B decays : Anomalies and Challenges

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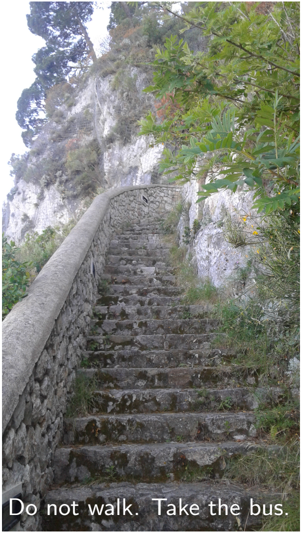
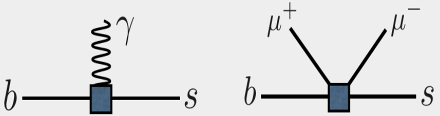
b UNIVERSITÄT BERN



:: Reminder

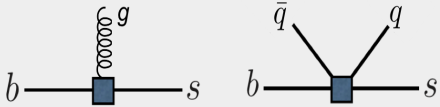
Radiative and Dileptonic $b \to s$ Operators

$$\mathcal{O}_{7(')} = [\bar{s}\sigma^{\mu\nu} P_{R(L)} b] F_{\mu\nu}$$
$$\mathcal{O}_{9(')} = [\bar{s}\gamma^{\mu} P_{L(R)} b][\bar{\ell}\gamma_{\mu}\ell]$$
$$\mathcal{O}_{10(')} = [\bar{s}\gamma^{\mu} P_{L(R)} b][\bar{\ell}\gamma_{\mu}\gamma_5\ell]$$
$$\mathcal{O}_{S(')}, \mathcal{O}_{P(')}, \mathcal{O}_{T,T5}$$



Hadronic $b \to s$ Operators

$$\mathcal{O}_{1} = [\bar{s}\gamma^{\mu} P_{L} c][\bar{c}\gamma_{\mu} P_{L} b]$$
$$\mathcal{O}_{3(5)} = [\bar{s}\gamma^{\mu} P_{L} b] \textstyle\sum_q [\bar{q}\gamma_{\mu} P_{L(R)} q]$$
$$\mathcal{O}_{8g} = [\bar{s}\sigma^{\mu\nu} P_{R(L)} T^a b] G^a_{\mu\nu}$$



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

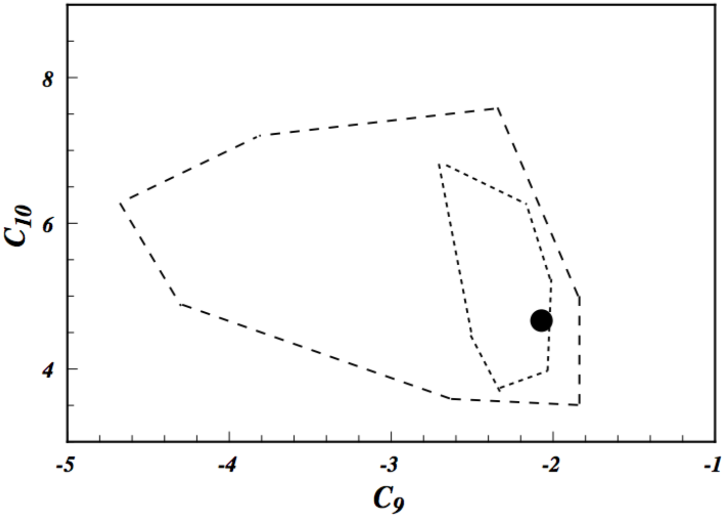
Effective Hamiltonian

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

$\mathcal{C}_{7\rm eff}^{\rm SM} = -0.3,\ \mathcal{C}_{9}^{\rm SM} = 4.1,\ \mathcal{C}_{10}^{\rm SM} = -4.3,\ \mathcal{C}_{1}^{\rm SM} = 1.1,\ \mathcal{C}_{2}^{\rm SM} = -0.4,\ \mathcal{C}_{\rm rest}^{\rm SM} \lesssim 10^{-2}$

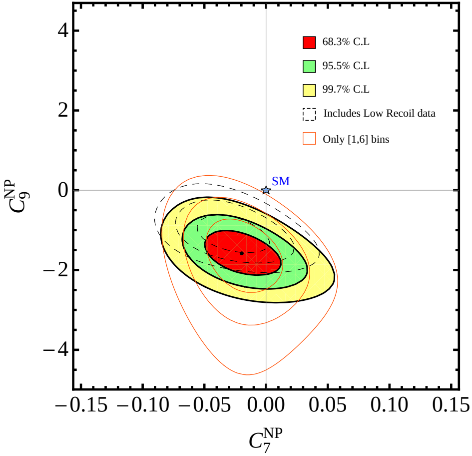
1994...

"Towards a Model-Independent Analysis of Rare B Decays"
A. Ali, G. Giudice, T. Mannel, hep-ph/9408213



...2013

"Understanding the $B \to K^* \mu\mu$ Anomaly"
S. Descotes-Genon, J. Matias, J.V., arXiv:1307.5683



Indication for $\mathcal{C}_9^{\text{NP}} \sim -1$

We have combined the recent LHCb measurements of $B \to K^* \mu^+ \mu^-$ observables [19, 20] with other radiative modes in a fit to Wilson coefficients, using the framework of our previous works [15, 21]. We have found a strong indication for a negative NP contribution to the coefficient $\mathcal{C}_9$, at $4.5\,\sigma$ using large-recoil data ($3.9\,\sigma$ using both large- and low-recoil data). Our results correspond to $\mathcal{C}_9$ inside a 68 % C.L. range $2.2 \le \mathcal{C}_9 \le 2.8$ to be compared with $\mathcal{C}_9^{\text{SM}} = 4.07$ at the scale $\mu_b = 4.8$ GeV. This is the main conclusion of our analysis of LHCb $B \to K^* \mu^+ \mu^-$ measurements.

We also observe a slight preference for negative values

...2013

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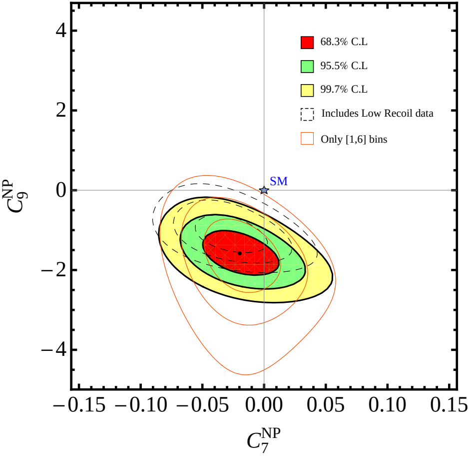

Charm-loop effect

the correlations among the various measurements. On the theoretical side, since $\mathcal{C}_9$ seems to be the main Wilson coefficient affected by NP, charm-loop effects become a very important issue, with several questions left open.

the scheme and the scale of the perturbative charm-quark contribution, as well as to provide alternative and/or improved estimates of the long-distance contribution obtained in Ref. [37], in particular above the charm threshold. Another significant source of uncertainties comes

Ref.[37] : Khodjamirian, Mannel, Pivovarov, Wang

...2013

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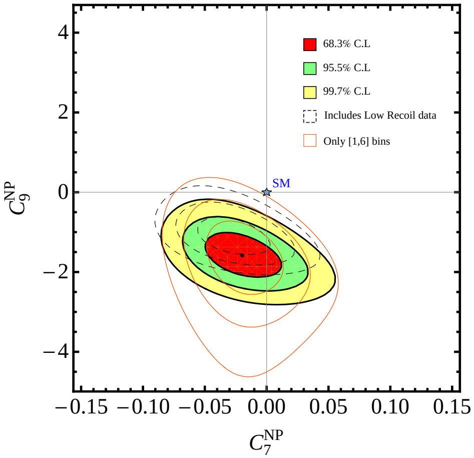

Wishes:

Measurements:

potential pollution of C_9 from charm-loop effects, it is essential that the LHCb experiment provides future results for $B \to K^* \mu^+ \mu^-$ with a finer q^2 binning, with several narrow bins between 1 and 6 GeV^2, and a summary of the correlations among the various measurements. On

Form Factors:

tained in Ref. [37], in particular above the charm threshold. Another significant source of uncertainties comes from the form factors, for which new lattice results should bring more control on the low recoil region [42, 43]. In order to decrease the uncertainty attached to the form factors, it will also become essential that their estimates are provided including correlations, or in the basis of helicity form factors discussed in Refs. [36, 44].

...2013

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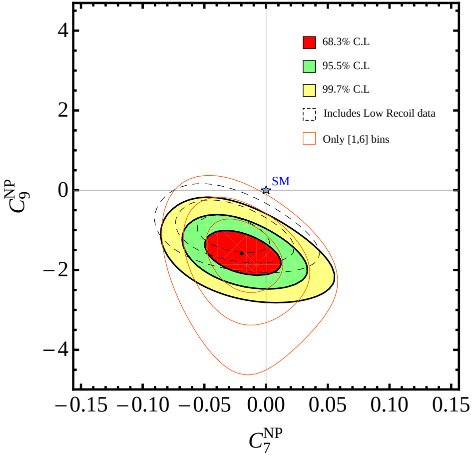


Wishes:

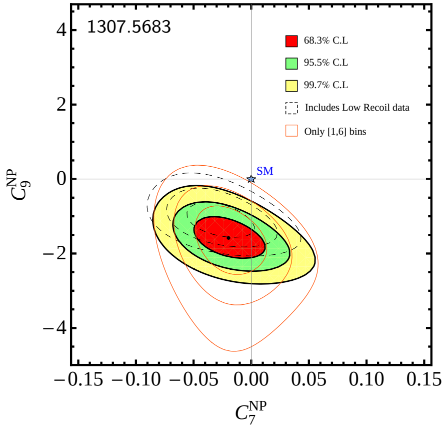
Other modes:

An essential aspect consists in cross-checking and confirming the results from $B \to K^*\mu^+\mu^-$ on $\mathcal{C}_9^{\rm NP}$ through other channels accessible to LHCb and with good prospects of improving on our knowledge of the form factors. The $B \to K\mu^+\mu^-$ decay [45] gives a linear constraint between $\mathcal{C}_7$ and $\mathcal{C}_9$ involving pseudoscalar-to-pseudoscalar form factors well suited for lattice simulations [42, 46, 47]. The $B_s \to \phi\mu^+\mu^-$ [48] has the same potential as $B \to K^*\mu^+\mu^-$ in terms of angular observables, with the added interest of a very narrow ϕ final state, avoiding the difficult simulation of wide resonances on the lattice. Finally, the $\Lambda_b \to \Lambda\mu^+\mu^-$ decay [49, 50] is also a useful cross-check, with a different angular struc-

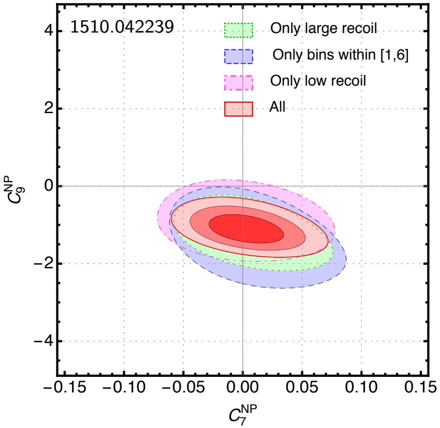
From 2013 to 2016

Many improvements from experiment and theory, but ...

