\Rightarrow$ Hypothesis with NP in the six Wilson coefficients (**6D fits**).

1D hypothesis

- Canonical fit

Coefficient	Best Fit	1σ	Pull_{SM} (σ)	p-value (%)
$C_{9\mu}^{\text{NP}}$	-1.10	$[-1.27, -0.92]$	5.7	72
$C_{9\mu}^{\text{NP}} = -C_{10\mu}^{\text{NP}}$	-0.61	$[-0.73, -0.48]$	5.2	61
$C_{9\mu}^{\text{NP}} = -C'_{9\mu}$	-1.01	$[-1.18, -0.84]$	5.4	66
$C_{9\mu}^{\text{NP}} = -3C_{9e}^{\text{NP}}$	-1.06	$[-1.23, -0.89]$	5.8	74

$\Rightarrow$ SM goodness of fit (canonical fit): p-value = 14.6%.

$\Rightarrow$ The inclusion of the new data (mainly R_{K^*}) increases the significances (comparing with 2015 analysis).

$\Rightarrow$ $C_{9\mu}^{\text{NP}} = -C'_{9\mu}$ would predict $R_K \simeq 1$ and $R_{K^*} < 1$.

$\Rightarrow$ Scenarios with positive $C_{10\mu}$ (and/or C'_{10}) imply $R_K < 1$.

1D hypothesis

LFUV fit

Coefficient	Best Fit	1σ	Pull_{SM} (σ)	p-value (%)
$C_{9\mu}^{\text{NP}}$	-1.76	$[-2.36, -1.23]$	3.9	69
$C_{9\mu}^{\text{NP}} = -C_{10\mu}^{\text{NP}}$	-0.66	$[-0.84, -0.48]$	4.1	78
$C_{9\mu}^{\text{NP}} = -C'_{9\mu}$	-1.64	$[-2.12, -1.05]$	3.2	31
$C_{9\mu}^{\text{NP}} = -3C_{9e}^{\text{NP}}$	-1.35	$[-1.82, -0.95]$	4.0	71

$\Rightarrow$ SM goodness of fit (LFUV fit): p-value $= 4.4\%$.

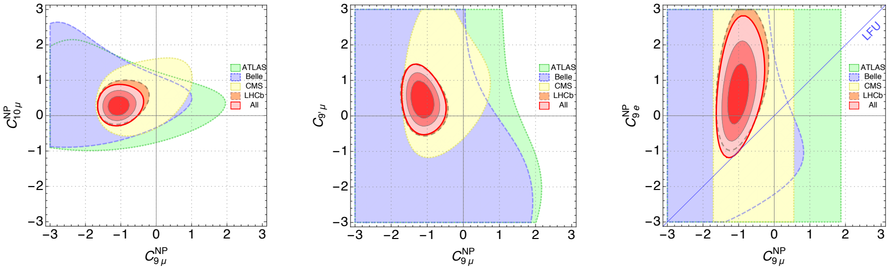
$\Rightarrow$ High level of preference for NP over the SM considering the limited subset of observables included in the fit.

$\Rightarrow$ Remarkable compatibility with canonical fit results ($b \to s\mu\mu$ dominated).

$\Rightarrow$ $C_{9\mu}^{\text{NP}} = -C'_{9\mu}$ loses relative weight since it predicts $R_K \simeq 1$.

2D hypothesis

Confidence regions plots



⇒ 3σ regions experiment by experiment.

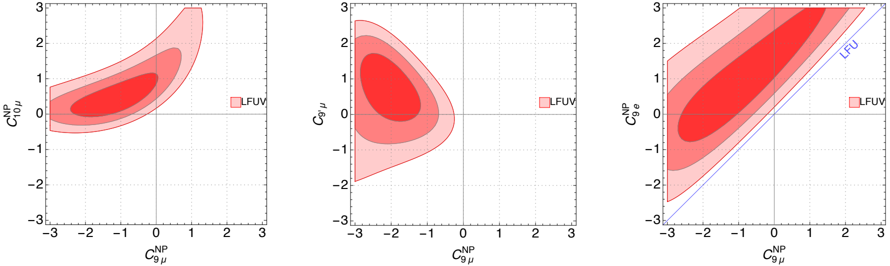
⇒ Pulls_{SM} (p-values): 5.5σ (74%), 5.6σ (75%) & 5.4σ (72%) (respectively).

