Global analysis of $b \to s\ell\ell$ anomalies

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Descotes-Genon, Hofer, Matias, JV, 1510.04239 [hep-ph]

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:: The theory at the B-meson scale

Effective Lagrangian relevant for $b \to s\gamma/s\ell\ell$ transitions:

$$\mathcal{L}_W = \mathcal{L}_{\rm QCD} + \mathcal{L}_{\rm QED} + \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^\star \sum_i C_i(\mu)\, \mathcal{O}_i(\mu)$$

$$\mathcal{O}_1 = (\bar{c}\gamma_\mu P_L b)(\bar{s}\gamma^\mu P_L c) \qquad \mathcal{O}_2 = (\bar{c}\gamma_\mu P_L T^a b)(\bar{s}\gamma^\mu P_L T^a c)$$

$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu} \qquad \mathcal{O}_{7'} = \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_L b) F^{\mu\nu}$$

$$\mathcal{O}_{9\ell} = \frac{\alpha}{4\pi} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell) \qquad \mathcal{O}_{9'\ell} = \frac{\alpha}{4\pi} (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)$$

$$\mathcal{O}_{10\ell} = \frac{\alpha}{4\pi} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell) \qquad \mathcal{O}_{10'\ell} = \frac{\alpha}{4\pi} (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell),$$

SM contributions to $C_i(\mu_b)$ known to NNLL Bobeth, Misiak, Urban '99; Misiak, Steinhauser '04, Gorbahn, Haisch '04; Gorbahn, Haisch, Misiak '05; Czakon, Haisch, Misiak '06

$$\mathcal{C}_{7\rm eff}^{\rm SM} = -0.3,\ \mathcal{C}_9^{\rm SM} = 4.1,\ \mathcal{C}_{10}^{\rm SM} = -4.3,\ \mathcal{C}_1^{\rm SM} = 1.1,\ \mathcal{C}_2^{\rm SM} = -0.4,\ \mathcal{C}_{\rm rest}^{\rm SM} \lesssim 10^{-2}$$

:: Observables

- Inclusive
  - $B \to X_s\gamma$ (BR) .... $\mathcal{C}_7^{(\prime)}$, $\mathcal{C}_{1,2}$
  - $B \to X_s\ell^+\ell^-$ (dBR/dq^2) .... $\mathcal{C}_7^{(\prime)}$, $\mathcal{C}_9^{(\prime)}$, $\mathcal{C}_{10}^{(\prime)}$, $\mathcal{C}_{1,2}$
- Exclusive leptonic
  - $B_s \to \ell^+\ell^-$ (BR) .... $\mathcal{C}_{10}^{(\prime)}$
- Exclusive radiative/semileptonic
  - $B \to K^*\gamma$ (BR, S, A_I) .... $\mathcal{C}_7^{(\prime)}$, $\mathcal{C}_{1,2}$
  - $B \to K\ell^+\ell^-$ (dBR/dq^2) .... $\mathcal{C}_7^{(\prime)}$, $\mathcal{C}_9^{(\prime)}$, $\mathcal{C}_{10}^{(\prime)}$, $\mathcal{C}_{1,2}$
  - $B \to K^*\ell^+\ell^-$ (dBR/dq^2, Angular Observables) .... $\mathcal{C}_7^{(\prime)}$, $\mathcal{C}_9^{(\prime)}$, $\mathcal{C}_{10}^{(\prime)}$, $\mathcal{C}_{1,2}$
  - $B_s \to \phi\ell^+\ell^-$ (dBR/dq^2, Angular Observables) .... $\mathcal{C}_7^{(\prime)}$, $\mathcal{C}_9^{(\prime)}$, $\mathcal{C}_{10}^{(\prime)}$, $\mathcal{C}_{1,2}$

$\ell = \mu$ and sometimes also $\ell = e$.

:: 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)

:: Theory calculations

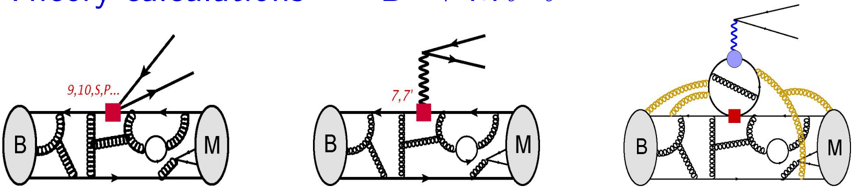
- $BR(B \to X_s\gamma)$
  - New theory update: $\mathcal{B}_{s\gamma}^{\text{SM}} = (3.36 \pm 0.23) \cdot 10^{-4}$ (Misiak et al 2015)
  - $+6.4\%$ shift in central value w.r.t 2006 $\to$ excellent agreement with WA

- $BR(B_s \to \mu^+\mu^-)$
  - "New" theory update (Bobeth et al 2013)

- $BR(B \to X_s\mu^+\mu^-)$
  - New theory update (Huber et al 2015), providing new physics expressions.