Descotes-Genon, Matias, JV 2013



Descotes-Genon, Hofer, Matias, JV 2015

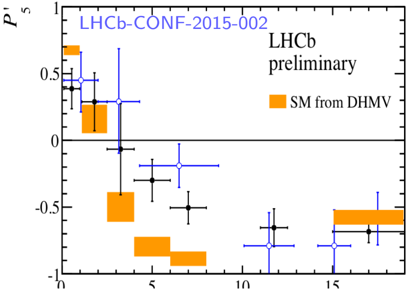


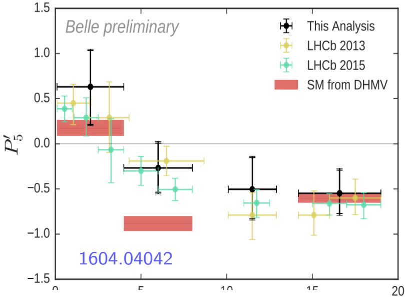
You may be worried that ...

P_5' is a statistical fluctuation / experimental issue

First: The fit is not driven by P_5'. Talk by Nazila (slide 15). But guess which three people insisted on that in 2013...

Second: The experimental results of LHCb are nicely confirmed by Belle.
$\Rightarrow$ now less likely that this is an experimental issue



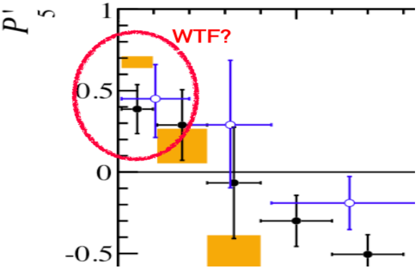


LHCb: two bins with $2.9\,\sigma$ each; **Belle:** $2.1\,\sigma$ in one bin.

⚠ Belle results are combination of $B^0 \to K^{0\star}\mu\mu$ and $B^0 \to K^{0\star}ee$ modes

P_5': Descotes-Genon, Matias, Ramon, JV 2012; DHMV = Descotes-Genon, Hofer, Matias, JV 2014

You may be worried that ...



Explanation: Capdevila, Descotes-Genon, Matias, J.V. 2016

For $m_\ell^2/q^2 \to 0 \;\Rightarrow\; J_{1s} = 3J_{2s}$ and $J_{1c} = -J_{2c}$.

This simplifies the angular distribution, and it is used by LHCb in its analysis:

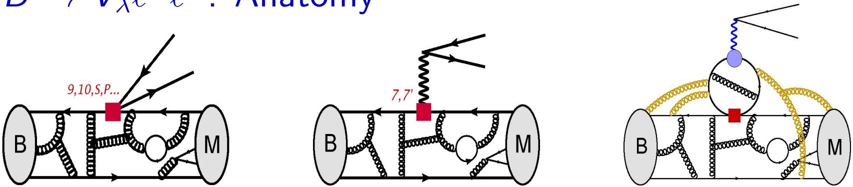
$$P_5'^{\rm TH} = \frac{J_5}{2\sqrt{-J_{2s}J_{2c}}} \quad \text{vs.} \quad P_5'^{\rm LHCb} = \frac{2J_5}{\sqrt{J_{1c}(6J_{1s} - J_{1c} - 2J_{2s} - J_{2c})}}$$

So for $m_\ell^2/q^2 \to 0 \;\Rightarrow\; P_5'^{\rm LHCb} \to P_5'^{\rm TH}$, which is only a bad approximation in the first bin.

You may be worried that ...

For the next worries we need a little of preparation

:: $B \to V_\lambda \ell^+ \ell^-$: Anatomy



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

Local:

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

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

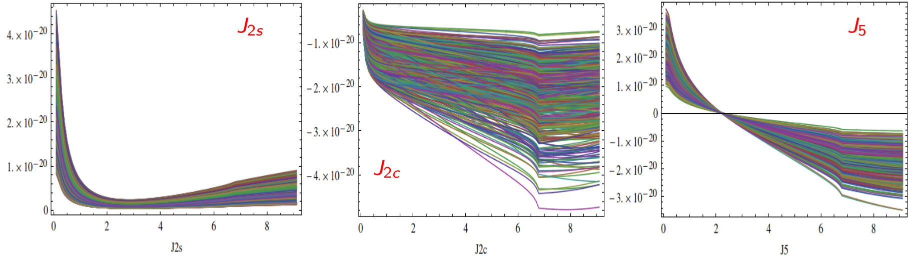
Non-Local:

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

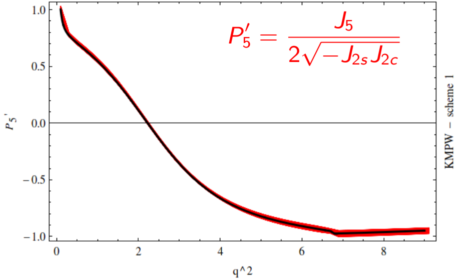
2 main issues:

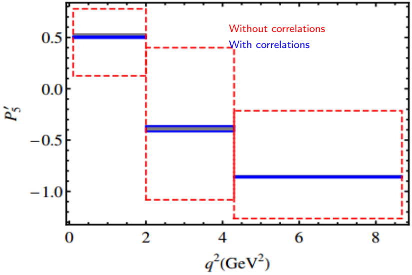
1. Determination of (7) Form Factors $[V, A_{0,1,2}, T_{1,2,3}]$ (LCSRs, LQCD, ...)
2. Computation of the hadronic contribution (SCET/QCDF, OPE, ...)

:: Form Factors : Clean Observables



Form − factor uncertainties

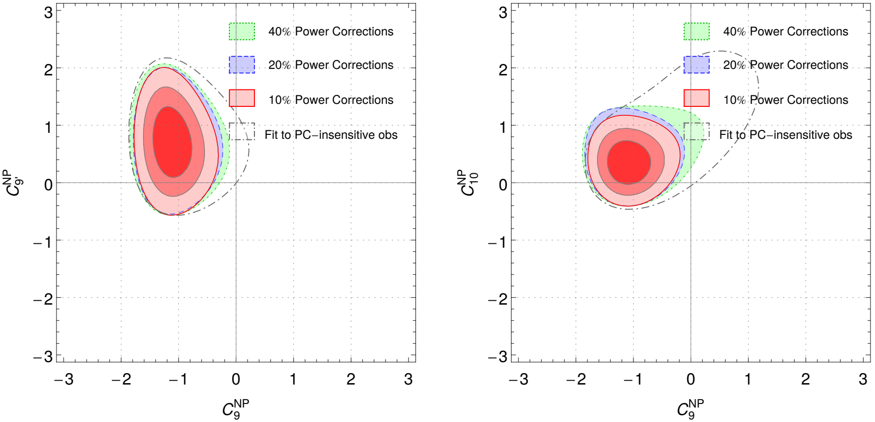




⇒ But Power Corrections spoil these correlations...

You may be worried that ...

Power Corrections in Form Factors might be underestimated?



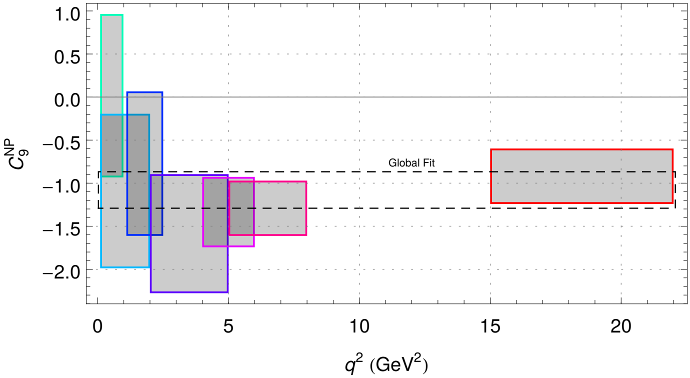
As a worst case, remove observables sensitive to PCs from the fit.

Descotes-Genon, Hofer, Matias, JV 2015 (1510.042239)

You may be worried that ...

We got the wrong charm-loop contribution? We use Khodjamirian, Mannel, Pivovarov, Wang

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

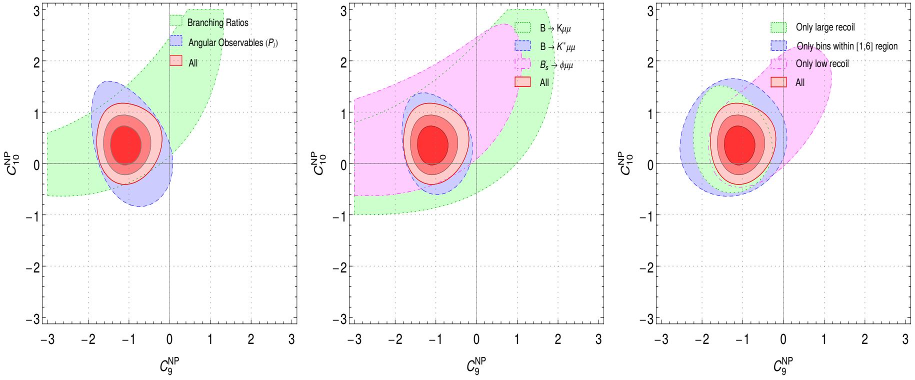


$\Rightarrow$ No evidence for q^2-dependence $\to$ Good crosscheck of hadronic contribution!

Descotes-Genon, Hofer, Matias, JV 2015 (1510.042239)

:: More consistency cross-checks 1510.042239

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



▷ Good consistency between BRs and Angular observables (AOs 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!

