

Global Analysis of $b \rightarrow sll$ Anomalies

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Rare B Decays 2016 – Barcelona – April 19, 2016

Collaboration with Sébastien, Lars and Quim



Theoretische Physik 1



DFG FOR 1873

Rare $b \rightarrow s$ processes

- Inclusive

- ▶ $B \rightarrow X_s \gamma$ (BR)
- ▶ $B \rightarrow X_s \ell^+ \ell^-$ (dBR/dq^2)

- Exclusive leptonic

- ▶ $B_s \rightarrow \ell^+ \ell^-$ (BR)

- Exclusive radiative/semileptonic

- ▶ $B \rightarrow K^* \gamma$ (BR, S, A_I)
- ▶ $B \rightarrow K \ell^+ \ell^-$ (dBR/dq^2)
- ▶ $B \rightarrow K^* \ell^+ \ell^-$ (dBR/dq^2 , Angular Observables) → Huge set of observables!!
- ▶ $B_s \rightarrow \phi \ell^+ \ell^-$ (dBR/dq^2 , Angular Observables)
- ▶ $\Lambda_b \rightarrow \Lambda \ell^+ \ell^-$ (see Meinel and van Dyk)
- ▶ etc.

EFT at $\mu = m_b$ and $b \rightarrow s$ transitions

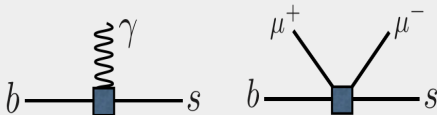
Radiative and Dileptonic $b \rightarrow s$ Operators

$$\mathcal{O}_{7(\prime)} = [\bar{s}\sigma^{\mu\nu}P_{R(L)}b]F_{\mu\nu}$$

$$\mathcal{O}_{9(\prime)} = [\bar{s}\gamma^\mu P_{L(R)}b][\bar{\ell}\gamma_\mu\ell]$$

$$\mathcal{O}_{10(\prime)} = [\bar{s}\gamma^\mu P_{L(R)}b][\bar{\ell}\gamma_\mu\gamma_5\ell]$$

$$\mathcal{O}_{S(\prime)}, \mathcal{O}_{P(\prime)}, \mathcal{O}_{T, T5}$$

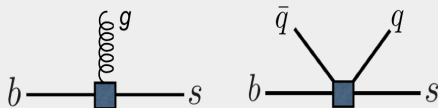


Hadronic $b \rightarrow s$ Operators

$$\mathcal{O}_1 = [\bar{s}\gamma^\mu P_L c][\bar{c}\gamma_\mu P_L b]$$

$$\mathcal{O}_{3(5)} = [\bar{s}\gamma^\mu P_L b] \sum_q [\bar{q}\gamma_\mu P_{L(R)} q]$$

$$\mathcal{O}_{8g} = [\bar{s}\sigma^{\mu\nu}P_{R(L)}T^a b]G_{\mu\nu}^a$$



($\mathcal{O}_{2,4,6} \sim \mathcal{O}_{1,3,5}$ with mixed color indices)

Effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[\sum_{7,7',9,9',10,10'} c_i \mathcal{O}_i + \sum_{1,\dots,6,8g} c_i \mathcal{O}_i \right]$$

$$C_{7\text{eff}}^{\text{SM}} = -0.3, C_9^{\text{SM}} = 4.1, C_{10}^{\text{SM}} = -4.3, C_1^{\text{SM}} = 1.1, C_2^{\text{SM}} = -0.4, C_{\text{rest}}^{\text{SM}} \lesssim 10^{-2}$$

Rare $b \rightarrow s$ processes

- Inclusive

- ▶ $B \rightarrow X_s \gamma$ (BR) $\mathcal{C}_7^{(\prime)}$, \mathcal{C}_{had}
- ▶ $B \rightarrow X_s \ell^+ \ell^-$ (dBR/dq^2) $\mathcal{C}_7^{(\prime)}$, $\mathcal{C}_9^{(\prime)}$, $\mathcal{C}_{10}^{(\prime)}$, \mathcal{C}_{had}

- Exclusive leptonic

- ▶ $B_s \rightarrow \ell^+ \ell^-$ (BR) $\mathcal{C}_{10}^{(\prime)}$

- Exclusive radiative/semileptonic

- ▶ $B \rightarrow K^* \gamma$ (BR, S, A_I) $\mathcal{C}_7^{(\prime)}$, \mathcal{C}_{had}
- ▶ $B \rightarrow K \ell^+ \ell^-$ (dBR/dq^2) $\mathcal{C}_7^{(\prime)}$, $\mathcal{C}_9^{(\prime)}$, $\mathcal{C}_{10}^{(\prime)}$, \mathcal{C}_{had}
- ▶ $B \rightarrow K^* \ell^+ \ell^-$ (dBR/dq^2 , Angular Observables) $\mathcal{C}_7^{(\prime)}$, $\mathcal{C}_9^{(\prime)}$, $\mathcal{C}_{10}^{(\prime)}$, \mathcal{C}_{had}
- ▶ $B_s \rightarrow \phi \ell^+ \ell^-$ (dBR/dq^2 , Angular Observables) $\mathcal{C}_7^{(\prime)}$, $\mathcal{C}_9^{(\prime)}$, $\mathcal{C}_{10}^{(\prime)}$, \mathcal{C}_{had}
- ▶ $\Lambda_b \rightarrow \Lambda \ell^+ \ell^-$ (see Meinel and van Dyk)
- ▶ etc.