⇒ While $C_{9\mu}^{NP} \sim -1$ is preferred over SM at the 5σ level, C_{9e}^{NP} is already compatible at 1σ. Clear hint of LFUV.

⇒ LHCb data drives most of the effect.

2D hypothesis

Confidence regions plots



- ⇒ 3σ regions experiment by experiment.
- ⇒ Pulls_{SM} (p-values): 5.5σ (74%), 5.6σ (75%) & 5.4σ (72%) (respectively).
- ⇒ While $C^{\text{NP}}_{9\mu} \sim -1$ is preferred over SM at the 5σ level, C^{NP}_{9e} is already compatible at 1σ.
- ⇒ LHCb data drives most of the effect.
- ⇒ LFUV fit results are poiting towards the same direction.

6D hypothesis

- We fit the six Wilson coefficients (assumed real) to all data.

Coefficient	Best Fit	1σ	2σ
$C_7^{\rm NP}$	$+0.02$	$[-0.01, +0.05]$	$[-0.03, +0.07]$
$C_{9\mu}^{\rm NP}$	-1.12	$[-1.34, -0.85]$	$[-1.51, -0.61]$
$C_{10\mu}^{\rm NP}$	$+0.33$	$[+0.09, +0.59]$	$[-0.10, +0.80]$
C_7'	$+0.03$	$[-0.00, +0.06]$	$[-0.02, +0.08]$
$C_{9\mu}'$	$+0.59$	$[+0.01, +1.12]$	$[-0.50, +1.56]$
$C_{10\mu}'$	$+0.07$	$[-0.23, +0.37]$	$[-0.50, +0.64]$

$\Rightarrow$ $C_{9\mu}$ only compatible with the SM above the 3σ level.

$\Rightarrow$ $C_{10\mu}$ & $C_{9\mu}'$ SM compatible at 2σ.

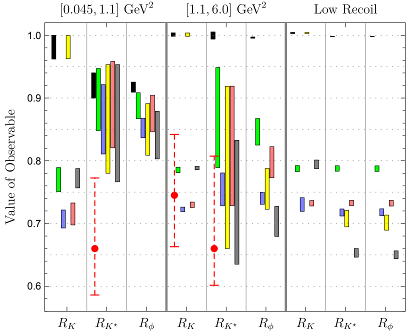
$\Rightarrow$ All the other coefficients are already SM compatible at 1σ.

$\Rightarrow$ **Pull$_{\rm SM}$ of the 6D hypothesis is at the level of 5σ (3.6σ in 2015).**

Future opportunities for LFUV

Motivation: R_K & R_{K^*}

- ⇒ R_K & R_{K^*} show tensions around $\sim 2.5\sigma$ with their (very precise) SM predictions.
- ⇒ R_K & R_{K^*} tension is **coherent** with the pattern of tensions observed in the $B \to K^*$ angular analysis.
- ⇒ $C_9^{\text{NP}} = -1.1$ alleviates **both** R_K & R_{K^*} and angular anomalies.
- ⇒ **But**, with current data, more information than R_K and R_{K^*} is needed to distinguish between NP scenarios.



Hyp. 0 Standard Model
Hyp. 1 $C_{9\mu}^{\text{NP}} = -1.1$
Hyp. 2 $C_{9\mu}^{\text{NP}} = -C_{10\mu}^{\text{NP}} = -0.61$
Hyp. 3 $C_{9\mu}^{\text{NP}} = -C'_{9\mu} = -1.0$
Hyp. 4 $C_{9\mu}^{\text{NP}} = -3C_{9e}^{\text{NP}} = -1.06$
Hyp. 5 6D fit bfp

A new generation of observables

What do we want? To probe the different NP scenarios suggested by global fits with the highest possible precision.