:: Compendium of fits for the $\mathcal{C}_{9\mu}$ 1D hypothesis

Fit	$\mathcal{C}_{9\ \mathrm{Bestfit}}^{\mathrm{NP}}$	1σ	$\mathrm{Pull}_{\mathrm{SM}}$	N_{dof}	p-value (%)
All $b \to s\mu\mu$ in SM	–	–	–	96	16.0
All $b \to s\mu\mu$	-1.09	$[-1.3, -0.9]$	4.5	95	63.0
All $b \to s\ell\ell$, $\ell = e, \mu$	-1.11	$[-1.3, -0.9]$	4.9	101	74.0
All $b \to s\mu\mu$ excluding [5,8]	-0.99	$[-1.2, -0.8]$	3.8	77	37.0
Only $b \to s\mu\mu$ BRs	-1.58	$[-2.2, -1.1]$	3.7	31	43.0
Only $b \to s\mu\mu$ P_i's	-1.01	$[-1.3, -0.7]$	3.1	68	75.0
Only $b \to s\mu\mu$ S_i's	-0.95	$[-1.2, -0.7]$	2.9	68	96.0
Only $B \to K\mu\mu$	-0.85	$[-1.7, -0.2]$	1.4	18	20.0
Only $B \to K^*\mu\mu$	-1.05	$[-1.3, -0.8]$	3.7	61	74.0
Only $B_s \to \phi\mu\mu$	-1.98	$[-2.8, -1.3]$	3.5	24	94.0
Only $b \to s\mu\mu$ at large recoil	-1.30	$[-1.6, -1.0]$	4.0	78	61.0
Only $b \to s\mu\mu$ at low recoil	-0.93	$[-1.2, -0.6]$	2.8	21	75.0
Only $b \to s\mu\mu$ within [1,6]	-1.30	$[-1.7, -0.9]$	3.4	43	73.0
Only $BR(B \to K\ell\ell)_{[1,6]}$, $\ell = e, \mu$	-1.55	$[-2.7, -0.8]$	2.4	10	76.0
All $b \to s\mu\mu$, 20% PCs	-1.10	$[-1.3, -0.9]$	4.3	95	69.0
All $b \to s\mu\mu$, 40% PCs	-1.08	$[-1.3, -0.8]$	3.8	95	73.0
All $b \to s\mu\mu$, charm$\times$2	-1.12	$[-1.3, -0.9]$	4.4	95	73.0
All $b \to s\mu\mu$, charm$\times$4	-1.06	$[-1.3, -0.8]$	4.0	95	81.0
Only $b \to s\mu\mu$ within [0.1,6]	-1.21	$[-1.6, -0.8]$	3.1	60	30.0
Only $b \to s\mu\mu$ within [0.1,0.98]	$+0.08$	$[-0.9, 1.0]$	0.1	13	33.0
Only $b \to s\mu\mu$ within [0.1,2]	-1.03	$[-1.9, -0.2]$	1.3	22	4.6
Only $b \to s\mu\mu$ within [1.1,2.5]	-0.74	$[-1.6, 0.1]$	0.9	13	85.0
Only $b \to s\mu\mu$ within [2,5]	-1.56	$[-2.3, -0.9]$	2.5	23	95.0
Only $b \to s\mu\mu$ within [4,6]	-1.34	$[-1.7, -0.9]$	3.1	16	93.0
Only $b \to s\mu\mu$ within [5,8]	-1.30	$[-1.6, -1.0]$	3.5	22	96.0
All $b \to s\mu\mu$ excluding large-recoil $B_s \to \phi\mu\mu$	-1.04	$[-1.3, -0.8]$	4.0	80	55.0
All $b \to s\ell\ell$, $\ell = e, \mu$ excl. large-recoil $B_s \to \phi\mu\mu$	-1.06	$[-1.3, -0.8]$	4.5	86	35.0

Implications for NP

$$\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha}{4\pi} \mathcal{C}_9 = \frac{c}{\Lambda^2}$$

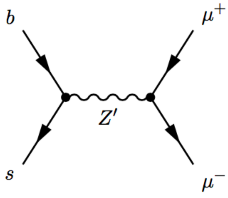
For $\mathcal{C}_9 \sim 1$ the NP scale Λ would be:

Type of NP	coupling	c	NP scale
Tree-level flavor-generic	$g \sim 1$	~ 1	$\Lambda \sim 38\,\mathrm{TeV}$
Tree-level flavor-CKMish	$g \sim 1$	$\sim V_{tb} V_{ts}^*$	$\Lambda \sim 8\,\mathrm{TeV}$
Tree-level flavor-generic	$g \sim 0.1$	~ 0.01	$\Lambda \sim 3.8\,\mathrm{TeV}$
Loop-level flavor-generic	$g \sim 1$	$\sim \frac{1}{(4\pi)^2}$	$\Lambda \sim 3\,\mathrm{TeV}$
Loop-level flavor-CKMish	$g \sim 1$	$\sim \frac{V_{tb} V_{ts}^*}{(4\pi)^2}$	$\Lambda \sim 600\,\mathrm{GeV}$

Implications for NP

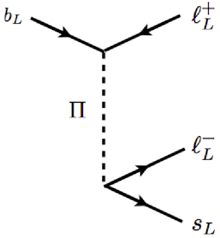
Two obvious candidates: (but much more extensive literature)

▷ **Massive $U(1)$ gauge boson: Z'**



- VL coupling to μ and FC couplings to LH quarks.
- Satisfies $\mathcal{C}_9 \cdot \mathcal{C}'_{10} = \mathcal{C}'_9 \cdot \mathcal{C}_{10}$
- Anomalies
- Strong correlation with B_s mixing
- Popular model: Gauged $(L_\mu - L_\tau)$ + VL quarks
  Altmannshofer, Gori, Pospelov, Yavin 2014

▷ **Scalar Leptoquark**



- Required gauge rep: $(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$ Hiller, Schmaltz 2014
- Satisfies $\mathcal{C}_9 = -\mathcal{C}_{10}$
- No obvious correlations, more freedom
- Can be related to the breaking of a GUT
- Can be a composite Gripaios, Nardecchia, Renner 2015

Lepton non-universality

Flavour Non-Universality : R_K

- What is R_K? [Hiller, Kruger, 2004]

$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+ \mu\mu)_{[1,6]\mathrm{GeV}^2}}{\mathcal{B}(B^+ \to K^+ ee)_{[1,6]\mathrm{GeV}^2}}$$

- **Very clean** Standard Model prediction: [Bobeth, Hiller, Piranishvili, 2007]

$$R_K^{\mathrm{SM}} = 1.0003 \pm 0.0001$$

[Log-enhanced EM corrections under control Bordone, Isidori, Pattori, 2016]

- **Measured** by LHCb [LHCb, 1406.6482[hep-ex]]

$$R_K^{\mathrm{LHCb}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

- Tension at $2.6\sigma \longrightarrow$ **Flavor Non-Universal New Physics??**

Flavour Non-Universality : R_K

R_K is consistent with $C_{9\mu}^{\text{NP}} \sim -1$ needed in $b \to s\mu\mu$.

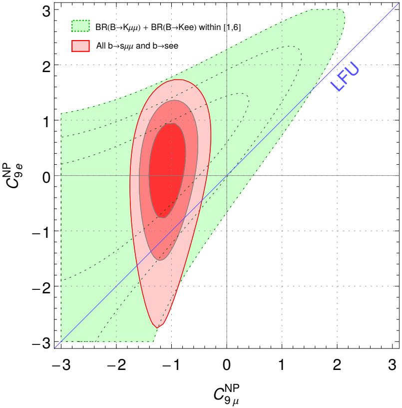
The correct credit goes to Alonso, Grinstein, Camalich 2014:

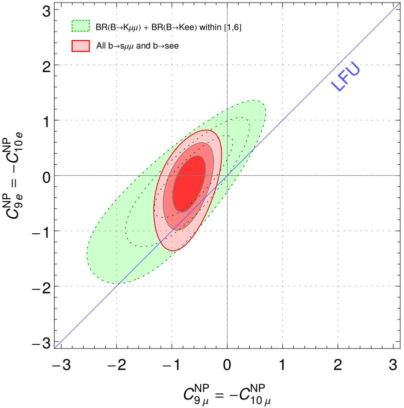
> not very well bound, especially for the electronic case, so different scenarios of NP could currently explain [15]. For example one could entertain the possibility of a sizable and negative effect in C_9 affecting only the muonic mode, $\delta C_9^{\mu} = -1$. In this scenario one obtains $R_K \simeq 0.79$. As a side remark, it is worth emphasizing that such a negative NP contribution to $\mathcal{O}_9^{(\prime)}$ has been argued to be necessary to understand the current $b \to s\mu\mu$ data set [27–30].

See also Hiller, Smaltz 2014, Ghosh, Nardecchia, Renner 2014

Fits including $b \to see$ modes

▷ Include LHCb $BR(B \to Kee)$ and $B \to K^\star ee$ at very low q^2.





▷ Fit favors violation of LFU, compatible with no NP in $(\bar{s}b)(\bar{e}e)$ operators.

▷ Taking $\mathcal{C}_{ie}^{\rm NP} = 0$: Favored scenarios for $\mathcal{C}_{i\mu}$ have SM pull increased by $\sim 0.5\,\sigma$ (not $\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP}$, which does not explain R_K)

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

In red: scenarios that explain R_K

Reminder: $R_K^{\rm LHCb} = 0.745^{+0.090}_{-0.074} \pm 0.036 \simeq 0.75 \pm 0.09$

See also Nazila, Hurth, Neshatpour and Capdevila, Descotes-Genon, Matias, J.V. 2016

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
$\mathcal{C}_9^{\rm NP}$	$+$					
	$-$	✓	✓	✓	✓	X
$\mathcal{C}_{10}^{\rm NP}$	$+$	✓		✓	✓	X
	$-$		✓			
$\mathcal{C}_{9'}^{\rm NP}$	$+$			✓	✓	X
	$-$	✓	✓			
$\mathcal{C}_{10'}^{\rm NP}$	$+$	✓	✓			
	$-$			✓	✓	X

▷ $\boldsymbol{\mathcal{C}_{9\mu}^{\rm NP} \sim -1}$ consistent with all anomalies

▷ No consistent and global alternative from long-distance dynamics:

- R_K – stat. fluctuation, exp. issues with e vs. μ
- P_5' – power corrections, $c\bar{c}$ contributions
- $BR(B_s \to \phi\mu\mu)$ – form factors, $c\bar{c}$ contributions
- Low recoil – lattice, duality violations

R_K: Lepton Flavor Violation?

Lepton Non-Universality "necessarily associated" with **Lepton Flavor Violation**
[Glashow, Guadagnoli, Lane, 2014]

Example: Consider a New Physics operator

$$\mathcal{H}_{\rm NP} = G\ \bar{b}'_L \gamma^\alpha b'_L\ \bar{\tau}'_L \gamma_\alpha \tau'_L$$

In terms of the mass eigenstates:

$$b'_L = U^d_{L3i} d_{Li} \qquad \tau'_L = U^\ell_{L3i} \ell_{Li}$$

We obtain contributions to $b \to s\mu\mu$ and also to $b \to s\mu\tau$ and $d \to d\mu e$, etc:

- $G\ U^{d*}_{L33} U^d_{L32} |U^\ell_{L32}|^2 [\bar{b}_L \gamma_\alpha s_L\ \bar{\mu}_L \gamma^\alpha \mu_L] \quad \longrightarrow \quad R_K,\ B \to K^* \mu\mu$
- $G\ U^{d*}_{L33} U^d_{L32} U^{\ell*}_{L33} U^\ell_{L32} [\bar{b}_L \gamma_\alpha s_L\ \bar{\tau}_L \gamma^\alpha \mu_L] \quad \longrightarrow \quad B \to K\tau\mu$
- $G\ |U^d_{L31}|^2 U^{\ell*}_{L31} U^\ell_{L32} [\bar{d}_L \gamma_\alpha d_L\ \bar{e}_L \gamma^\alpha \mu_L] \quad \longrightarrow \quad \mu \to e$ conversion

▷ **Look for LFV processes!!**

More Lepton Non-Universality: $\mathcal{R}(D^{(*)})$

- What is $\mathcal{R}(D^{(*)})$?