- $BR(B \to K\ell^+\ell^-)$, $B_{(s)} \to (K^*, \phi)\ell^+\ell^-$: Next slide

:: Theory calculations - $B \to M\ell^+\ell^-$



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

Local:

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

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

Non-Local:

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

2 main issues:

1. Form Factors (LCSRs, LQCD, symmetry relations . . .)
2. Hadronic contribution (SCET/QCDF, OPE, LCOPE . . .)

$B \to M\ell\bar{\ell}$: Form Factors

Low q^2 ::

- SCET relations (choice of scheme)
  $+ \alpha_s$ symmetry-breaking corrections Beneke-Feldman 2000.
- Two soft form factors from LCSRs with B DAs (uncorrelated) from Khodjamirian et al 2010 (KMPW)
- Power corrections: correlated central values from KMPW
  + uncorrelated 10% "factorizable power corrections"
- For $B_s \to \phi\ell\ell$ we use Bharucha, Straub, Zwicky 2015 (BSZ)

This is much more conservative than BSZ, but a bit less conservative than $[-\infty, \infty]$

Large q^2 ::

- Lattice QCD
  - Bouchard et al 2013, 2015 for $B \to K$
  - Horgan et al 2013 for $B \to K^\star$ and $B_s \to \phi$

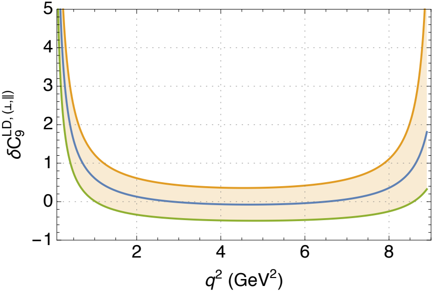
$B \to M\ell\bar{\ell}$: Charm – Low q^2

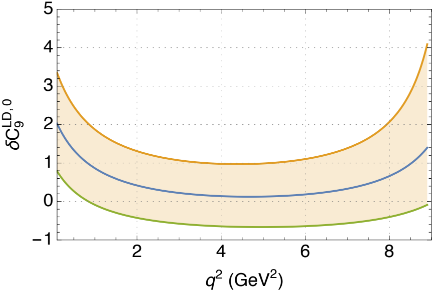
From KMPW: $C_9^{\rm eff} \to C_9^{\rm eff} + s_i\, \delta C_9^{{\rm LD}(i)}(q^2)$

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

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

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





$B \to M\ell\bar{\ell}$: 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 2013
- $\pm 10\%$ by hand to account for possible Duality Violations
- Only a large low-recoil bin to be as inclusive as possible

Fits

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

- **Fit 1 (Canonical): $B_{(s)} \to (K^{(*)}, \phi)\mu^+\mu^-$, 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**: $B \to K\mu^+\mu^-$ only (14 obs)
- **Fit 6**: $B \to K^*\mu^+\mu^-$ only (57 obs)
- **Fit 7**: $B_s \to \phi\mu^+\mu^-$ only (20 obs)

- **Fit 8**: Large Recoil only (74 obs)
- **Fit 9**: Low Recoil only (17 obs)
- **Fit 10**: Only bins within [1,6] 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)

:: Canonical Fit: 1D hypotheses

- ▷ Pull$_{\rm SM}$: $\sim \chi^2_{\rm SM} - \chi^2_{\rm min}$ (metrology: how less likely is SM vs. best fit?)
- ▷ p-value: $p(\chi^2_{\rm min}, N_{\rm dof})$ (goodness of fit: is the best fit a good fit?)
- ▷ Contribution $\mathcal{C}_9^{\rm NP} < 0$ always favoured.