What do we need? New observables matching the following criteria:

- Sensitivity only to the short distance part of C_9 (**high SM precision**).
- Capacity to test for lepton flavour universality violation between the electronic and muonic modes.
- Sensitivity to other Wilson coefficients than C_9.

Exploiting the angular analyses of both $B \to K^* \mu\mu$ and $B \to K^* ee$ decays, certain combinations of the angular observables fulfill the requirements

$$\langle Q_i \rangle = \langle P_i^\mu \rangle - \langle P_i^e \rangle \quad \langle \hat{Q}_i \rangle = \langle \hat{P}_i^\mu \rangle - \langle \hat{P}_i^e \rangle \quad \langle B_k \rangle = \frac{\langle J_k^\mu \rangle}{\langle J_k^e \rangle} - 1 \quad \langle \tilde{B}_k \rangle = \frac{\langle J_k^\mu / \beta_\mu^2 \rangle}{\langle J_k^e / \beta_e^2 \rangle} - 1$$

$i = 1, \ldots, 9$ & $k = 5, 6s$

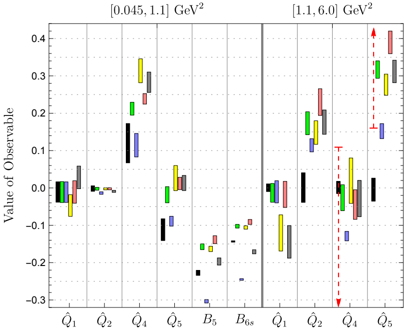
where ˆ means correcting for lepton-mass effects in the first bin (backup slides).

Discrimination tests: $\hat{Q}_i$ & $B_{5,6s}$

⇒ $\langle \hat{Q}_2 \rangle^{[0.045,1.1]}$ is very SM-like. Potential as a control observable.

⇒ $\langle \hat{Q}_5 \rangle^{[1.1,6]}$ promising power of discrimination. Especially capable to distinguish the SM from hyp. 2 and the other NP hyp.

⇒ $\langle B_5 \rangle^{[0.045,1.1]}$ and $\langle B_{6s} \rangle^{[0.045,1.1]}$ are very sensitive to hyp. 2. Capacity to distinguish hyp. 2 from hyp. 1, 3 and 4 (if the experimental errors are small).



Hyp. 0 Standard Model
Hyp. 1 $C_{9\mu}^{\rm NP} = -1.1$
Hyp. 2 $C_{9\mu}^{\rm NP} = -C_{10\mu}^{\rm NP} = -0.61$
Hyp. 3 $C_{9\mu}^{\rm NP} = -C'_{9\mu} = -1.0$
Hyp. 4 $C_{9\mu}^{\rm NP} = -3C_{9e}^{\rm NP} = -1.06$
Hyp. 5 6D fit bfp

Conclusions

Conclusions

- The SM is substantially disfavoured against other NP solutions.
  $\Rightarrow$ p-value$_{\text{SM}}$(canonical) $= 14,6\%$ (p-value$_{\text{SM}}$(LFUV) $= 4,4\%$).
  $\Rightarrow$ 6D fit: Pull$_{SM} = 5\sigma$.
- $C_{9\mu}$ is still the most strong signal of NP, but now with increased significance $\sim 5.5\sigma$.
- Several other NP hypothesis are also very favoured compared to the SM (but all containing $C_{9\mu}$).
- Our global fits also provide clear hints of LFUV.
  $\Rightarrow$ Framework for the definition of LFUV observables.
  $\Rightarrow$ Future measurements of these observables will help further increasing the significances, plus clarifying the possible underlying type of NP.