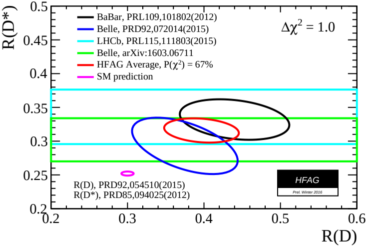
$$\mathcal{R}(D^{(*)}) \equiv \frac{\mathcal{B}(\bar{B} \to D^{(*)+}\tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)+}\ell^- \bar{\nu}_\ell)}$$

- **Rather clean** Standard Model predictions: [Fajfer, Kamenik, Nisandzic, 2012]

$$\mathcal{R}(D)^{\text{SM}} = 0.297 \pm 0.017 \;; \qquad \mathcal{R}(D^*)^{\text{SM}} = 0.252 \pm 0.003$$

- Measurements by BaBar, Belle and LHCb

$$\mathcal{R}(D)^{\text{exp}} = 0.397 \pm 0.049$$
$$\mathcal{R}(D^*)^{\text{exp}} = 0.316 \pm 0.019$$



- Tensions at 2σ and 2.7σ respectively. Combined$=3.4\sigma$

Inclusive vs. exclusive $b \to c\ell\nu$

- Inclusive decay rate $B \to X_c \tau \bar{\nu}$ from OPE Ligeti, Tackmann

$$BR^{\rm th}(B \to X_c \tau \bar{\nu}) = (2.42 \pm 0.06)\%$$

- There is a measurement by LEP (B-hadron admixture)

$$BR^{\rm exp}(B \to X_c \tau \bar{\nu}) = (2.41 \pm 0.23)\%$$

- Theory predictions for the exclusive channels Fajfer, Kamenik

$$BR^{\rm th}(B \to D \tau \bar{\nu}) + BR^{\rm th}(B \to D^\star \tau \bar{\nu}) = (2.01 \pm 0.07)\%$$

- **On the other hand** Babar 2012, compatible with LHCb 2015

$$BR^{\rm exp}(B \to D \tau \bar{\nu}) + BR^{\rm exp}(B \to D^\star \tau \bar{\nu}) = (2.78 \pm 0.25)\%$$

- and more recently Belle 2015

$$BR^{\rm exp}(B \to D \tau \bar{\nu}) + BR^{\rm exp}(B \to D^\star \tau \bar{\nu}) = (2.39 \pm 0.32)\%$$

R_K vs. $\mathcal{R}(D^{(*)})$

How is $\mathcal{R}(D^{(*)})$ related to R_K?? (is it??)

[Bhattacharya, Datta, London, Shivashankara, 2014]

Consider the same New Physics operator as before:

$$\mathcal{H}_{\rm NP} = G\ \bar{b}'_L \gamma^\mu b'_L\ \bar{\tau}'_L \gamma_\mu \tau'_L$$

If generated above the EW scale, it should be made $SU(2)_L$ invariant:

$$G_1\ [\bar{Q}'_{3L}\gamma_\mu Q'_{3L}][\bar{L}'_{3L}\gamma^\mu L'_{3L}] + G_2\ [\bar{Q}'_{3L}\gamma_\mu \sigma^a Q'_{3L}][\bar{L}'_{3L}\gamma^\mu \sigma^a L'_{3L}]$$

Expanding we obtain the following operators:

$$G_2(\bar{t}'_L\gamma_\mu t'_L)(\bar{\nu}'_{\tau_L}\gamma^\mu \nu'_{\tau_L})\ ,$$

$$\boxed{G_2(\bar{b}'_L\gamma_\mu b'_L)(\bar{\tau}'_L\gamma^\mu \tau'_L)\ ,} \longrightarrow \text{GGL}$$

$$-G_2(\bar{t}'_L\gamma_\mu t'_L)(\bar{\tau}'_L\gamma^\mu \tau'_L)\ ,$$

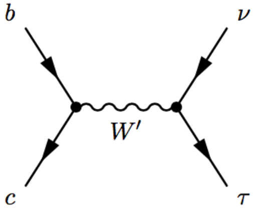
$$-G_2(\bar{b}'_L\gamma_\mu b'_L)(\bar{\nu}'_{\tau L}\gamma^\mu \nu'_{\tau L})\ ,$$

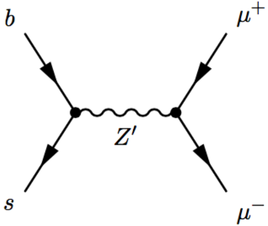
$$\boxed{2G_2(\bar{t}'_L\gamma_\mu b'_L)(\bar{\tau}'_L\gamma^\mu \nu'_{\tau L}) + h.c.} \longrightarrow \mathcal{R}(D^{(*)})$$

▷ Plenty of opportunities to look for correlated effects elsewhere.

Gauge extensions for R_K and $R_{D^{(\star)}}$

- Massive vector boson triplets (W'_a) are natural candidates to UV-complete this effective picture
  Greljo, Isidori, Marzocca 2015
- But have to face stringent constraints from LEP, LHC, and LFU in leptonic and meson decays. Correlated effects pile-up.





- $SU(2)$ gauge extensions provide massive vector boson triplets.
  Boucenna, Celis, Fuentes, Vicente, JV 1604.03088

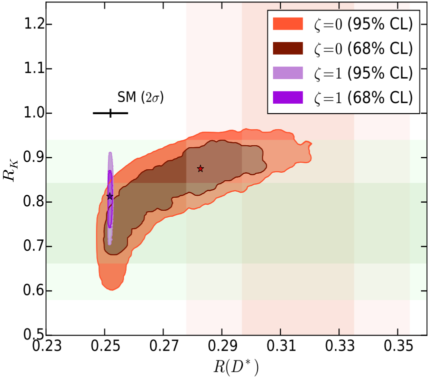
  But the symmetry-breaking pattern and the source of non-universality must be chosen carefully (non-trivial).

Gauge extensions for R_K and $R_{D^{(\star)}}$

Boucenna, Celis, Fuentes, Vicente, JV 1604.03088

▷ Gauge Model based on $\mathrm{SU}(2)_1 \otimes \mathrm{SU}(2)_2 \otimes \mathrm{U}(1)_Y \xrightarrow{u} \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y \xrightarrow{v} \mathrm{U}(1)_{\text{em}}$

with 2 generations of VL fermions sourcing non-universality.



Global Fit to:

- ▷ LEP W,Z-pole observables
- ▷ Leptonic τ decays: $\tau \to \{e,\mu\}\nu\bar{\nu}$
- ▷ $d \to u$: $\pi \to \{e,\mu\}\bar{\nu}$, $\tau \to \pi\nu$
- ▷ $s \to u$: $K \to \{e,\mu\}\bar{\nu}$, $\tau \to K\nu$
- ▷ $c \to s$: $D \to K\{e,\mu\}\bar{\nu}$, $D_s \to \{\tau,\mu\}\bar{\nu}$
- ▷ $b \to s$: $\Delta M_s/\Delta M_d$, $b \to s\{ee,\mu\mu\}$
- ▷ $b \to c$: $B \to D^{(\star)}\{e,\mu\}\bar{\nu}$, $R(D^{(\star)})$
  $b \to X_c\{\tau, e\}\bar{\nu}$

▷ Message to experimentalists: Always try to separate μ and e (do not give ℓ !!)

Time Dependence in $B \to V\ell\ell$

Possibilities for Belle-II?

Time Dependence in $B \to V\ell\ell$ Descotes-Genon, JV 2015

$$B_q^0 \overset{mixing}{\longleftrightarrow} \bar{B}_q^0 \overset{decay}{\longrightarrow} (V\ell\ell)_{\rm CP}$$

⋆ For the rest think of the following examples:

$$B_d \to K^* (\to K_S \pi^0)\ell^+\ell^-$$

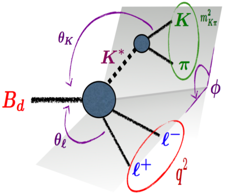
$$B_s \to \phi (\to K_S K_L)\ell^+\ell^-$$

$$B_s \to \phi (\to K^+ K^-)\ell^+\ell^-$$

⋆ Time-dependent angular distributions

$$\frac{d\Gamma(B(t) \to (V\ell\ell)_{\rm CP})}{ds\ d\cos\theta_\ell d\cos\theta_M d\phi} = \sum_i J_i(t,s)\,\Omega_i(\theta_\ell,\theta_M,\phi)$$

$$\frac{d\Gamma(\overline{B}(t) \to (V\ell\ell)_{\rm CP})}{ds\ d\cos\theta_\ell d\cos\theta_M d\phi} = \sum_i \widetilde{J}_i(t,s)\,\Omega_i(\theta_\ell,\theta_M,\phi)$$



Time Dependence in $B \to V\ell\ell$

Descotes-Genon, JV 2015

$$
\begin{aligned}
J_i(t) + \widetilde{J}_i(t) &\equiv e^{-\Gamma t}\Big[(J_i + \widetilde{J}_i)\cosh(y\Gamma t) - h_i \sinh(y\Gamma t)\Big] \\
J_i(t) - \widetilde{J}_i(t) &\equiv e^{-\Gamma t}\Big[(J_i - \widetilde{J}_i)\cos(x\Gamma t) - s_i \sin(x\Gamma t)\Big]
\end{aligned}
$$

where $y \equiv \Delta\Gamma/(2\Gamma)$ and $x \equiv \Delta m/\Gamma$: $x_d \simeq 0.77$, $x_s \simeq 27$, $y_d \simeq 0$, $y_s \simeq 0.06$

Representative Example

$$
\begin{aligned}
J_8 &= \frac{1}{\sqrt{2}}\beta_\ell^2\left[\mathrm{Im}(A_0^L A_\perp^{L*} + A_0^R A_\perp^{R*})\right] \\
\widetilde{J}_8 &= -\frac{1}{\sqrt{2}}\beta_\ell^2\left[\mathrm{Im}(\bar{A}_0^L \bar{A}_\perp^{L*} + \bar{A}_0^R \bar{A}_\perp^{R*})\right] \\
h_8 &= \frac{1}{\sqrt{2}}\beta_\ell^2 \mathrm{Im}[e^{i\phi}\{\bar{A}_0^L A_\perp^{L*} + \bar{A}_0^R A_\perp^{R*}\} - e^{-i\phi}\{A_0^L \bar{A}_\perp^{L*} + A_0^R \bar{A}_\perp^{R*}\}] \\
s_8 &= -\frac{1}{\sqrt{2}}\beta_\ell^2 \mathrm{Re}[e^{i\phi}\{\bar{A}_0^L A_\perp^{L*} + \bar{A}_0^R A_\perp^{R*}\} + e^{-i\phi}\{A_0^L \bar{A}_\perp^{L*} + A_0^R \bar{A}_\perp^{R*}\}]
\end{aligned}
$$

Time Dependence in $B \to V\ell\ell$

Descotes-Genon, JV 2015

$$J_i(t) + \widetilde{J}_i(t) \equiv e^{-\Gamma t}\Big[(J_i + \widetilde{J}_i)\cosh(y\Gamma t) - h_i \sinh(y\Gamma t)\Big]$$
$$J_i(t) - \widetilde{J}_i(t) \equiv e^{-\Gamma t}\Big[(J_i - \widetilde{J}_i)\cos(x\Gamma t) - s_i \sin(x\Gamma t)\Big]$$

where $y \equiv \Delta\Gamma/(2\Gamma)$ and $x \equiv \Delta m/\Gamma$: $x_d \simeq 0.77$, $x_s \simeq 27$, $y_d \simeq 0$, $y_s \simeq 0.06$