Coefficient	Best fit	3σ	Pull$_{\rm SM}$	p-value (%)
SM	–	–	–	16.0
$\mathcal{C}_7^{\rm NP}$	-0.02	$[-0.07, 0.03]$	1.2	17.0
$\boldsymbol{\mathcal{C}_9^{\rm NP}}$	-1.09	$[-1.67, -0.39]$	**4.5**	63.0
$\mathcal{C}_{10}^{\rm NP}$	0.56	$[-0.12, 1.36]$	2.5	25.0
$\mathcal{C}_{7'}^{\rm NP}$	0.02	$[-0.06, 0.09]$	0.6	15.0
$\mathcal{C}_{9'}^{\rm NP}$	0.46	$[-0.36, 1.31]$	1.7	19.0
$\mathcal{C}_{10'}^{\rm NP}$	-0.25	$[-0.82, 0.31]$	1.3	17.0
$\mathcal{C}_9^{\rm NP} = \mathcal{C}_{10}^{\rm NP}$	-0.22	$[-0.74, 0.50]$	1.1	16.0
$\boldsymbol{\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{10}^{\rm NP}}$	-0.68	$[-1.22, -0.18]$	**4.2**	56.0
$\mathcal{C}_{9'}^{\rm NP} = \mathcal{C}_{10'}^{\rm NP}$	-0.07	$[-0.86, 0.68]$	0.3	14.0
$\mathcal{C}_{9'}^{\rm NP} = -\mathcal{C}_{10'}^{\rm NP}$	0.19	$[-0.17, 0.55]$	1.6	18.0
$\boldsymbol{\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP}}$	-1.06	$[-1.60, -0.40]$	**4.8**	72.0

:: Canonical Fit: 2D hypotheses

- ▷ $\text{Pull}_{\rm SM}$: $\sim \chi^2_{\rm SM} - \chi^2_{\rm min}$ (metrology: how less likely is SM vs. best fit?)
- ▷ p-value: $p(\chi^2_{\rm min}, N_{\rm dof})$ (goodness of fit: is the best fit a good fit?)
- ▷ Several favoured scenarios, all with $\mathcal{C}_9^{\rm NP} < 0$, hard to distinguish.

Coefficient	Best Fit Point	$\text{Pull}_{\rm SM}$	p-value (%)
SM	–	–	16.0
$(\mathcal{C}_7^{\rm NP}, \mathcal{C}_9^{\rm NP})$	$(-0.00, -1.07)$	4.1	61.0
$(\mathcal{C}_9^{\rm NP}, \mathcal{C}_{10}^{\rm NP})$	$(-1.08, 0.33)$	4.3	67.0
$(\mathcal{C}_9^{\rm NP}, \mathcal{C}_{7'}^{\rm NP})$	$(-1.09, 0.02)$	4.2	63.0
$(\mathcal{C}_9^{\rm NP}, \mathcal{C}_{9'}^{\rm NP})$	$(-1.12, 0.77)$	**4.5**	72.0
$(\mathcal{C}_9^{\rm NP}, \mathcal{C}_{10'}^{\rm NP})$	$(-1.17, -0.35)$	**4.5**	71.0
$(\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP}, \mathcal{C}_{10}^{\rm NP} = \mathcal{C}_{10'}^{\rm NP})$	$(-1.15, 0.34)$	**4.7**	75.0
$(\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP}, \mathcal{C}_{10}^{\rm NP} = -\mathcal{C}_{10'}^{\rm NP})$	$(-1.06, 0.06)$	4.4	70.0

(only scenarios with $\text{Pull}_{\rm SM} > 4$)

:: Canonical Fit: 6D hypotheses

▷ All 6 WCs free (but real).

Coefficient	1σ	2σ	3σ
$\mathcal{C}_7^{\rm NP}$	$[-0.02, 0.03]$	$[-0.04, 0.04]$	$[-0.05, 0.08]$
$\mathcal{C}_9^{\rm NP}$	$[-1.4, -1.0]$	$[-1.7, -0.7]$	$[-2.2, -0.4]$
$\mathcal{C}_{10}^{\rm NP}$	$[-0.0, 0.9]$	$[-0.3, 1.3]$	$[-0.5, 2.0]$
$\mathcal{C}_{7'}^{\rm NP}$	$[-0.02, 0.03]$	$[-0.04, 0.06]$	$[-0.06, 0.07]$
$\mathcal{C}_{9'}^{\rm NP}$	$[0.3, 1.8]$	$[-0.5, 2.7]$	$[-1.3, 3.7]$
$\mathcal{C}_{10'}^{\rm NP}$	$[-0.3, 0.9]$	$[-0.7, 1.3]$	$[-1.0, 1.6]$