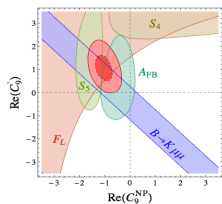
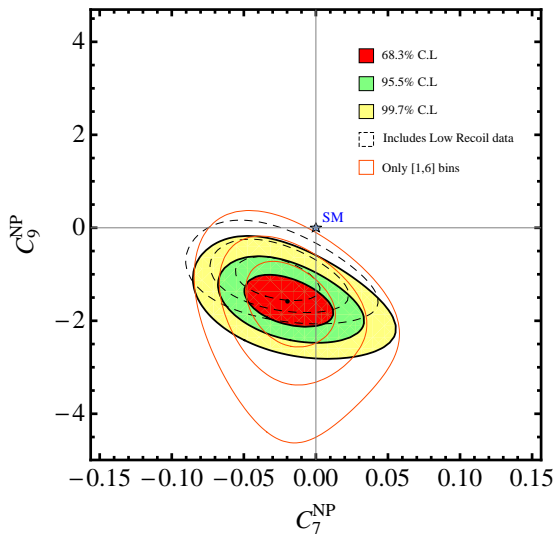
Fits

We fit **all available data** to constrain the **Wilson coefficients**
paying especial attention to:

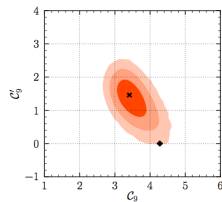
- Issues with form factors and hadronic contributions
- Role of different observables in the fit
- Role of different q^2 regions (different theory issues and approaches)

A bit of (pre)history

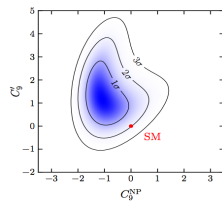
Descotes-Genon, Matias, JV 1307.5683



[Altmannshofer, Straub]



[Beaujean, Bobeth, van Dyk]



[Horgan et al.]

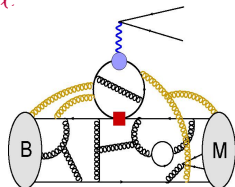
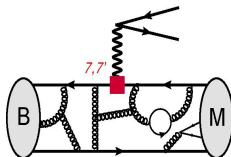
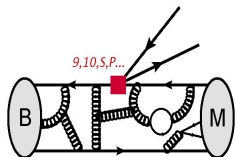
Updates for 2015 Fits

- $BR(B \rightarrow X_s \gamma)$
 - ▶ New theory update: $\mathcal{B}_{s\gamma}^{\text{SM}} = (3.36 \pm 0.23) \cdot 10^{-4}$ (Misiak et al 2015)
 - ▶ +6.4% shift in central value w.r.t 2006 \rightarrow excellent agreement with WA
- $BR(B_s \rightarrow \mu^+ \mu^-)$
 - ▶ New theory update (Bobeth et al 2013), New LHCb+CMS average (2014)
- $BR(B \rightarrow X_s \mu^+ \mu^-)$
 - ▶ New theory update (Huber et al 2015)
- $BR(B \rightarrow K \mu^+ \mu^-)$:
 - ▶ LHCb 2014 + Lattice form factors at large q^2 (Bouchard et al 2013, 2015)
- $B_{(s)} \rightarrow (K^*, \phi) \mu^+ \mu^-$: BRs & Angular Observables
 - ▶ LHCb 2015 + Lattice form factors at large q^2 (Horgan et al 2013)
- $BR(B \rightarrow Ke^+e^-)_{[1,6]}$ (or R_K) and $B \rightarrow K^*e^+e^-$ at very low q^2
 - ▶ LHCb 2014, 2015

Comments on $B \rightarrow V\ell\ell$

EFT Amplitudes:

$$B \rightarrow V\gamma, B \rightarrow M\ell^+\ell^-$$



$$\mathcal{M} = \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* \left[(\mathcal{A}_\mu + \mathcal{T}_\mu) \bar{u}_\ell \gamma^\mu v_\ell + \mathcal{B}_\mu \bar{u}_\ell \gamma^\mu \gamma_5 v_\ell \right]$$

Local: $\mathcal{A}_\mu = -\frac{2m_b q^\nu}{q^2} \mathcal{C}_7 \langle M_\lambda | \bar{s} \sigma_{\mu\nu} P_R b | B \rangle + \mathcal{C}_9 \langle M_\lambda | \bar{s} \gamma_\mu P_L b | B \rangle$

$$\mathcal{B}_\mu = \mathcal{C}_{10} \langle M_\lambda | \bar{s} \gamma_\mu P_L b | B \rangle$$

Non-Local: $\mathcal{T}_\mu = -\frac{16i\pi^2}{q^2} \sum_{i=1..6,8} \mathcal{C}_i \int d^4x e^{iq \cdot x} \langle M_\lambda | T \{ \mathcal{J}_\mu^{\text{em}}(x) \mathcal{O}_i(0) \} | B \rangle$

2 main issues:

1. Determination of **Form Factors** (LCSRs, LQCD, ...)
2. Computation of the **hadronic contribution** (SCET/QCDF, OPE, ...)

$B \rightarrow K^* \ell \bar{\ell}$: Form Factors

Low q^2 ::

- Altmannshofer, Bharucha, Straub, Zwicky:

LCSRs with K^* DAs + Correlations + EOM constraint
 q^2 dependence given by simplified z -expansion

- Descotes-Genon, Hofer, Matias, JV (DHMV):

LCSRs with B DAs (uncorrelated) + SCET relations + Power corrections
 q^2 dependence given by simplified z -expansion

- Jäger + Camalich:

Try to rely only on HQ/LE expansion, both for $q^2 = 0$ and q^2 -dependence
Input: LCSRs, DSE, $B \rightarrow K^* \gamma$, + power corrections

Large q^2 ::

- Horgan et al: Lattice QCD

$B \rightarrow K^* \ell \bar{\ell}$: Form Factors @ low q^2 – See talk by Lars

$$V(q^2) = \frac{m_B + m_{K^*}}{m_B} \xi_{\perp}(q^2) + \Delta V^{\alpha_s}(q^2) + \Delta V^{\Lambda}(q^2),$$

$$A_1(q^2) = \frac{2E}{m_B + m_{K^*}} \xi_{\perp}(q^2) + \Delta A_1^{\alpha_s}(q^2) + \Delta A_1^{\Lambda}(q^2),$$

$$A_2(q^2) = \frac{m_B}{m_B - m_{K^*}} [\xi_{\perp}(q^2) - \xi_{\parallel}(q^2)] + \Delta A_2^{\alpha_s}(q^2) + \Delta A_2^{\Lambda}(q^2),$$

$$A_0(q^2) = \frac{E}{m_{K^*}} \xi_{\parallel}(q^2) + \Delta A_0^{\alpha_s}(q^2) + \Delta A_0^{\Lambda}(q^2),$$

$$T_1(q^2) = \xi_{\perp}(q^2) + \Delta T_1^{\alpha_s}(q^2) + \Delta T_1^{\Lambda}(q^2),$$

$$T_2(q^2) = \frac{2E}{m_B} \xi_{\perp}(q^2) + \Delta T_2^{\alpha_s}(q^2) + \Delta T_2^{\Lambda}(q^2),$$

$$T_3(q^2) = [\xi_{\perp}(q^2) - \xi_{\parallel}(q^2)] + \Delta T_3^{\alpha_s}(q^2) + \Delta T_3^{\Lambda}(q^2),$$