Comments

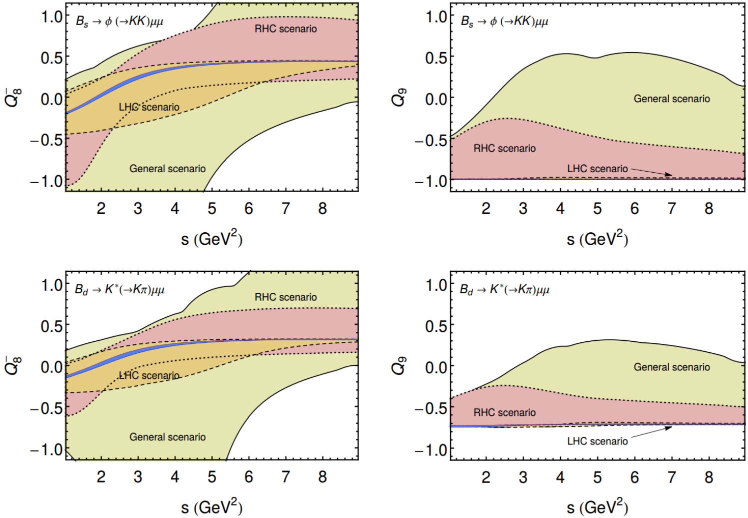
- h_i difficult to get ($y \ll 1$) $\to$ Time-dependence of untagged distribution provides essentially no new information
- For $i = 1, .., 6$, $s_i \sim \mathrm{Im}(e^{i\phi}\bar{A}_X A_Y^*)$ $\to$ Limited interest for B_s.
- For $\sim$real amplitudes $s_7 \simeq 0$. Also, $J_7 - \widetilde{J}_7$ is CP asymmetry.
- For $\sim$real amplitudes $J_{8,9} - \widetilde{J}_{8,9} \simeq 0$, but $s_{8,9}$ can be large.

The most interesting coefficients are then s_8, s_9 with

$$J_8(t) - \widetilde{J}_8(t) \simeq -s_8\, e^{-\Gamma t}\sin(x\Gamma t)\ , \quad J_9(t) - \widetilde{J}_9(t) \simeq -s_9\, e^{-\Gamma t}\sin(x\Gamma t)$$

Time-dependent "optimised" observables

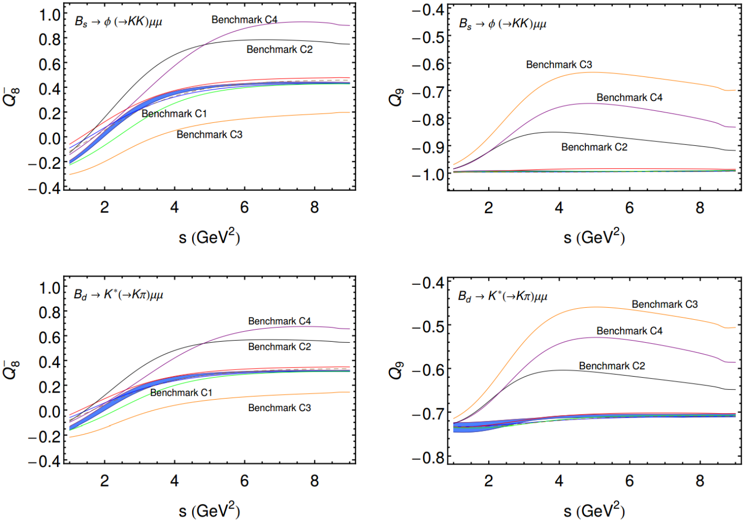
General New Physics reach: Using 3σ ranges from [Descotes-Genon, Matias, JV 2013]



▷ Blue: Standard Model

Time-dependent "optimised" observables

New Physics benchmarks:



▷ Blue: Standard Model

SUMMARY

- The SM must be complemented with New Physics at higher scales. Dedicated searches are ongoing in the context of the "Energy" and "Intensity" frontiers. Flavor Physics is a powerful door to the Intensity frontier.
- There are several tensions in B decays that conspire constructively:
  - Angular observables in $B \to K^* \mu\mu$
  - $B_{(s)} \to (K^{(*)}, \phi)\mu\mu$ branching ratios
  - R_K

  They all point to a NP contribution to the operator $\mathcal{O}_9^\mu = [\bar{s}_L \gamma_\alpha b_L][\bar{\mu}\gamma^\alpha \mu]$ such that $\mathcal{C}_9^{\rm NP} \sim -1$ (remember that $\mathcal{C}_9^{\rm SM} \sim 4$)
- 2013 Anomalies confirmed by LHCb(3/fb), and by Belle !
- Flavor non-universality opens the door to Lepton Flavor Violation. More dedicated analyses of $B \to K\tau\mu$, $B_s \to \tau\mu$, $\mu \to e$ conversion, etc, could confirm this!!
- Flavor non-universality in charged currents –$\mathcal{R}(D^{(*)})$– is related by $SU(2)_L$ to R_K, providing interesting correlations and future opportunities.
- Important to establish experimentally R_K, measure other FLNU in $b \to s$, resolve tension between exclusive and inclusive in $b \to c\tau\bar{\nu}$, and always try to separate μ and e modes.

Backup Slides

:: Chronology of $b \to s\gamma$, $b \to s\ell^+\ell^-$

$\lesssim$ **2012** WC fits use $B \to X_s\gamma$, $B \to X_s\mu\mu$, $B \to K^\star\gamma$ and a few $B \to K^\star\mu\mu$ observables (BR, $A_{\rm FB}$, F_L). Very loose constraints on $\mathcal{C}_{9,10}^{(\prime)}$.

Ali, Giudice, Mannel, Lunghi, Greub, Hiller, Kruger, Altmannshofer, Paradisi, Straub, Bobeth, van Dyk, Wacker, Descotes-Genon, Matias, JV, ...

2012 ▷ Complete basis of clean angular observables in $B \to K^\star\ell\ell$ (including P_5')

Descotes-Genon, Matias, Mescia, Ramon, JV, 1202.4266 and 1207.2753

▷ First evidence for $B_s \to \mu\mu$ LHCb 1211.2674

2013 ▷ Complete angular analysis of $B \to K^\star\mu\mu$ ($\Rightarrow$ P_5' Anomaly! $3.7\,\sigma$)

1304.6325, N. Serra talk at EPS 2013, LHCb 1308.1707

▷ First pheno analysis of $b \to s$ transitions including LHCb results

Descotes-Genon, Matias, JV 1307.5683, "Undestanding the $B \to K^\star\mu\mu$ Anomaly"

$\to$ Propose $\mathcal{C}_9^{\rm NP} \sim -1$ as the favoured NP scenario. ${\rm Pull}_{\rm SM} \sim 3\text{-}4\,\sigma$

▷ Result is confirmed by other groups, including a large-q^2-only analysis with Lattice form factors.

Altmannshofer, Straub, Beaujean, Bobeth, van Dyk, Horgan, Liu, Meinel, Wingate

:: Chronology of $b \to s\gamma$, $b \to s\ell^+\ell^-$

2013 ▷ Many theory papers...
Gauld, Goerz, Haisch, Buras, Girrbach, Datta, Duraisamy, Gosh, Fazio, Hurth, Mahmoudi

2014 ▷ Precise measurements of $B \to K\mu\mu$ branching ratios with fine binnings
LHCb-PAPER-2014-007

→ $\sim 2\,\sigma$ tension w.r.t SM, consistent with the $\mathcal{C}_9^{\rm NP} \sim -1$ benchmark!!

▷ Many more theory papers... Mahmoudi, Neshatpour, Altmannshofer, Gori, Pospelov, Yavin, Biancofiore, Colangelo, De Fazio, Lyon, Zwicky, JV ...

▷ LHCb measurement of $R_K = BR(B \to K\mu\mu)/BR(B \to Kee) \sim 0.75$
LHCb, 1406.6482

→ $\sim 2.6\,\sigma$ tension w.r.t SM. Lepton Non-Universality??!

→ Consistent with $\mathcal{C}_{9\mu}^{\rm NP} \sim -1$!! Alonso, Camalich, Grinstein, 1407.7044.

▷ Many many more theory papers... Descotes-Genon, Hofer, Matias, Hiller, Schmaltz, Ghosh, Nardecchia, Renner, Biswas, Chowdhury, Han, Lee, Crivellin, Hurth, Mahmoudi, Neshatpour, Glashow, Guadagnoli, Lane, Altmannshofer, Straub, Gripaios, Jäger, Camalich, Bhattacharya, Datta, London, Shivashankara, JV ...

:: Chronology of $b \to s\gamma$, $b \to s\ell^+\ell^-$

2015 ▷ LHCb update for $B \to K^\star \mu\mu$ angular analysis with 3 fb^{-1} (full run 1)
C.Langenbruch, talk at Moriond 2013; 1512.04442.

→ Confirmed P_5' anomaly in two bins ($\sim 2.9\,\sigma$ each)

▷ LHCb angular analysis of $B \to K^\star ee$ at very low q^2
LHCb 1501.03038.

▷ Updated global fits with new data and various theoretical improvements
Altmannshofer, Straub 1411.3161, Descotes-Genon, Hofer, Matias, JV 1510.04239, Hurth, Mahmoudi, Neshatpour 1603.00865

→ Confirmed $\mathcal{C}_{9\mu}^{\rm NP} \sim -1$ scenario !

▷ Many many many more theory papers... Crivellin, D'Ambrosio, Heeck, Hofer, Matias, Descotes-Genon, Niehoff, Stangl, Straub, Bharucha, Zwicky, Guevara, Lopez, Roig, Tostado, Boucenna, Valle, Vicente, Becirevic, Fajfer, Kosnik, Nierste, Pokorski, Rosiek, Celis, Fuentes-Martin, Jung, Serodio, Lee, Tandean, Alonso, Grinstein, Camalich, Greljo, Isidori, Marzzoca, Calibbi, Ota, Gratrex, Hopfer, Guadagnoli, Lane, Sahoo, Mohanta, Belanger, Delaunay, Westhoff, Beaujean, Bobeth, Jahn, Altmannshofer, Yavin, Falkowski, Nardecchia, Ziegler, Gripaios, Renner, Allanach, Queiroz, Strumia, Sun, Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli, JV ...

:: Chronology of $b \to s\gamma$, $b \to s\ell^+\ell^-$

2016 ▷ Belle angular analysis of $B^0 \to K^{0\star}\ell\ell$

S. Wehle, talk at LHC Ski 2016; 1604.04042.

→ Confirmed P_5' anomaly in one bin ($\sim 2.1\,\sigma$) !!!

▷ ATLAS "measurement" of $B_s \to \mu\mu$

ATLAS 1604.04263.

▷ Many many many more theory papers... ...

Next ▷ Belle angular analysis of $B^+ \to K^{\star+}\ell\ell$ ($\sim$ 40% more statistics)
Separation of e/μ??