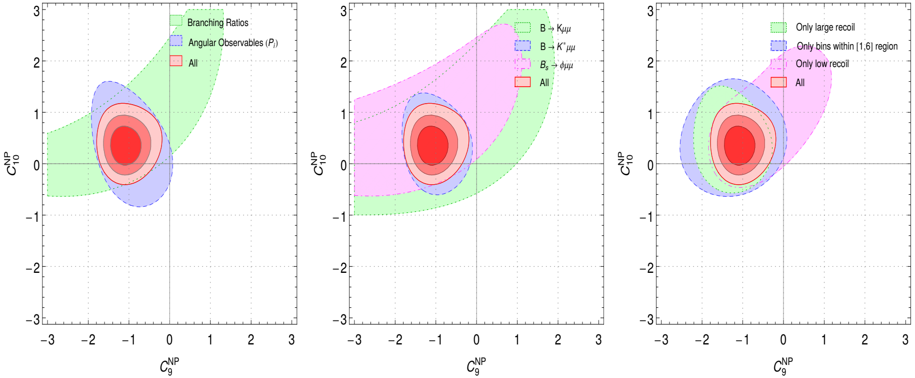
▷ $\mathcal{C}_9$ consistent with SM only above $3\,\sigma$.

▷ All others consistent with the SM at $1\,\sigma$, except for $\mathcal{C}_9'$ at $2\,\sigma$.

▷ Pull_{SM} for the 6D fit is $3.6\,\sigma$.

:: Consistency of different fits

▷ $3\,\sigma$ constraints, always including $b \to s\gamma$ and inclusive.



▷ Good consistency between BRs and Angular observables (P_i's dominate).

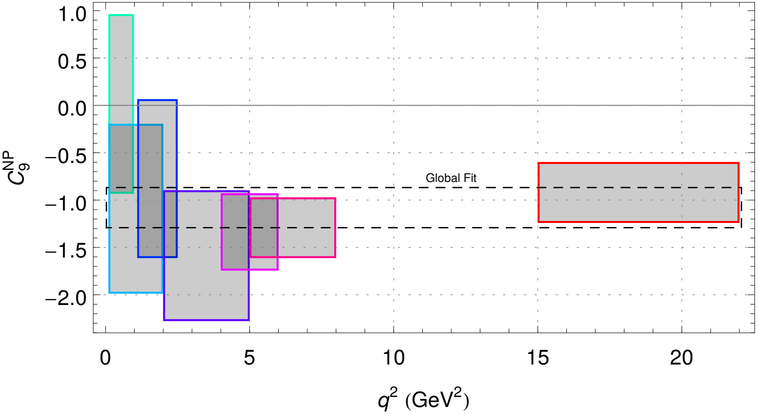
▷ Good consistency between different modes ($B \to K^\star$ dominates).

▷ Good consistency between different q^2 regions (Large-R dominates, [1,6] bulk).

▷ Remember: Quite different theory issues in each case!

:: Hadronic correlator: are we missing something?

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

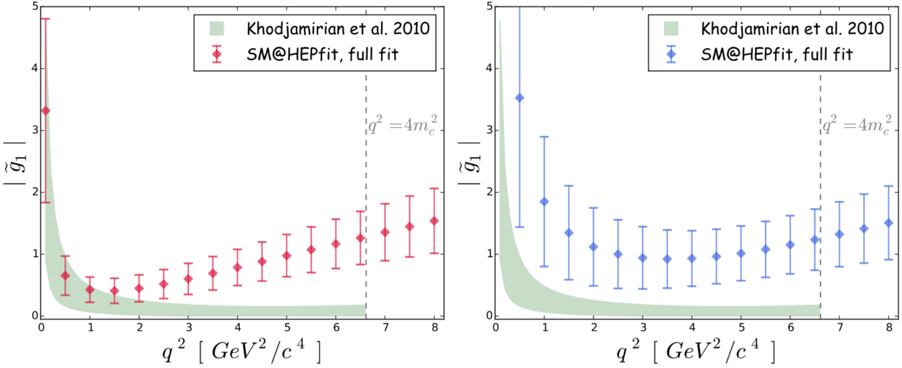


$\Rightarrow$ No evidence for q^2-dependence $\rightarrow$ Good crosscheck of hadronic contribution!

:: Hadronic correlator: are we missing something?