Fact. Power corrections:
$$\Delta F^{\Lambda}(q^2) = a_F + b_F \frac{q^2}{m_B^2} + c_F \frac{q^4}{m_B^4} + \dots,$$

Clean Observables

Optimized Observables

Several Form Factor ratios can be predicted:

- At large recoil \rightarrow SCET [Charles et.al. 1998, Beneke, Feldmann, 2000]
- At low recoil \rightarrow HQET [Grinstein, Pirjol, 2004, Bobeth, Hiller, van Dyk, 2011]

Example

SCET relation at large recoil

$$\frac{\epsilon_-^{*\mu} q^\nu \langle K_-^* | \bar{s} \sigma_{\mu\nu} P_R b | B \rangle}{im_B \langle K_-^* | \bar{s} \not{e}_-^* P_L b | B \rangle} = 1 + \mathcal{O}(\alpha_s, \Lambda/m_b)$$

This allows to build observables with **reduced dependence on FFs**.

Optimized observables at large recoil

[Matias, Mescia, Ramon, JV, 2012]
[Descotes-G, Matias, Ramon, JV, 2013]

$$P_1 = \frac{J_3}{2J_{2s}}$$

$$P_2 = \frac{J_{6s}}{8J_{2s}}$$

$$P'_4 = \frac{J_4}{\sqrt{-J_{2s}J_{2c}}}$$

$$P'_5 = \frac{J_5}{2\sqrt{-J_{2s}J_{2c}}}$$

$$P'_6 = \frac{-J_7}{2\sqrt{-J_{2s}J_{2c}}}$$

$$P'_8 = \frac{-J_8}{\sqrt{-J_{2s}J_{2c}}}$$

Clean Observables: Dictionary!

$$\theta_K^{\text{LHCb}} = \theta_K \quad \theta_\ell^{\text{LHCb}} = \pi - \theta_\ell \quad \phi^{\text{LHCb}} = -\phi$$

$$S_{4,6c,6s,7,9}^{\text{LHCb}} = -S_{4,6c,6s,7,9} \quad ; \quad \text{others unchanged}$$

$$P_1^{\text{LHCb}} = P_1, \quad P_2^{\text{LHCb}} = -P_2, \quad P_3^{\text{LHCb}} = -P_3,$$

$$P_4^{\text{LHCb}} = -\frac{1}{2}P_4', \quad P_5^{\text{LHCb}} = P_5', \quad P_6^{\text{LHCb}} = P_6', \quad P_8^{\text{LHCb}} = -\frac{1}{2}P_8'.$$

Credit to Roman Z., James G., Damir B and Olcyr S. for finding mistakes in the literature and settling this issue definitely.

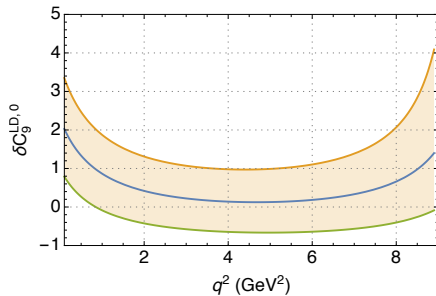
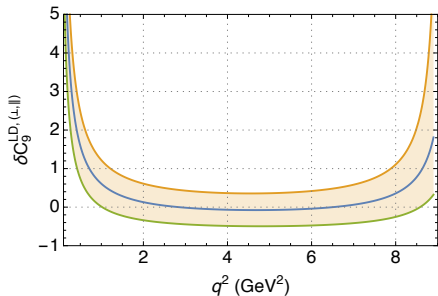
$B \rightarrow K^* \ell \bar{\ell}$: Charm – Low q^2

Inspired by Khodjamirian et al (KMPW): $C_9 \rightarrow C_9 + s_i \delta C_9^{\text{LD}(i)}(q^2)$

$$\delta C_9^{\text{LD},(\perp,\parallel)}(q^2) = \frac{a^{(\perp,\parallel)} + b^{(\perp,\parallel)} q^2 [c^{(\perp,\parallel)} - q^2]}{b^{(\perp,\parallel)} q^2 [c^{(\perp,\parallel)} - q^2]}$$

$$\delta C_9^{\text{LD},0}(q^2) = \frac{a^0 + b^0 [q^2 + s_0] [c^0 - q^2]}{b^0 [q^2 + s_0] [c^0 - q^2]}$$

We vary s_i independently in the range $[-1, 1]$ (only $s_i = 1$ in KMPW).



$B \rightarrow K^* \ell \bar{\ell} : \text{large-}q^2$

- OPE up to dimension 3 ops (Buchalla et al)
- NLO QCD corrections to the OPE coeffs (Greub et al)
- Lattice QCD form factors with correlations (Horgan et al proceeding update)
- $\pm 10\%$ by hand to account for possible Duality Violations

SM predictions and Pulls : $B \rightarrow K\mu\mu$

$BR(B^+ \rightarrow K^+ \mu^+ \mu^-)$	Standard Model	Experiment	Pull
[0.1, 0.98]	0.314 ± 0.092	0.292 ± 0.022	+0.2
[1.1, 2]	0.321 ± 0.100	0.210 ± 0.017	+ 1.1
[2, 3]	0.354 ± 0.113	0.282 ± 0.021	+0.6
[3, 4]	0.351 ± 0.115	0.254 ± 0.020	+0.8
[4, 5]	0.348 ± 0.117	0.221 ± 0.018	+ 1.1
[5, 6]	0.345 ± 0.120	0.231 ± 0.018	+0.9
[6, 7]	0.343 ± 0.125	0.245 ± 0.018	+0.8
[7, 8]	0.343 ± 0.131	0.231 ± 0.018	+0.8
[15, 22]	0.975 ± 0.133	0.847 ± 0.049	+0.9
$BR(B^0 \rightarrow K^0 \mu^+ \mu^-)$	Standard Model	Experiment	Pull
[0.1, 2]	0.629 ± 0.191	0.232 ± 0.105	+ 1.8
[2, 4]	0.654 ± 0.211	0.374 ± 0.106	+ 1.2
[4, 6]	0.643 ± 0.221	0.346 ± 0.103	+ 1.2
[6, 8]	0.636 ± 0.237	0.540 ± 0.115	+0.4
[15, 19]	0.904 ± 0.124	0.665 ± 0.116	+ 1.4