▷ ATLAS angular analysis of $B \to K^\star\ell\ell$

▷ LHCb: Flavour-Non-Universality ratios (R_K, $R_{K^\star}$, R_ϕ, ...)

What about other FNU observables??

Capdevila, Descotes-Genon, Matias, JV 1605.03156.

▷ Can BaBar measure P_5' et al?

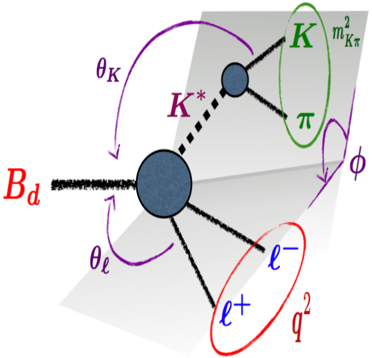
▷ Time Dependence in $B \to V\ell\ell$?? Descotes-Genon, JV 1502.05509 .

▷ ...

:: Rare $b \to s$ processes

- Inclusive
  - $B \to X_s\gamma$ (BR) .... $\mathcal{C}_7^{(\prime)}$, $\mathcal{C}_{\rm had}$
  - $B \to X_s\ell^+\ell^-$ (dBR/dq^2) .... $\mathcal{C}_7^{(\prime)}$, $\mathcal{C}_9^{(\prime)}$, $\mathcal{C}_{10}^{(\prime)}$, $\mathcal{C}_{\rm had}$
- Exclusive leptonic
  - $B_s \to \ell^+\ell^-$ (BR) .... $\mathcal{C}_{10}^{(\prime)}$
- Exclusive radiative/semileptonic
  - $B \to K^*\gamma$ (BR, S, A_I) .... $\mathcal{C}_7^{(\prime)}$, $\mathcal{C}_{\rm had}$
  - $B \to K\ell^+\ell^-$ (dBR/dq^2) .... $\mathcal{C}_7^{(\prime)}$, $\mathcal{C}_9^{(\prime)}$, $\mathcal{C}_{10}^{(\prime)}$, $\mathcal{C}_{\rm had}$
  - $B \to K^*\ell^+\ell^-$ (dBR/dq^2, Angular Observables) .... $\mathcal{C}_7^{(\prime)}$, $\mathcal{C}_9^{(\prime)}$, $\mathcal{C}_{10}^{(\prime)}$, $\mathcal{C}_{\rm had}$
  - $B_s \to \phi\ell^+\ell^-$ (dBR/dq^2, Angular Observables) .... $\mathcal{C}_7^{(\prime)}$, $\mathcal{C}_9^{(\prime)}$, $\mathcal{C}_{10}^{(\prime)}$, $\mathcal{C}_{\rm had}$
  - $\Lambda_b \to \Lambda\ell^+\ell^-$ (see e.g. Meinel, van Dyk 2016)
  - etc.

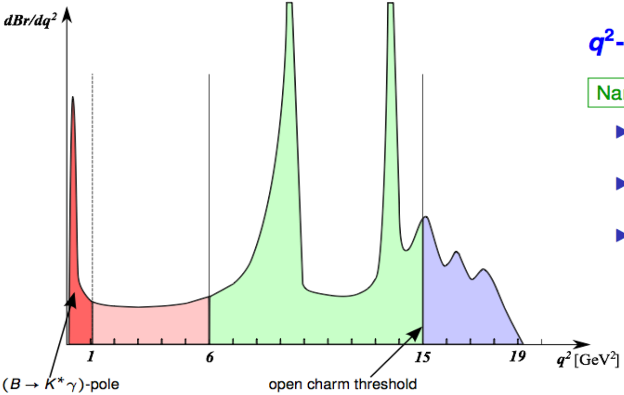
:: $B \to V(\to M_1 M_2)\ell^+\ell^-$ Angular Distribution



$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\times$$
$$\Big[\mathbf{J}_{1s}\sin^2\theta_K + \mathbf{J}_{1c}\cos^2\theta_K + \mathbf{J}_{2s}\sin^2\theta_K\cos 2\theta_l$$
$$+\mathbf{J}_{2c}\cos^2\theta_K\cos 2\theta_l + \mathbf{J}_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+\mathbf{J}_4\sin 2\theta_K\sin 2\theta_l\cos\phi + \mathbf{J}_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\mathbf{J}_{6s}\sin^2\theta_K\cos\theta_l + \mathbf{J}_{6c}\cos^2\theta_K\cos\theta_l$$
$$+\mathbf{J}_7\sin 2\theta_K\sin\theta_l\sin\phi + \mathbf{J}_8\sin 2\theta_K\sin 2\theta_l\sin\phi$$
$$+\mathbf{J}_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

- $\mathbf{J}_i(q^2) \sim c_i^{\lambda\lambda'} H_\lambda H^\star_{\lambda'}$, where H_λ are helicity amplitudes.
- $\mathbf{J}_i$ have large uncertainties from FF normalisations ($H_\lambda \propto F_i$).
- If **FF correlations** are known, suitable ratios $\sim \mathbf{J}_i/\mathbf{J}_k$ can be predicted with good precision $\Rightarrow$ **Clean observables**

:: Regions in q^2



q^2-Regions in $B \to K^* \bar{\ell}\ell$

Narrow resonances

- dominated by charged-cur. (tree-level) op's
- not sensitive to new physics in $b \to s\bar{\ell}\ell$
- nonperturbative predictions via: dispersion relations + $B \to K^*(\bar{c}c)$ data

Large Recoil (low-q^2)

- very low-q^2 ($\lesssim 1$ GeV^2) dominated by $\mathcal{O}_7$
- low-q^2 ($[1, 6]$ GeV^2) dominated by $\mathcal{O}_{9,10}$
- 1) QCD factorization or SCET
  2) LCSR
  3) non-local OPE of $\bar{c}c$-tails

Low Recoil (high-q^2)

- dominated by $\mathcal{O}_{9,10}$
- local OPE (+ HQET) $\Rightarrow$ theory only for sufficiently large q^2-integrated obs's

(slide from C. Bobeth)

:: Clean Observables : $B \to V(\to M_1 M_2)\ell^+\ell^-$

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 : $B \to V(\to M_1 M_2)\ell^+\ell^-$

Optimized Observables

Several Form Factor ratios can be predicted:

- At large recoil $\longrightarrow$ SCET [Charles et.al. 1998, Beneke, Feldmann, 2000]
- At low recoil $\longrightarrow$ CURRENTLY WE USE LATTICE FULL FORM FACTORS

Example — SCET relation at large recoil

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

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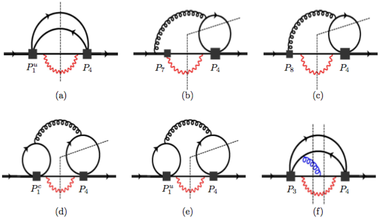
Updates for 2015 Fits

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

Quick merchardising:

Four-body contributions to $B \to X_s\gamma$ at NLO,
T.Huber, M.Poradzinski and JV
arXiv:1411.7677 [hep-ph] – JHEP



Updated NNLO QCD predictions for the Weak Radiative B-meson decays,
M. Misiak, H. M. Asatrian, R. Boughezal, M. Czakon, T. Ewerth, A. Ferroglia, P. Fiedler, P. Gambino, C. Greub, U. Haisch, T. Huber, M. Kamiński, G. Ossola, M. Poradziński, A. Rehman, T. Schutzmeier, M. Steinhauser, and JV
arXiv:1503.03328 [hep-ph] – PRL

Updates for 2015 Fits

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

:: 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	$+0.9$

▷ $B_s \to \phi$ results rely on BSZ form factors – Bharucha, Straub, Zwicky 2015
▷ All the others rely on KMPW – Khodjamirian, Mannel, Pivovarov, Wang 2010
▷ Low recoil always relies on Lattice – Horgan, Liu, Meinel, Wingate 2013

:: 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

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

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

Coefficient	Best Fit Point	Pull$_{\text{SM}}$	p-value (%)
SM	–	–	16.0
$(\mathcal{C}_7^{\text{NP}}, \mathcal{C}_9^{\text{NP}})$	$(-0.00, -1.07)$	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: 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 $3.6\,\sigma$.

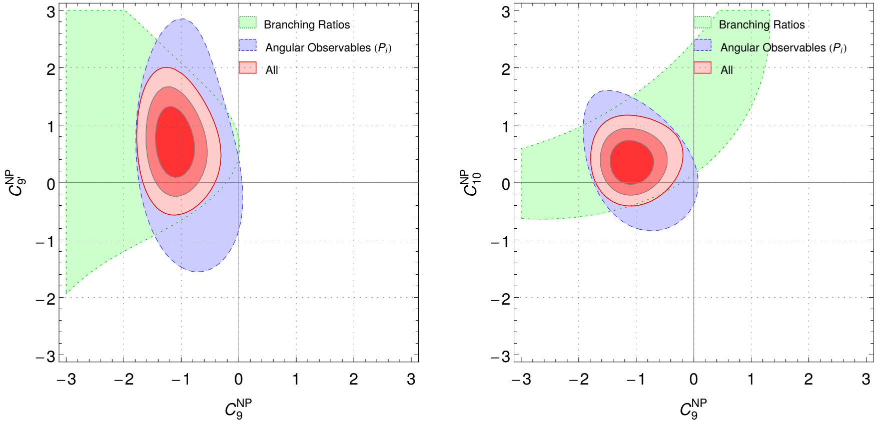
Recent Analyses

	[SDG, Hofer Matias, Virto]	[Straub & Altmannshofer]	[Hurth, Mahmoudi, Neshatpour]
Statistical approach	Frequentist $\Delta\chi^2$	Frequentist $\Delta\chi^2$	Frequentist $\Delta\chi^2$ & χ^2
Data	LHCb	Averages	LHCb
$B \to K^*\mu\mu$ data	P_i, Max likelihood	S_i, Max likelihood	S_i, Max l.& moments
Form factors	B-meson LCSR [Khodjamirian et al.] + lattice QCD	[Bharucha, Straub, Zwicky] fit light-meson LCSR + lattice QCD	[Bharucha, Straub, Zwicky]
Theo approach	soft and full ff	full ff	soft and full ff
$c\bar{c}$ large recoil	magnitude from [Khodjamirian et al.]	polynomial param	polynomial param
$\mathcal{C}_9^\mu$ 1D 1σ	[-1.29,-0.87]	[-1.54,-0.53]	[-0.27,-0.13]
pull$_{SM}$	4.5 σ	3.7 σ	4.2σ
"good scenarios"	see before	$\mathcal{C}_9^{\rm NP}, \mathcal{C}_9^{\rm NP} = -\mathcal{C}_{10}^{\rm NP}$ $(\mathcal{C}_9^{\rm NP}, \mathcal{C}_{9'}^{\rm NP}), (\mathcal{C}_9, \mathcal{C}_{10}^{\rm NP})$	$(\mathcal{C}_9^{\rm NP}, \mathcal{C}_{9'}^{\rm NP}), (\mathcal{C}_9^{\rm NP}, \mathcal{C}_{10}^{\rm NP})$