Thank you

Backup Slides

"Hats"

LHCb currently determines $F_{L,T}$ using a simplified description of the angular kinematics:

$$\left.\begin{matrix} J_{2s} \\ J_{2c} \end{matrix}\right\} \longmapsto J_{1c} \text{ (equivalent in the massless limit)}$$

Then, to match this convention, the angular observables are redefined in the following way:

$$F_L = \frac{-J_{2c}}{d\Gamma/dq^2} \to \hat{F}_L = \frac{J_{1c}}{d\Gamma/dq^2} \qquad F_T = \frac{4J_{2s}}{d\Gamma/dq^2} \to \hat{F}_T = 1 - \hat{F}_L$$

$$P_1 = \frac{J_3}{2J_{2s}} \to \hat{P}_1 = \frac{J_3}{2\hat{J}_{2s}} \qquad P_2 = \frac{J_{6s}}{8J_{2s}} \to \hat{P}_2 = \frac{J_{6s}}{8\hat{J}_{2s}}$$

$$P_3 = -\frac{J_9}{4J_{2s}} \to \hat{P}_3 = -\frac{J_9}{4\hat{J}_{2s}} \qquad P_4' = \frac{J_4}{\sqrt{-J_{2s}J_{2c}}} \to \hat{P}_4' = \frac{J_4}{\sqrt{\hat{J}_{2s}J_{1c}}}$$

$$P_5' = \frac{J_5}{2\sqrt{-J_{2s}J_{2c}}} \to \hat{P}_5' = \frac{J_5}{2\sqrt{\hat{J}_{2s}J_{1c}}} \qquad P_6' = -\frac{J_7}{2\sqrt{-J_{2s}J_{2c}}} \to \hat{P}_6' = -\frac{J_7}{2\sqrt{\hat{J}_{2s}J_{1c}}}$$

$$P_8' = -\frac{J_8}{\sqrt{-J_{2s}J_{2c}}} \to \hat{P}_8' = -\frac{J_8}{\sqrt{\hat{J}_{2s}J_{1c}}} \qquad \text{with } \hat{J}_{2s} = \frac{1}{16}(6J_{1s} - J_{1c} - 2J_{2s} - J_{2c})$$

"Hats"

Why is there a need to compute the predictions from $\hat{F}_{L,T}$ instead of $F_{L,T}$? Let's consider the decay distribution

$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^3(\Gamma+\bar{\Gamma})}{d\Omega} = \frac{9}{32\pi}\Big[\frac{3}{4}\hat{F}_T\sin^2\theta_K + \hat{F}_L\cos^2\theta_K + \frac{1}{4}F_T\sin^2\theta_K\cos 2\theta_l - F_L\cos^2\theta_K\cos 2\theta_l + ...\Big]$$

- With the current limited statistics, $\hat{F}_{L,T}$ and $F_{L,T}$ cannot be distinguished by LHCb.
- $\cos\theta_K^2$ is the dominant term, so they extract $\hat{F}_L$ and not F_L.

Scheme dependence

- Different possibilities for what to take as input for the two independent soft FFs $\{\xi_\perp, \xi_\|\}$

  e.g. scheme 1 [DHMV] $\{V, a_1 A_1 + a_2 A_2\}$ or scheme 2 [JC] $\{T_1, A_0\}$ or...

  $\Rightarrow$ choice defines **input scheme**.
- Observables are scheme independent **if and only if** all the correlations among FF are included.

  $\Rightarrow$ also correlations among $\Delta a_F, \Delta b_F, \ldots$!

  $\Rightarrow$ Uncorrelated errors in ΔF^Λ $\Rightarrow$ scheme dependence at $\mathcal{O}(\Lambda/m_B)$.
- Input FF **do not receive** power corrections

  $\Rightarrow$ Appropiate scheme choices reduce the impact of ΔF^Λ.

  $\Rightarrow$ Non-optimal schemes **can artificially inflate** the errors due to ΔF^Λ.

An illustrative example: $BR(B \to K^*\gamma)$

- How a non-optimal scheme can artificially inflate the errors?

  $\Rightarrow$ Take $BR(B \to K^*\gamma)$ as an example:

  $$BR(B \to K^*\gamma) \propto T_1(0)$$

  $\Rightarrow$ **Natural choice**: Choose an scheme where T_1 is used as input,

  $$T_1(0) = T_1^{\text{LCSR}}(0) \pm \Delta T_1^{\text{LCSR}}(0) \;\Rightarrow\; \Delta BR(B \to K^*\gamma) \propto \Delta T_1^{\text{LCSR}}(0)$$

  $\Rightarrow$ **"Wrong" choice**: Use any other FF related to T_1 as input (e.g. T_2),

  $$T_1(0) = \left(T_2^{\text{LCSR}}(0) + a_{T_1}\right) \pm \left(\Delta T_1^{\text{LCSR}}(0) + \Delta a_{T_1}\right)$$
  $$\Rightarrow\; \Delta BR(B \to K^*\gamma) \propto \Delta T_1^{\text{LCSR}}(0) + \Delta a_{T_1}$$

- **Unnatural scheme choices** generate **extra** contributions in error computations.