SM predictions and Pulls : $BR(B \rightarrow V\mu\mu)$

$BR(B^0 \rightarrow K^{*0}\mu^+\mu^-)$	Standard Model	Experiment	Pull
[0.1, 2]	1.359 ± 1.075	1.140 ± 0.181	+0.2
[2, 4.3]	0.768 ± 0.523	0.690 ± 0.115	+0.1
[4.3, 8.68]	2.278 ± 1.776	2.146 ± 0.307	+0.1
[16, 19]	1.652 ± 0.152	1.230 ± 0.195	+1.7
$BR(B^+ \rightarrow K^{*+}\mu^+\mu^-)$	Standard Model	Experiment	Pull
[0.1, 2]	1.405 ± 1.123	1.121 ± 0.266	+0.2
[2, 4]	0.723 ± 0.487	1.120 ± 0.320	-0.7
[4, 6]	0.856 ± 0.625	0.500 ± 0.200	+0.5
[6, 8]	1.054 ± 0.831	0.660 ± 0.220	+0.5
[15, 19]	2.586 ± 0.247	1.600 ± 0.320	+2.4
$BR(B_s \rightarrow \phi\mu^+\mu^-)$	Standard Model	Experiment	Pull
[0.1, 2.]	1.880 ± 0.372	1.112 ± 0.161	+1.9
[2., 5.]	1.702 ± 0.281	0.768 ± 0.135	+3.0
[5., 8.]	2.024 ± 0.357	0.963 ± 0.150	+2.7
[15, 18.8]	2.198 ± 0.167	1.616 ± 0.202	+2.2

SM predictions and Pulls : $P_i(B \rightarrow K^* \mu \mu)$

$P_1(B \rightarrow K^* \mu^+ \mu^-)$	Standard Model	Experiment	Pull
[15, 19]	-0.643 ± 0.055	-0.497 ± 0.109	-1.2
$P_2(B \rightarrow K^* \mu^+ \mu^-)$	Standard Model	Experiment	Pull
[0.1, 0.98]	0.117 ± 0.016	0.003 ± 0.054	+2.0
[6, 8]	-0.371 ± 0.071	-0.241 ± 0.072	-1.3
$P'_5(B \rightarrow K^* \mu^+ \mu^-)$	Standard Model	Experiment	Pull
[0.1, 0.98]	0.676 ± 0.139	0.386 ± 0.144	+1.4
[2.5, 4]	-0.468 ± 0.122	-0.067 ± 0.338	-1.1
[4, 6]	-0.808 ± 0.082	-0.299 ± 0.160	-2.8
[6, 8]	-0.935 ± 0.078	-0.504 ± 0.128	-2.9
[15, 19]	-0.574 ± 0.047	-0.684 ± 0.083	+1.2
$P'_6(B \rightarrow K^* \mu^+ \mu^-)$	Standard Model	Experiment	Pull
[1.1, 2.5]	-0.073 ± 0.028	0.462 ± 0.225	-2.4
$P'_8(B \rightarrow K^* \mu^+ \mu^-)$	Standard Model	Experiment	Pull
[0.1, 0.98]	0.021 ± 0.025	0.359 ± 0.354	-1.0
[4, 6]	0.031 ± 0.019	0.685 ± 0.399	-1.6
[6, 8]	0.018 ± 0.012	-0.344 ± 0.297	+1.2

SM predictions and Pulls : $P_i(B_s \rightarrow \Phi\mu\mu)$

$P_1(B_s \rightarrow \phi\mu^+\mu^-)$	Standard Model	Experiment	Pull
[15, 18.8]	-0.689 ± 0.033	-0.253 ± 0.341	-1.3
$P'_4(B_s \rightarrow \phi\mu^+\mu^-)$	Standard Model	Experiment	Pull
[15, 18.8]	1.296 ± 0.014	0.617 ± 0.486	+1.4
$P'_6(B_s \rightarrow \phi\mu^+\mu^-)$	Standard Model	Experiment	Pull
[15, 18.8]	-0.003 ± 0.072	-0.286 ± 0.243	+1.1
$F_L(B_s \rightarrow \phi\mu^+\mu^-)$	Standard Model	Experiment	Pull
[0.1, 2.]	0.431 ± 0.081	0.200 ± 0.087	+2.0
[5., 8.]	0.655 ± 0.048	0.540 ± 0.097	+1.0
[15, 18.8]	0.356 ± 0.023	0.290 ± 0.068	+0.9

Fits

Fit: Statistical Approach

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

- $Cov = Cov^{\text{exp}} + Cov^{\text{th}}$
- We have Cov^{exp} for the first time
- Calculate Cov^{th} : correlated multigaussian scan over all nuisance parameters
- Cov^{th} depends on C_i : Must check this dependence

For the Fit:

- Minimise $\chi^2 \rightarrow \chi_{\text{min}}^2 = \chi^2(C_i^0)$ (Best Fit Point = C_i^0)
- Confidence level regions: $\chi^2(C_i) - \chi_{\text{min}}^2 < \Delta\chi_{\sigma,n}$
- Compute pulls by inversion of the above formula

Fits

All include $B \rightarrow X_s \gamma$, $B \rightarrow K^* \gamma$, $B_s \rightarrow \mu^+ \mu^-$, $B \rightarrow X_s \mu^+ \mu^-$ by default.