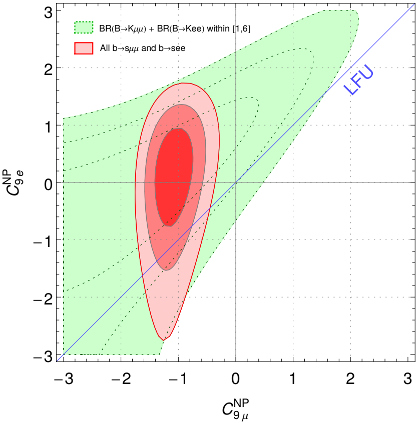
Use the data to fit for (a parametrization of) $C_9^{\rm eff}(q^2) + C_9^{NP}$

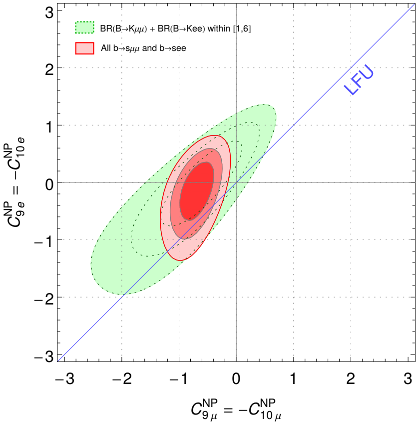
Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli 2015



- ▷ Left: Imposing KMPW at $q^2 < 1$ GeV^2 (so $C_9^{NP} = 0$) ⇒ "large" q^2-dependence
- ▷ Right: Releasing the constraint ⇒ consistent with $\mathrm{KMPW} + (C_9^{NP} = -1)$!!!
- ▷ We agree on the results, but not necessarily on their conclusions.

:: Fits including Flavour Non-Universality





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

:: Predictions for Flavour Non-Universality

Assume there is no NP coupling to electrons. ($\star$) 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
$\mathcal{C}_9^{\rm NP} = -1.11$	$\star$	0.79 ± 0.01	0.87 ± 0.08	0.84 ± 0.02
$\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP} = -1.09$	$\star$	1.00 ± 0.01	0.79 ± 0.14	0.74 ± 0.03
$\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{10}^{\rm NP} = -0.69$	$\star$	0.67 ± 0.01	0.71 ± 0.03	0.69 ± 0.01
$\mathcal{C}_9^{\rm NP} = -1.15, \mathcal{C}_{9'}^{\rm NP} = 0.77$	$\star$	0.91 ± 0.01	0.80 ± 0.12	0.76 ± 0.03
$\mathcal{C}_9^{\rm NP} = -1.16, \mathcal{C}_{10}^{\rm NP} = 0.35$	$\star$	0.71 ± 0.01	0.78 ± 0.07	0.76 ± 0.01
$\mathcal{C}_9^{\rm NP} = -1.23, \mathcal{C}_{10'}^{\rm NP} = -0.38$		0.87 ± 0.01	0.79 ± 0.11	0.76 ± 0.02
$\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP} = -1.14$ $\mathcal{C}_{10}^{\rm NP} = -\mathcal{C}_{10'}^{\rm NP} = 0.04$	$\star$	1.00 ± 0.01	0.78 ± 0.13	0.74 ± 0.03
$\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP} = -1.17$ $\mathcal{C}_{10}^{\rm NP} = \mathcal{C}_{10'}^{\rm NP} = 0.26$		0.88 ± 0.01	0.76 ± 0.12	0.71 ± 0.03

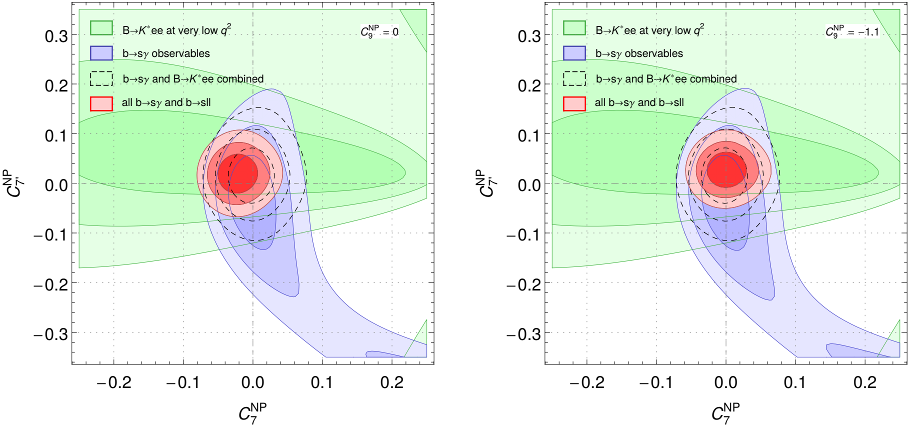
See also the talk by Quim on the Q_i, B_i observables

:: Anomaly patterns

		R_K	$\langle P_5' \rangle_{[4,6],[6,8]}$	$BR(B_s \to \phi\mu\mu)$	low recoil BR	Best fit now
$\mathcal{C}_9^{\text{NP}}$	$+$					
	$-$	✓	✓	✓	✓	X
$\mathcal{C}_{10}^{\text{NP}}$	$+$	✓		✓	✓	X
	$-$		✓			
$\mathcal{C}_{9'}^{\text{NP}}$	$+$			✓	✓	X
	$-$	✓	✓			
$\mathcal{C}_{10'}^{\text{NP}}$	$+$	✓	✓			
	$-$			✓	✓	X

- ▷ $\mathcal{C}_9 < 0$ consistent with all the anomalies
- ▷ No consistent and global alternative from long-distance dynamics.