Scheme dependence of P_5'

Explicit analytic formulae for the power corrections to P_5' [CDHM]:

- Helicity basis,

$$P_5' = P_5'|_\infty \left(1 + \frac{2a_{V_-} - 2a_{T_-}}{\xi_\perp} \frac{C_7^{\rm eff}(C_{9,\perp} C_{9,\parallel} - C_{10}^2)}{(C_{9,\perp} + C_{9,\parallel})(C_{9,\perp}^2 + C_{10}^2)} \frac{m_b m_B}{q^2} \right.$$
$$\left. + \frac{2a_{V_0} - 2a_{T_0}}{\tilde{\xi}_\parallel} \frac{C_7^{\rm eff}(C_{9,\perp} C_{9,\parallel} - C_{10}^2)}{(C_{9,\perp} + C_{9,\parallel})(C_{9,\parallel}^2 + C_{10}^2)} \frac{m_b}{m_B} - \frac{2a_{V_+}}{\xi_\perp} \frac{C_{9,\parallel}}{C_{9,\perp} + C_{9,\parallel}} + \ldots \right)$$

$\Rightarrow$ We recovered the expression in JC12 + an additional term

- Transversity basis,

$$P_5' = P_5'|_\infty \left(1 + \frac{a_{A_1} + a_V - 2a_{T_1}}{\xi_\perp} \frac{C_7^{\rm eff}(C_{9,\perp} C_{9,\parallel} - C_{10}^2)}{(C_{9,\perp} + C_{9,\parallel})(C_{9,\perp}^2 + C_{10}^2)} \frac{m_b m_B}{q^2} \right.$$
$$\left. - \frac{a_{A_1} - a_V}{\xi_\perp} \frac{C_{9,\parallel}}{C_{9,\perp} + C_{9,\parallel}} - \frac{a_{T_1} - a_{T_3}}{\tilde{\xi}_\parallel} \frac{C_7^{\rm eff}(C_{9,\perp} C_{9,\parallel} - C_{10}^2)}{(C_{9,\perp} + C_{9,\parallel})(C_{9,\parallel}^2 + C_{10}^2)} \frac{m_b}{m_{K^*}} + \ldots \right)$$

with $C_{9,\perp} = C_9^{\rm eff} + \frac{2m_b m_B}{q^2} C_7^{\rm eff}$ and $C_{9,\parallel} = C_9^{\rm eff} + \frac{2m_b}{m_B} C_7^{\rm eff}$

Scheme dependence of P_5'

- The FF ratio A_1/V dominates P_5',

  $\Rightarrow$ **Convenient**: scheme 1 [DHMV] $\{V, a_1 A_1 + a_2 A_2\}$
  $\Rightarrow$ **Inconvenient**: scheme 2 [JC] $\{T_1, A_0\}$

- Evaluating the expression for the power corrections to P_5' at $q^2 = 6$ GeV^2 (around the anomaly),

$$P_5'(6\,\mathrm{GeV}^2) = P_5'|_\infty(6\,\mathrm{GeV}^2)\left(1+0.18\frac{a_{A_1}+a_V-2a_{T_1}}{\xi_\perp} - 0.14\frac{a_{T_1}-a_{T_3}}{\tilde{\xi}_\parallel} - 0.73\frac{a_{A_1}-a_V}{\xi_\perp}\right)$$

$\Rightarrow$ Scheme 1: $P_5'(6\,\mathrm{GeV}^2) \simeq P_5'|_\infty(6\,\mathrm{GeV}^2)\left(1-0.73\frac{a_{A_1}}{\xi_\perp}\right) \Rightarrow$ reduced errors.