-
- **Fit 1 (Canonical):** $B_{(s)} \rightarrow (K^{(*)}, \phi) \mu^+ \mu^-$, BR's and P_i 's, All q^2 (91 obs)
-
- **Fit 2:** Branching Ratios only (27 obs)
 - **Fit 3:** P_i Angular Observables only (64 obs)
 - **Fit 4:** S_i Angular Observables only (64 obs)
-
- **Fit 5:** $B \rightarrow K \mu^+ \mu^-$ only (14 obs)
 - **Fit 6:** $B \rightarrow K^* \mu^+ \mu^-$ only (57 obs)
 - **Fit 7:** $B_s \rightarrow \phi \mu^+ \mu^-$ only (20 obs)
-
- **Fit 8:** Large Recoil only (74 obs)
 - **Fit 9:** Low Recoil only (17 obs)
 - **Fit 10:** Only bins within $[1,6] \text{ GeV}^2$ (39 obs)
 - **Fits 11:** Bin-by-bin analysis.
-
- **Fit 12:** Full form factor approach [a la ABSZ] (91 obs)
 - **Fit 13:** Enhanced Power Corrections (91 obs)
 - **Fit 14:** Enhanced Charm loop effect (91 obs)
-

Fit 1: 1D fits

Coefficient	Best fit	1σ	Pull _{SM}	p-value (%)
C_7^{NP}	-0.02	[-0.04, -0.00]	1.2	17.0
C_9^{NP}	-1.09	[-1.29, -0.87]	4.5	63.0
C_{10}^{NP}	0.56	[0.32, 0.81]	2.5	25.0
$C_{7'}^{\text{NP}}$	0.02	[-0.01, 0.04]	0.6	15.0
$C_{9'}^{\text{NP}}$	0.46	[0.18, 0.74]	1.7	19.0
$C_{10'}^{\text{NP}}$	-0.25	[-0.44, -0.06]	1.3	17.0
$C_9^{\text{NP}} = C_{10}^{\text{NP}}$	-0.22	[-0.40, -0.02]	1.1	16.0
$C_9^{\text{NP}} = -C_{10}^{\text{NP}}$	-0.68	[-0.85, -0.50]	4.2	56.0
$C_{9'}^{\text{NP}} = C_{10'}^{\text{NP}}$	-0.07	[-0.33, 0.19]	0.3	14.0
$C_{9'}^{\text{NP}} = -C_{10'}^{\text{NP}}$	0.19	[0.07, 0.31]	1.6	18.0
$C_9^{\text{NP}} = -C_{9'}^{\text{NP}}$	-1.06	[-1.25, -0.86]	4.8	72.0

Fit 1: 2D fits :: only scenarios with $\text{Pull}_{\text{SM}} > 4$

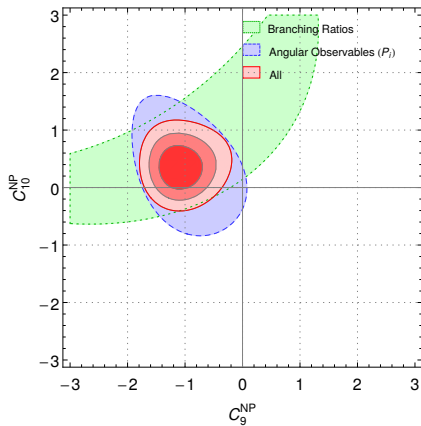
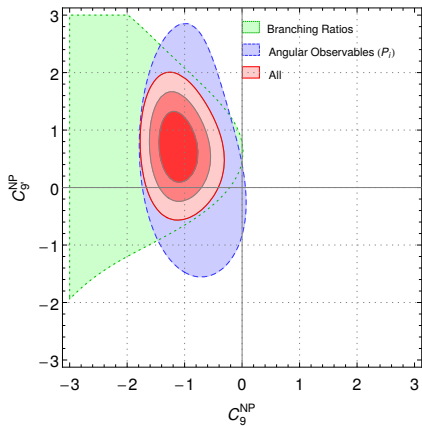
Coefficient	Best Fit Point	Pull_{SM}	p-value (%)
$(\mathcal{C}_7^{\text{NP}}, \mathcal{C}_9^{\text{NP}})$	$(-0.00, -1.07)$	4.1	61.0
$(\mathcal{C}_9^{\text{NP}}, \mathcal{C}_{10}^{\text{NP}})$	$(-1.08, 0.33)$	4.3	67.0
$(\mathcal{C}_9^{\text{NP}}, \mathcal{C}_{7'}^{\text{NP}})$	$(-1.09, 0.02)$	4.2	63.0
$(\mathcal{C}_9^{\text{NP}}, \mathcal{C}_{9'}^{\text{NP}})$	$(-1.12, 0.77)$	4.5	72.0
$(\mathcal{C}_9^{\text{NP}}, \mathcal{C}_{10'}^{\text{NP}})$	$(-1.17, -0.35)$	4.5	71.0
$(\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{9'}^{\text{NP}}, \mathcal{C}_{10}^{\text{NP}} = \mathcal{C}_{10'}^{\text{NP}})$	$(-1.15, 0.34)$	4.7	75.0
$(\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{9'}^{\text{NP}}, \mathcal{C}_{10}^{\text{NP}} = -\mathcal{C}_{10'}^{\text{NP}})$	$(-1.06, 0.06)$	4.4	70.0

Fit 1: 6D fits

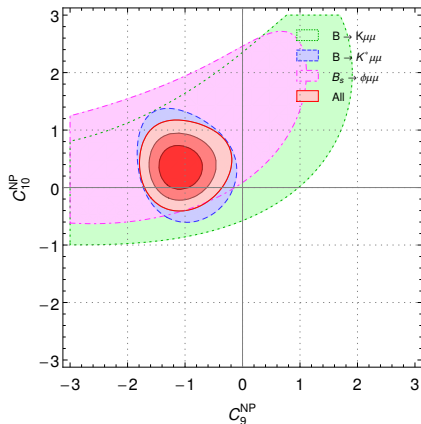
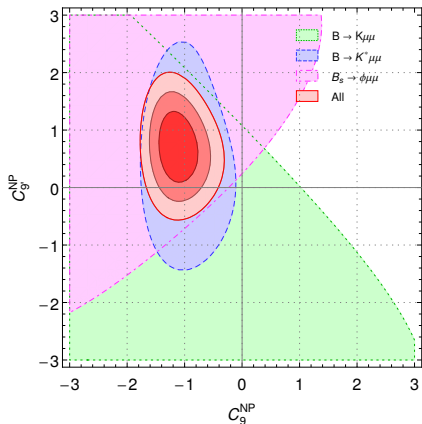
Coefficient	1σ	2σ	3σ
C_7^{NP}	$[-0.02, 0.03]$	$[-0.04, 0.04]$	$[-0.05, 0.08]$
C_9^{NP}	$[-1.4, -1.0]$	$[-1.7, -0.7]$	$[-2.2, -0.4]$
C_{10}^{NP}	$[-0.0, 0.9]$	$[-0.3, 1.3]$	$[-0.5, 2.0]$
$C_{7'}^{\text{NP}}$	$[-0.02, 0.03]$	$[-0.04, 0.06]$	$[-0.06, 0.07]$
$C_{9'}^{\text{NP}}$	$[0.3, 1.8]$	$[-0.5, 2.7]$	$[-1.3, 3.7]$
$C_{10'}^{\text{NP}}$	$[-0.3, 0.9]$	$[-0.7, 1.3]$	$[-1.0, 1.6]$