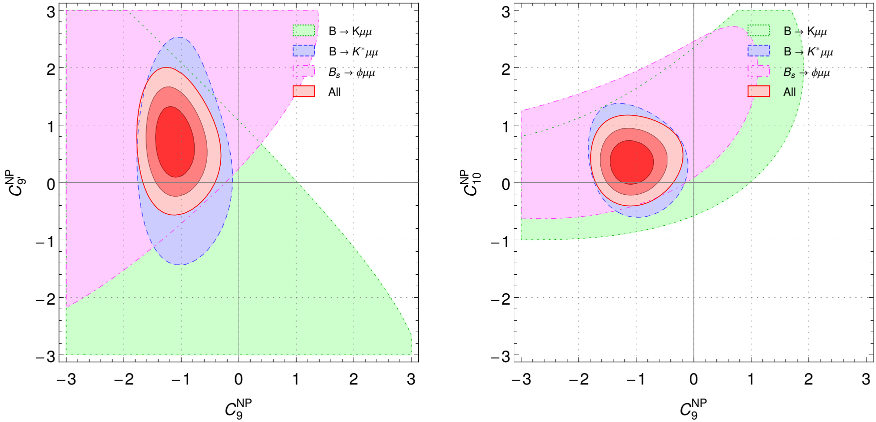
$\Longrightarrow$Good overall agreement for the results of the three fits

Comparing different fits

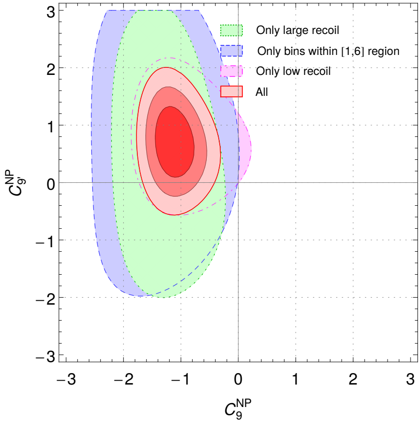
Branching Ratios vs. Angular Observables

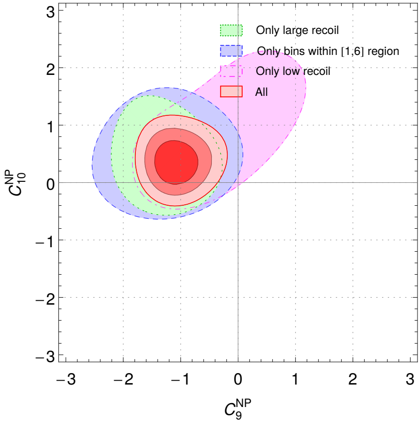


$B \to K\mu\mu$ vs. $B \to K^*\mu\mu$ vs. $B_s \to \phi\mu\mu$



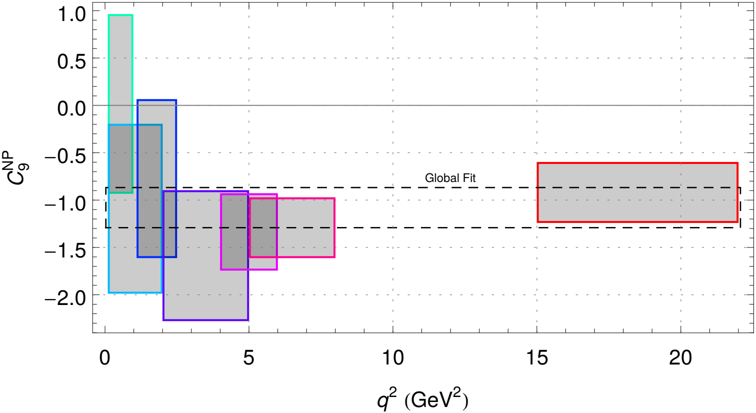
Different q^2 regions





Different q^2 regions

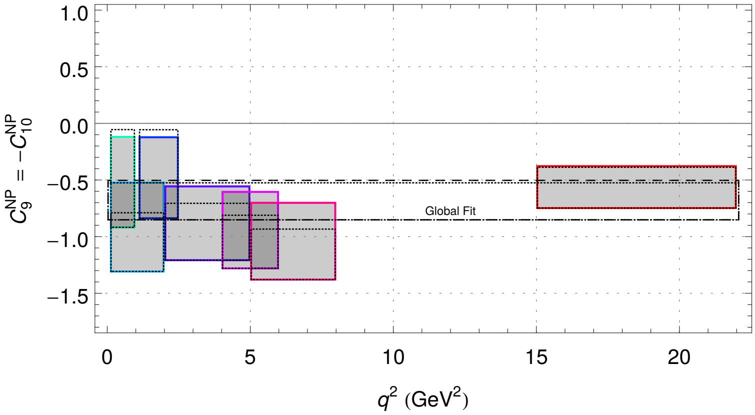
$\rightarrow \; \mathcal{T}_\mu \;=\; -\frac{16 i \pi^2}{q^2} \sum_{i=1..6,8} \mathcal{C}_i \int dx^4 e^{iq\cdot x} \langle M_\lambda | T\{\mathcal{J}^{\rm em}_\mu(x) \mathcal{O}_i(0)\} | B\rangle$ is q^2-dependent



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

Different q^2 regions

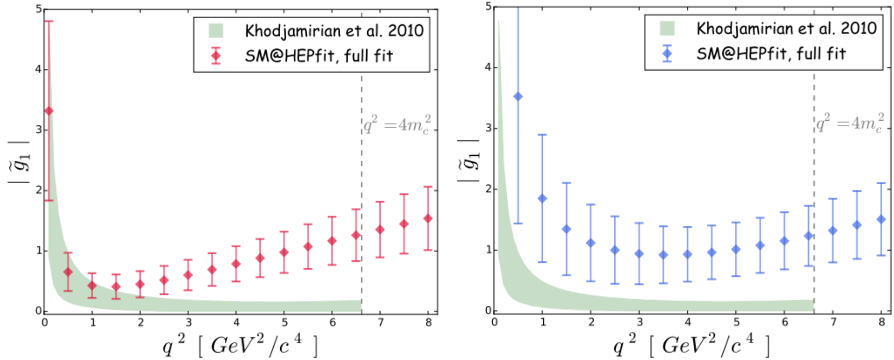
→ $\mathcal{C}_{10}$ is **never** q^2-dependent



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

q^2 dependence

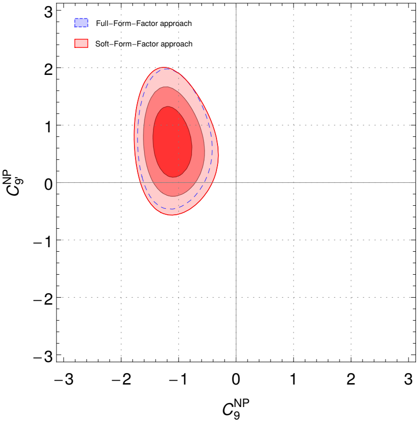
Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli 2015

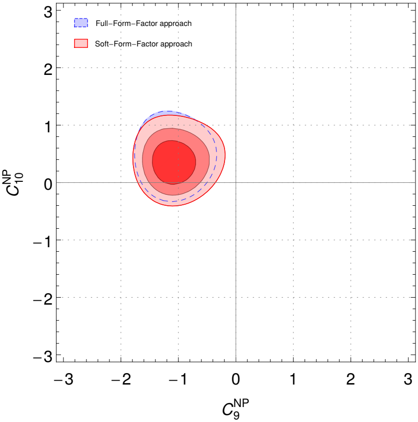


Removing the constraint from KMPW at low q^2:

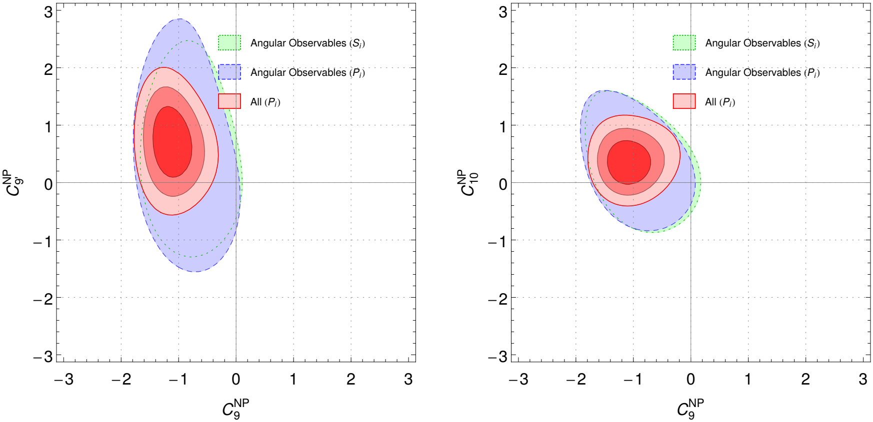
- ▷ Improves the fit
- ▷ Compatible with KMPW + constant $\delta\mathcal{C}_9 \sim -1$!!

DHMV vs. Full form factors

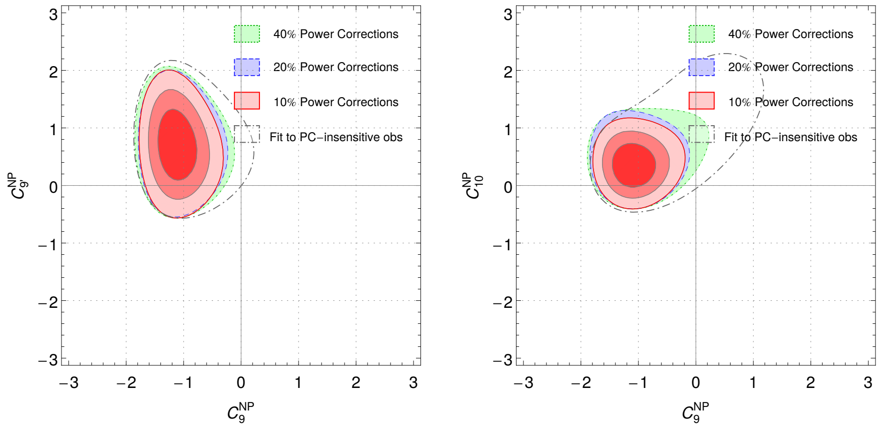




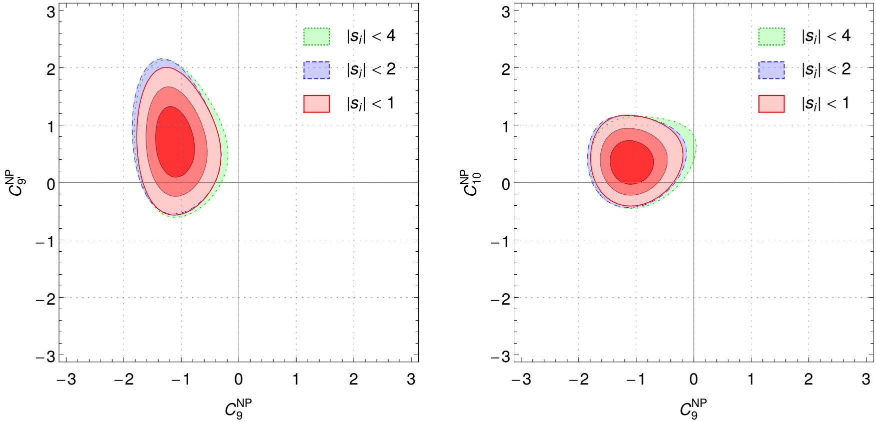
P_i's vs. S_i's


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



Enhanced charm-loop effect



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).