$\Rightarrow$ Scheme 2: $P_5'(6\,\mathrm{GeV}^2) \simeq P_5'|_\infty(6\,\mathrm{GeV}^2)\left(1-0.73\frac{a_{A_1}-a_V}{\xi_\perp}\right) \Rightarrow$ increased errors.

Correlations and scheme dependence of P_5'

Assessing the impact of the correlations among power corrections (PC) + scheme dependence,

1 PC Analysis

- $\Delta F^\Lambda = F \times \mathcal{O}(\Lambda/m_B) \sim 10\% \times F$
- **correlations** from large-recoil sym. $\Rightarrow \xi_{\perp,\parallel}$, ΔF^Λ uncorr.

2 PC Analysis

- ΔF^Λ from fit to LCSR [BSZ].
- **correlations** from large-recoil sym. $\Rightarrow \xi_{\perp,\parallel}$, ΔF^Λ uncorr.

3 PC Analysis

- ΔF^Λ from fit to LCSR [BSZ].
- **correlations** from LCSR [BSZ] $\Rightarrow \xi_{\perp,\parallel}$, ΔF^Λ corr.

$P_5'[4.0, 6.0]$	scheme 1 [CDHM]	scheme 2 [JC]
1	$-0.72 \pm \mathbf{0.05}$	$-0.72 \pm \mathbf{0.12}$
2	-0.72 ± 0.03	-0.72 ± 0.03
3	-0.72 ± 0.03	-0.72 ± 0.03
full BSZ	$-0.72 \pm \mathbf{0.03}$	

errors only from pc with BSZ form factors

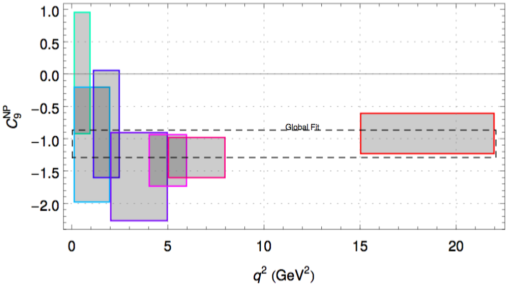
Disentangling $c\bar{c}$ loops from New Physics

NP and hadronic effects have different signatures on C_9:

- NP effects: universal and q^2-independent.
- Hadronic effects: transversity dependent and (most likely) q^2-depedent.

Testing the q^2 dependence of the contributions to C_9 by means of data,

- $C_9^{\rm NP}$ bin-by-bin fit to $b \to s\ell\ell$ data (assuming KMPW-like $C_9^{c\bar{c}\, i}(q^2)$):



$\Rightarrow$ Excellent agreement with a q^2-independent $C_9 \simeq -1$.

Fitting a charm-loop parametrization to data

Following *Ciuchini et al.*, we performed a fit of the charm loop contributions to data using a polinomial paramatrization,

$$A^0_{L,R} = A^0_{L,R}(Y(q^2)) + \frac{N}{q^2}\left(h_0^{(0)} + \frac{q^2}{1\,GeV^2}h_0^{(1)} + \frac{q^4}{1\,GeV^4}h_0^{(2)} + \frac{q^6}{1\,GeV^6}h_0^{(3)}\right)$$

- Non-zero $h_\lambda^{(2),(3)}$ $(\lambda = +,-,0)$ introduce q^2-dependent terms in C_9.
  $\Rightarrow$ Disclaimer: $C^{\rm NP}_{7,9}$ contribute to $h_i^{(2),(3),\cdots} \Rightarrow C_i^{\rm NP} \times F(q^2)$.
- Frequentist fit of $h_\lambda^{(i)}$ to $B \to K^*\mu\mu$ data: using KMPW FF and without including any charm-loop estimate to $C_{7,9}$.
- Comparing hypothesis with increasing orders of the h_λ polinomials $(n = 0, 1, 2, 3)$, we conclude [CDHM]:
  $\Rightarrow$ Hypotheses with linear h_λ polinomials are the ones with better improvement of the fit.
  $\Rightarrow$ Setting $C_9^{\rm NP} = -1.1$ significantly improves the fit (already with $h_\lambda = 0$).