Comparing different fits

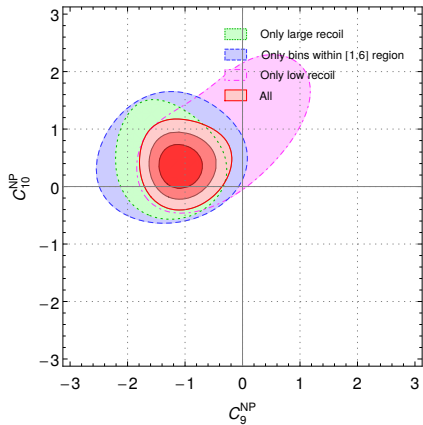
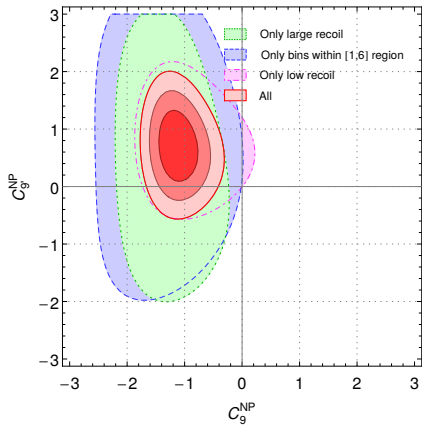
Branching Ratios vs. Angular Observables



$B \rightarrow K\mu\mu$ vs. $B \rightarrow K^*\mu\mu$ vs. $B_s \rightarrow \phi\mu\mu$

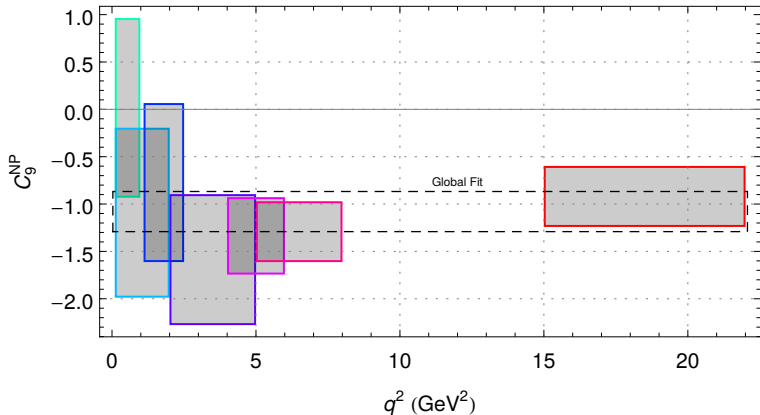


Different q^2 regions



Different q^2 regions

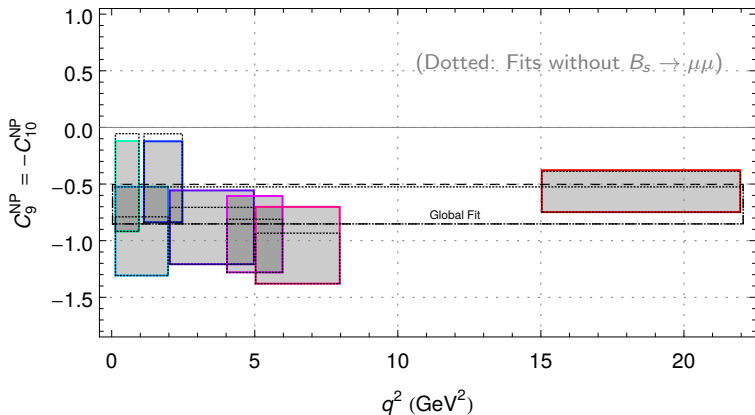
$$\rightarrow \mathcal{T}_\mu = -\frac{16i\pi^2}{q^2} \sum_{i=1..6,8} c_i \int dx^4 e^{iq \cdot x} \langle M_\lambda | T \{ \mathcal{J}_\mu^{\text{em}}(x) \mathcal{O}_i(0) \} | B \rangle \text{ is } q^2\text{-dependent}$$



\Rightarrow No evidence for q^2 -dependence \rightarrow Good crosscheck of hadronic contribution!

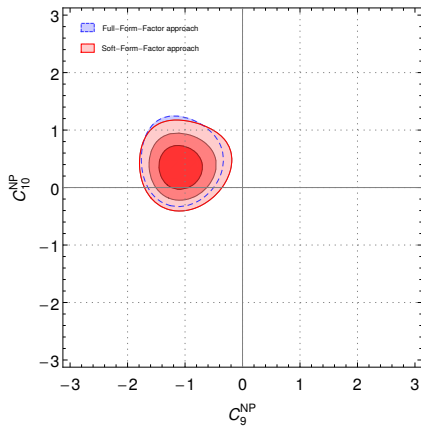
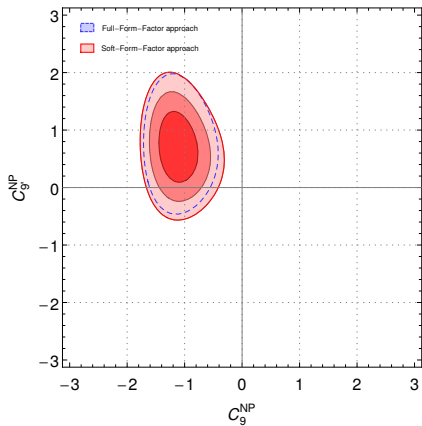
Different q^2 regions

→ C_{10} is **never** q^2 -dependent

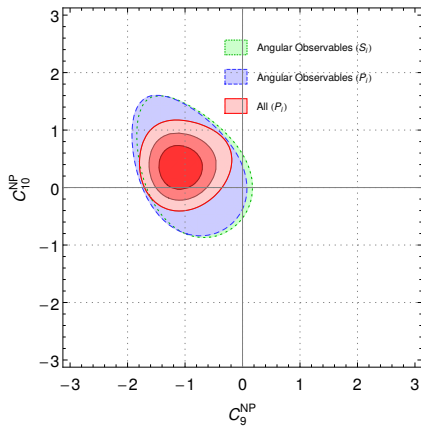
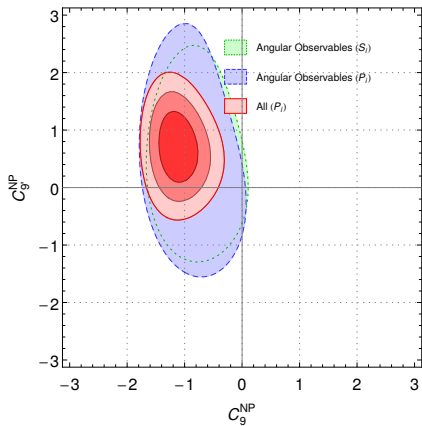


⇒ No evidence for q^2 -dependence → Good crosscheck: the fit is still good!