:: $\mathcal{C}_7, \mathcal{C}_{7'}$ from fits at very low q^2 :: $B \to K^* e^+ e^-$



$b \to s\gamma$ and $b \to see$ at very low q^2 are complementary

:: Conclusions of Fits

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 $\sim 10\%$

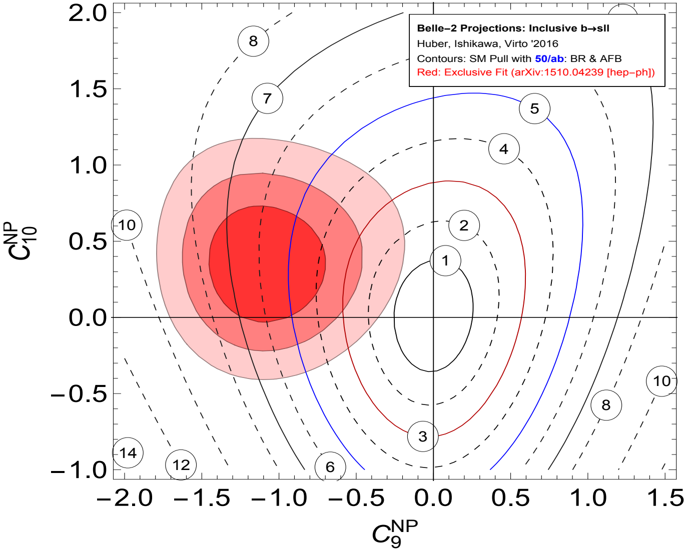
then, a NP contribution $\mathcal{C}_{9\mu}^{\rm NP} \sim -1$ gives a **substantially improved fit** for

- $B \to K\mu\mu$, $B \to K^*\mu\mu$ and $B_s \to \Phi\mu\mu$
- 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.

:: Outlook: Potential of inclusive measurements at Belle-2

If the (current) exclusive fit is accurate, inclusive $b \to s\ell\ell$ Belle-2 measurements alone have the potential for a NP discovery:



Back-up


"I WILL NOT DIE UNTIL AMERICA IS DESTROYED"
FIDEL CASTRO
1926-2016

$B \to K^*\ell\bar{\ell}$: Form Factors @ low q^2

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

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

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

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

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

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

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

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

Clean Observables

Optimized Observables

Several Form Factor ratios can be predicted:

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

Example SCET relation at large recoil

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

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]

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

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

Clean Observables: Dictionary!

$$\theta_K^{\rm LHCb} = \theta_K \qquad \theta_\ell^{\rm LHCb} = \pi - \theta_\ell \qquad \phi^{\rm LHCb} = -\phi$$

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

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

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

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

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

$BR(B^+ \to K^+\mu^+\mu^-)$	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	$+\mathbf{1.1}$
$[2, 3]$	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	$+\mathbf{1.1}$
$[5, 6]$	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	$+0.9$
$BR(B^0 \to K^0\mu^+\mu^-)$	Standard Model	Experiment	Pull
$[0.1, 2]$	0.629 ± 0.191	0.232 ± 0.105	$+\mathbf{1.8}$
$[2, 4]$	0.654 ± 0.211	0.374 ± 0.106	$+\mathbf{1.2}$
$[4, 6]$	0.643 ± 0.221	0.346 ± 0.103	$+\mathbf{1.2}$
$[6, 8]$	0.636 ± 0.237	0.540 ± 0.115	$+0.4$
$[15, 19]$	0.904 ± 0.124	0.665 ± 0.116	$+\mathbf{1.4}$