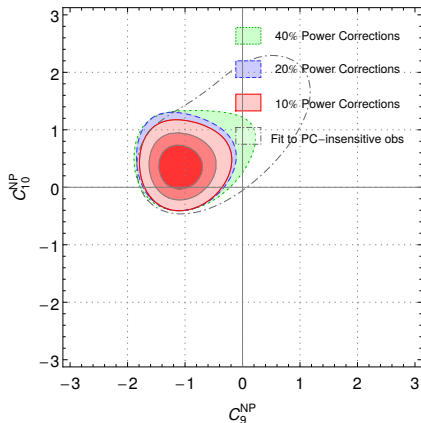
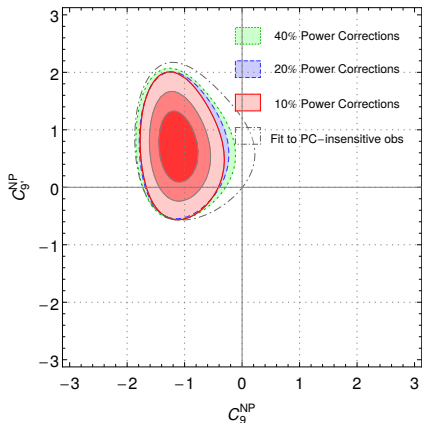
DHMV vs. Full form factors



P_i 's vs. S_i 's



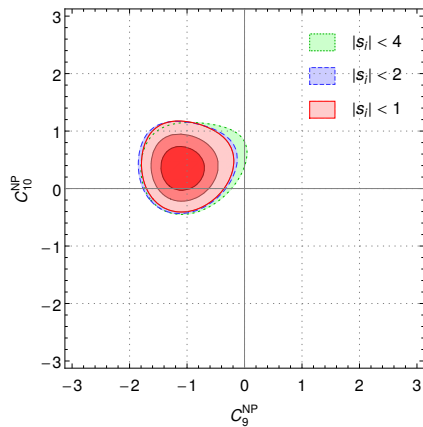
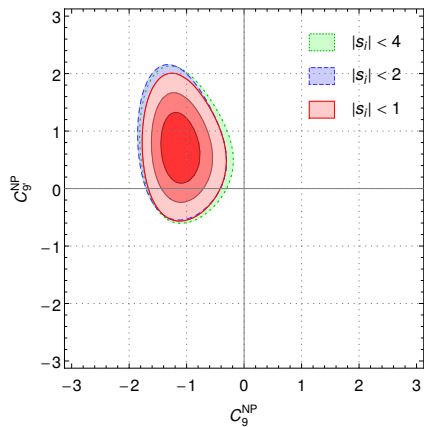
Enhanced Power Corrections



⇒ With very wide room for PCs

→ still PC-dependent observables have constraining power.

Enhanced charm-loop effect



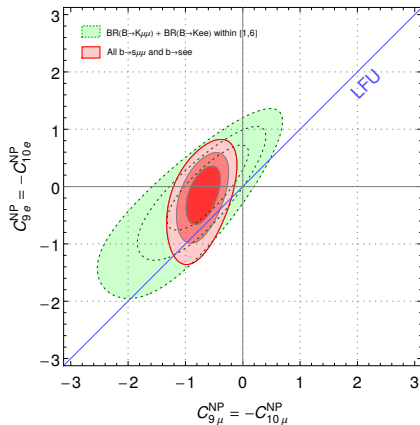
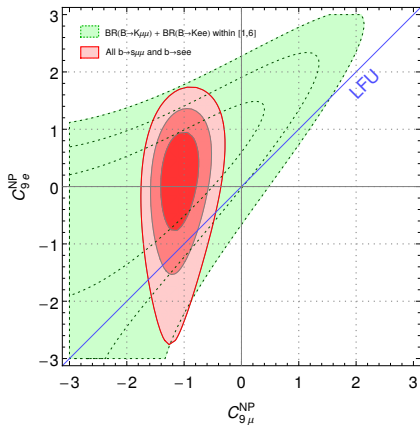
Predictions for Flavour Non-Universality

Assume there is no NP coupling to electrons.