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

$BR(B^0 \to K^{*0}\mu^+\mu^-)$	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	$+\mathbf{1.7}$
$BR(B^+ \to K^{*+}\mu^+\mu^-)$	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	$+\mathbf{2.4}$
$BR(B_s \to \phi\mu^+\mu^-)$	Standard Model	Experiment	Pull
$[0.1, 2.]$	1.880 ± 0.372	1.112 ± 0.161	$+\mathbf{1.9}$
$[2., 5.]$	1.702 ± 0.281	0.768 ± 0.135	$+\mathbf{3.0}$
$[5., 8.]$	2.024 ± 0.357	0.963 ± 0.150	$+\mathbf{2.7}$
$[15, 18.8]$	2.198 ± 0.167	1.616 ± 0.202	$+\mathbf{2.2}$

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

$P_1(B \to K^* \mu^+ \mu^-)$	Standard Model	Experiment	Pull
[15, 19]	-0.643 ± 0.055	-0.497 ± 0.109	**-1.2**

$P_2(B \to K^* \mu^+ \mu^-)$	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**

$P_5'(B \to K^* \mu^+ \mu^-)$	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	**$+1.2$**

$P_6'(B \to K^* \mu^+ \mu^-)$	Standard Model	Experiment	Pull
[1.1, 2.5]	-0.073 ± 0.028	0.462 ± 0.225	**-2.4**

$P_8'(B \to K^* \mu^+ \mu^-)$	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 : $P_i(B_s \to \Phi\mu\mu)$

$P_1(B_s \to \phi\mu^+\mu^-)$	Standard Model	Experiment	Pull
$[15, 18.8]$	-0.689 ± 0.033	-0.253 ± 0.341	$\mathbf{-1.3}$
$P_4'(B_s \to \phi\mu^+\mu^-)$	Standard Model	Experiment	Pull
$[15, 18.8]$	1.296 ± 0.014	0.617 ± 0.486	$\mathbf{+1.4}$
$P_6'(B_s \to \phi\mu^+\mu^-)$	Standard Model	Experiment	Pull
$[15, 18.8]$	-0.003 ± 0.072	-0.286 ± 0.243	$\mathbf{+1.1}$
$F_L(B_s \to \phi\mu^+\mu^-)$	Standard Model	Experiment	Pull
$[0.1, 2.]$	0.431 ± 0.081	0.200 ± 0.087	$\mathbf{+2.0}$
$[5., 8.]$	0.655 ± 0.048	0.540 ± 0.097	$\mathbf{+1.0}$
$[15, 18.8]$	0.356 ± 0.023	0.290 ± 0.068	$+0.9$

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

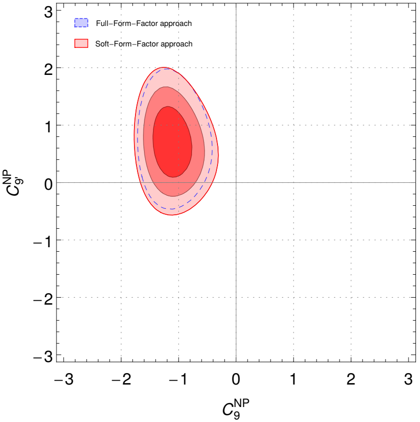
For the Fit:

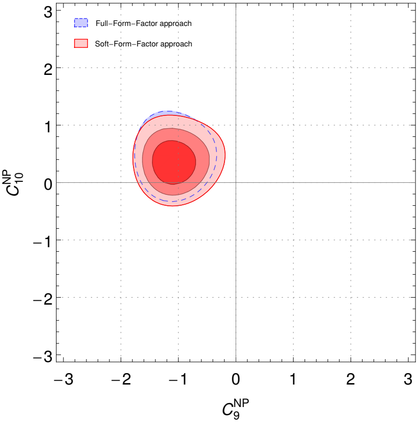
- Minimise $\chi^2 \to \chi^2_{\text{min}} = \chi^2(C_i^0)$ (Best Fit Point $= C_i^0$)
- Confidence level regions: $\chi^2(C_i) - \chi^2_{\text{min}} < \Delta\chi_{\sigma,n}$
- Compute pulls by inversion of the above formula