(★) potential Z' scenario

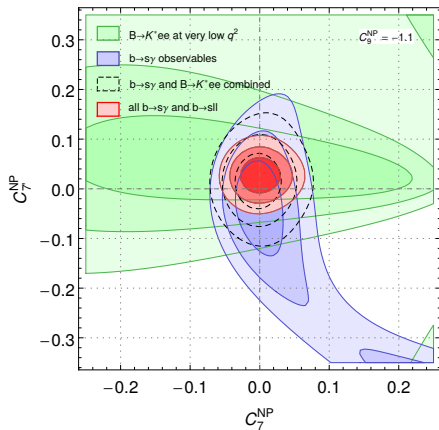
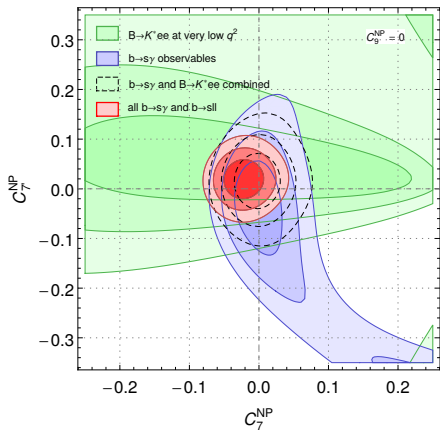
		$R_K[1, 6]$	$R_{K^*}[1.1, 6]$	$R_\phi[1.1, 6]$
SM		1.00 ± 0.01	1.00 ± 0.01	1.00 ± 0.01
$C_9^{\text{NP}} = -1.11$	★	0.79 ± 0.01	0.87 ± 0.08	0.84 ± 0.02
$C_9^{\text{NP}} = -C_{9'}^{\text{NP}} = -1.09$	★	1.00 ± 0.01	0.79 ± 0.14	0.74 ± 0.03
$C_9^{\text{NP}} = -C_{10}^{\text{NP}} = -0.69$	★	0.67 ± 0.01	0.71 ± 0.03	0.69 ± 0.01
$C_9^{\text{NP}} = -1.15, C_{9'}^{\text{NP}} = 0.77$	★	0.91 ± 0.01	0.80 ± 0.12	0.76 ± 0.03
$C_9^{\text{NP}} = -1.16, C_{10}^{\text{NP}} = 0.35$	★	0.71 ± 0.01	0.78 ± 0.07	0.76 ± 0.01
$C_9^{\text{NP}} = -1.23, C_{10'}^{\text{NP}} = -0.38$		0.87 ± 0.01	0.79 ± 0.11	0.76 ± 0.02
$C_9^{\text{NP}} = -C_{9'}^{\text{NP}} = -1.14$ $C_{10}^{\text{NP}} = -C_{10'}^{\text{NP}} = 0.04$	★	1.00 ± 0.01	0.78 ± 0.13	0.74 ± 0.03
$C_9^{\text{NP}} = -C_{9'}^{\text{NP}} = -1.17$ $C_{10}^{\text{NP}} = C_{10'}^{\text{NP}} = 0.26$		0.88 ± 0.01	0.76 ± 0.12	0.71 ± 0.03

Fits including Flavour Non-Universality



The assumption of no NP in $(\bar{s}b)(\bar{e}e)$ operators is supported by the global fit

Fits at very low q^2 :: $B \rightarrow K^* e^+ e^-$



$b \rightarrow s \gamma$ and $b \rightarrow s e e$ at very low q^2 are complementary

Compendium of fits for $\mathcal{C}_{9\mu}$

Fit	$\mathcal{C}_{9\mu}^{\text{NP Bestfit}}$	1σ		
All $b \rightarrow s\mu\mu$ in SM	-	-	Only $b \rightarrow s\mu\mu$ within [1,6]	-1.30 [-1.66, -0.93]
All $b \rightarrow s\mu\mu$	-1.09	[-1.29, -0.87]	Only $BR(B \rightarrow K\ell\ell)_{[1,6]}$, $\ell = e, \mu$	-1.55 [-2.73, -0.81]
All $b \rightarrow s\ell\ell$, $\ell = e, \mu$	-1.11	[-1.31, -0.90]	All $b \rightarrow s\mu\mu$, 20% PCs	-1.10 [-1.31, -0.87]
All $b \rightarrow s\mu\mu$ excluding [6,8] region	-0.99	[-1.23, -0.75]	All $b \rightarrow s\mu\mu$, 40% PCs	-1.08 [-1.32, -0.82]
Only $b \rightarrow s\mu\mu$ BRs	-1.58	[-2.22, -1.07]	All $b \rightarrow s\mu\mu$, charm \times 2	-1.12 [-1.33, -0.89]
Only $b \rightarrow s\mu\mu$ P_i 's	-1.01	[-1.25, -1.25]	All $b \rightarrow s\mu\mu$, charm \times 4	-1.06 [-1.29, -0.82]
Only $b \rightarrow s\mu\mu$ S_i 's	-0.95	[-1.19, -1.19]	Only $b \rightarrow s\mu\mu$ within [0.1,6]	-1.21 [-1.57, -0.84]
Only $B \rightarrow K\mu\mu$	-0.85	[-1.67, -0.20]	Only $b \rightarrow s\mu\mu$ within [0.1,0.98]	0.08 [-0.92, 0.95]
Only $B \rightarrow K^*\mu\mu$	-1.05	[-1.27, -0.80]	Only $b \rightarrow s\mu\mu$ within [0.1,2]	-1.03 [-1.98, -0.20]
Only $B_s \rightarrow \phi\mu\mu$	-1.98	[-2.84, -1.29]	Only $b \rightarrow s\mu\mu$ within [1.1,2.5]	-0.74 [-1.60, 0.06]
Only $b \rightarrow s\mu\mu$ at large recoil	-1.30	[-1.57, -1.02]	Only $b \rightarrow s\mu\mu$ within [2,5]	-1.56 [-2.27, -0.91]
Only $b \rightarrow s\mu\mu$ at low recoil	-0.93	[-1.23, -0.61]	Only $b \rightarrow s\mu\mu$ within [4,6]	-1.34 [-1.73, -0.94]
			Only $b \rightarrow s\mu\mu$ within [5,8]	-1.30 [-1.60, -0.98]

Conclusions of Fits

- Fits to $b \rightarrow s\gamma$, sll were a curiosity in 2012
By 2015 they are a serious industry.
 - Around 100 observables, many $\sim 1\sigma$, several $> 2\sigma$ w.r.t SM.
 - Global fits point to a $\gtrsim 4\sigma$ tension w.r.t the SM. ***
 - Best-fit scenarios provide good fits to data, with
 - ▶ compatibility between BRs and AOs
 - ▶ compatibility between different modes
 - ▶ compatibility between different q^2 regions
 - ▶ agreement between different form-factor approaches
 - Fit results seem robust under
 - ▶ power corrections
 - ▶ charm-loop effects
- correlations must play an important role (not absolute freedom after all!).
- Important to establish to what extent these best fits scenarios can be realised in renormalizable models (many extremely interesting papers already).

Conclusions of Fits

*** Comment / footnote

We show that:

1. Assuming KMPW is the right ballpark for $c\bar{c}$.
2. Assuming Fact. PCs are $\sim 10 - 20\%$ (supported by LCSR calculations).
3. Assuming the OPE for the large- q^2 bin is correct up to $\sim 10\%$

then, a **NP contribution** $\mathcal{C}_{9\mu}^{\text{NP}} \sim -1$ gives a **substantially improved fit** for

- $B \rightarrow K\mu\mu$, $B \rightarrow K^*\mu\mu$ and $B_s \rightarrow \Phi\mu\mu$
- BRs and angular observables (including P'_5)
- Low q^2 and large q^2
- R_K

All these receive, in general, quite different contributions from hadronic operators.