Fit: Some clarifying comments

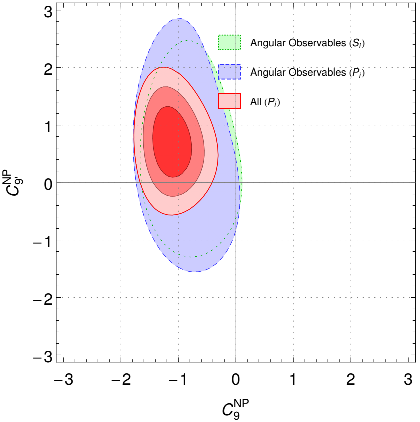
- A large deviation in a *single* observable (or a few) is inconsequential. One out of 100 observables having a tension of 5 σ w.r.t the SM is not very significant ("Look-elsewhere effect"). The global fit accounts for this automatically.
- A large global tension w.r.t the SM can result from a set of observables which individually are only in *mild* tension w.r.t SM predictions.
- Increasing some theoretical or experimental uncertainties does not necessarily imply that the tension w.r.t. the SM must decrease.
- Adding to the fit an observable that does not depend on any of the fitted quantities *may* have an impact in the fit, if this observable does depend on some of the hadronic/nuissance parameters.
- We assume that our "model space" contains the "true" model. The $\Delta\chi^2$ prescription provides a sensible means to compare statistically different model hypotheses.

DHMV vs. Full form factors

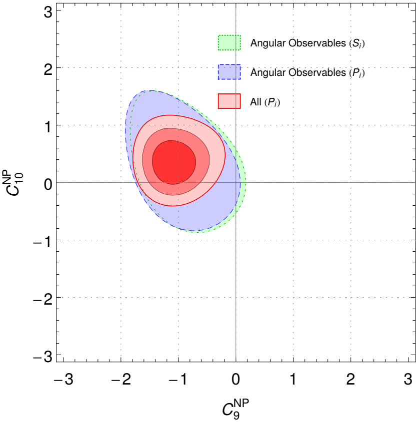




P_i's vs. S_i's

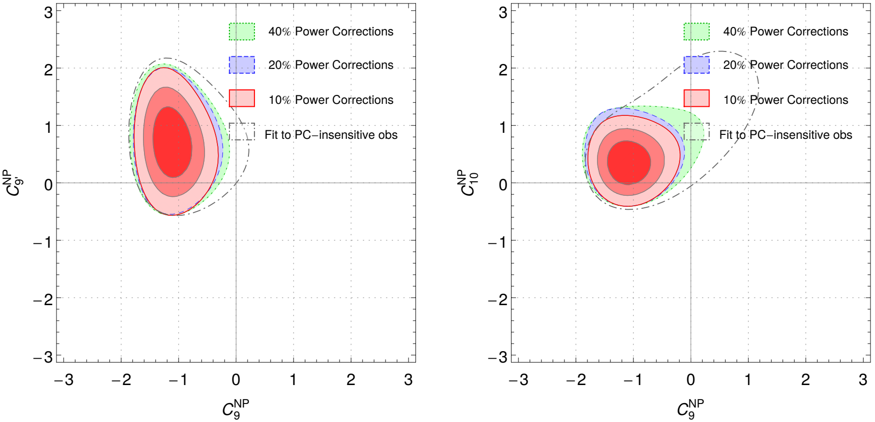


Angular Observables (S_i)
Angular Observables (P_i)
All (P_i)
$C_{9'}^{NP}$
C_9^{NP}



Angular Observables (S_i)
Angular Observables (P_i)
All (P_i)
C_{10}^{NP}
C_9^{NP}

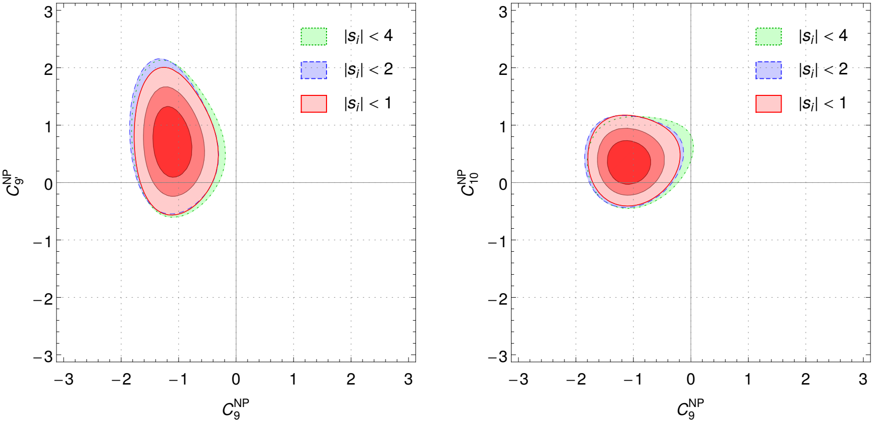
Enhanced Power Corrections



$\Rightarrow$ With very wide room for PCs

$\rightarrow$ still PC-dependent observables have constraining power.

Enhanced charm-loop effect



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

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

Conclusions of Fits

- Fits to $b \to s\gamma,\ s\ell\ell$ 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).