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 $\sim 10\%$

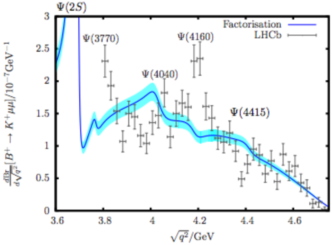
then, a NP contribution $\mathcal{C}_{9\mu}^{\mathrm{NP}} \sim -1$ gives a **substantially improved fit** for

- $B \to K\mu\mu$, $B \to K^*\mu\mu$ 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.

Charm loop at large q^2: resonances

- Low recoil: quark-hadron duality
  - Average "enough" resonances to equate quark and hadron levels
  - Model estimate yield a few % for $BR(B \to K\mu\mu)$ [Beylich, Buchalla, Feldmann]



- Probably (?) effect of similar size for $B \to K^*\mu\mu$ (BR and angular obs.)
- OPE corrections + NLO QCD corrections + complex correction of 10% for each transversity amplitude
- Difficulties to explain $B \to K\ell\ell$ low-recoil spectrum using $\sigma(e^+e^- \to hadrons)$ and naive factorisation [Lyon, Zwicky]

- Large recoil
  - $q^2 \leq$ 7-8 GeV^2 to limit the impact of J/ψ tail
  - Still need to include the effect of $c\bar{c}$ loop (tail of resonances + nonresonant)

General New Physics (for Slide 49)

We write

$$\mathcal{C}_i = \mathcal{C}_i^{\rm SM} + \mathcal{C}_i^{\rm NP} \ ,$$

and consider the $3\,\sigma$ ranges for the NP contributions obtained in the global fit to $b \to s\gamma$ and $b \to s\ell\ell$ data of 1307.5683:

$$\mathcal{C}_7^{\rm NP} \in (-0.08, 0.03)\ , \qquad \mathcal{C}_9^{\rm NP} \in (-2.1, -0.2)\ , \qquad \mathcal{C}_{10}^{\rm NP} \in (-2.0, 3.0)\ ,$$
$$\mathcal{C}_{7'}^{\rm NP} \in (-0.14, 0.10)\ , \qquad \mathcal{C}_{9'}^{\rm NP} \in (-1.2, 1.8)\ , \qquad \mathcal{C}_{10'}^{\rm NP} \in (-1.4, 1.2)\ .$$

The result of this scan is shown in Slide 42. We consider three scenarios:

- LHC (Left-Handed Currents) scenario: NP contributions to $\mathcal{C}_7, \mathcal{C}_9, \mathcal{C}_{10}$ only. This corresponds to the orange regions in the figs, delimited by dashed lines (along the line $Q_9 = -1$ on the right-hand plot).
- RHC (Right-Handed Currents) scenario: NP contributions to $\mathcal{C}_{7'}, \mathcal{C}_{9'}, \mathcal{C}_{10'}$ only. This corresponds to the red regions in the figs, delimited by dotted lines.
- General NP scenario: NP contributions to all six coefficients $\mathcal{C}_{7^{(\prime)}}, \mathcal{C}_{9^{(\prime)}}, \mathcal{C}_{10^{(\prime)}}$. This corresponds to the regions in green in the figs, with solid borders.

NP Benchmarks (for Slide 50)

A. Best fit point in the $\mathcal{C}_7 - \mathcal{C}_9$ scenario of 1307.5683:

$$\mathcal{C}_7^{\rm NP} = -0.02, \quad \mathcal{C}_9^{\rm NP} = -1.6 \ .$$

B. Best fit point in the $\mathcal{C}_9 - \mathcal{C}_{9'}$ scenario of 1411.3161:

$$\mathcal{C}_9^{\rm NP} = -1.28, \quad \mathcal{C}_{9'}^{\rm NP} = 0.47 \ .$$

C. Z'-motivated $\mathcal{C}_{9^{(\prime)}}, \mathcal{C}_{10^{(\prime)}}$ scenarios (see e.g. 1211.1896,1309.2466):

- C1. $\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{10}^{\rm NP} = -1$
- C2. $\mathcal{C}_{9'}^{\rm NP} = -\mathcal{C}_{10'}^{\rm NP} = 1$
- C3. $\mathcal{C}_9^{\rm NP} = \mathcal{C}_{9'}^{\rm NP} = -\mathcal{C}_{10}^{\rm NP} = -\mathcal{C}_{10'}^{\rm NP} = -1$
- C4. $\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP} = -\mathcal{C}_{10}^{\rm NP} = \mathcal{C}_{10'}^{\rm NP} = -1$

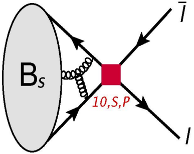
D. Best fit point in the general fit of 1307.5683:

$$\mathcal{C}_7^{\rm NP} = -0.02 \ , \ \mathcal{C}_9^{\rm NP} = -1.3 \ , \ \mathcal{C}_{10}^{\rm NP} = 0.3 \ , \ \mathcal{C}_{7'}^{\rm NP} = -0.01 \ , \ \mathcal{C}_{9'}^{\rm NP} = 0.3 \ , \ \mathcal{C}_{10'}^{\rm NP} = 0 \ .$$

Scenarios C.1 and C.2 arise also respectively in singlet/triplet and doublet leptoquark models motivated by recent data on R_K (see 1408.1627).

:: $BR(B_s \to \ell^+\ell^-)$

$$\mathcal{L} = \mathcal{L}_{QED+QCD} + \mathcal{C}_9^{(\prime)}\,[\bar{s}\gamma^\mu P_{L(R)} b]\,[\bar{\ell}\gamma_\mu \ell] + \mathcal{C}_{10}^{(\prime)}\,[\bar{s}\gamma^\mu P_{L(R)} b]\,[\bar{\ell}\gamma_\mu\gamma_5 \ell] + \cdots$$



$$\mathcal{A}_9^{(\prime)} = \mathcal{C}_9^{(\prime)}\,\langle \bar{\ell}\ell|\bar{\ell}\gamma_\mu\ell|0\rangle\,\underbrace{\langle 0|\bar{s}\gamma^\mu P_{L(R)} b|B_s\rangle}_{\sim p_B^\mu = p_\ell^\mu + p_{\bar{\ell}}^\mu} = 0 + \mathcal{O}(\alpha)$$

Contributions from $\mathcal{O}_7$ and other 4-quark ops are zero like $\mathcal{A}_9^{(\prime)}$.

$$\to\ \mathcal{A}_{10}^{(\prime)} = \mathcal{C}_{10}^{(\prime)}\,\langle \bar{\ell}\ell|\bar{\ell}\gamma_\mu\gamma_5\ell|0\rangle\langle 0|\bar{s}\gamma^\mu P_{L(R)} b|B_s\rangle = \mp i f_{B_s}\mathcal{C}_{10}^{(\prime)}\, m_\ell\,[\bar{u}_\ell\gamma_5 v_{\bar{\ell}}]$$

$$\to\ \sum_{\text{spins}} |\mathcal{A}_{10} + \mathcal{A}'_{10}|^2 = 2 f_{B_s}^2 m_{B_s}^2 m_\ell^2\,|\mathcal{C}_{10} - \mathcal{C}'_{10}|^2$$

$f_{B_s} = (224 \pm 5)$ MeV (FLAG)

$$BR(B_s \to \ell\bar{\ell}) = \frac{\tau_{B_s} f_{B_s}^2 m_{B_s}^3}{2\pi}\sqrt{1 - \frac{4m_\ell^2}{m_{B_s}^2}}\;|\mathcal{C}_S^-|^2 + \left|\mathcal{C}_P^- + \frac{2m_\ell}{m_{B_s}}(\mathcal{C}_{10} - \mathcal{C}'_{10})\right|^2$$

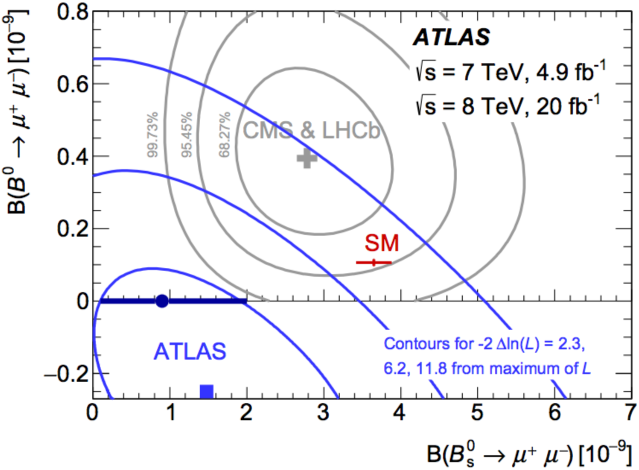
Note: Contributions from (pseudo)SCALAR operators are **not helicity suppressed**.

$\sigma(\bar{\mathcal{B}}_{s\mu}^{\rm th}) = (3.65 \pm 0.23)\cdot 10^{-9}$ (6.4%) *vs.* $\sigma(\bar{\mathcal{B}}_{s\mu}^{\rm exp}) = (2.9 \pm 0.7)\cdot 10^{-9}$ (24%)

main th. uncertainties: f_B and CKM.

Bobeth, Gorbahn, Hermann, Misiak, Stamou, Steinhauser'2014; CMS+LHCb 1411.4413

:: $BR(B_s \to \ell^+\ell^-)$ CMS+LHCb 1411.4413 vs. ATLAS 1604.04263



ATLAS: Evidence for $B_s \to \mu\mu$ at $1.4\,\sigma$ ($3.1\,\sigma$ expected).
(p-value)$_{\rm SM}$=0.048 ($2.0\,\sigma$); $B_{s\mu} < 3.0 \cdot 10^{-9}$ and $B_{d\mu} < 4.2 \cdot 10^{-10}$ at 95% C.L

$B \to K^* \ell\bar{\ell}$: 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, $B \to K^*\gamma$, + power corrections

Large q^2 ::

- Horgan et al: Lattice QCD

$B \to K^*\ell\bar{\ell}$: Form Factors – DHMV

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

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

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

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

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

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

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

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

$B \to K^*\ell\bar{\ell}$: h_i : Corrections to QCDF at low-q^2 – DHMV

$$\mathcal{T}_i^{\rm had} \to \big(1 + r_i(q^2)\big)\mathcal{T}_i^{\rm had},$$

$$r_i(s) = r_i^a e^{i\phi_i^a} + r_i^b e^{i\phi_i^b}(s/m_B^2) + r_i^c e^{i\phi_i^c}(s/m_B^2)^2.$$

With $r_i^{a,b,c} \in [0, 0.1]$ and $\phi_i^{a,b,c} \in [-\pi, \pi]$

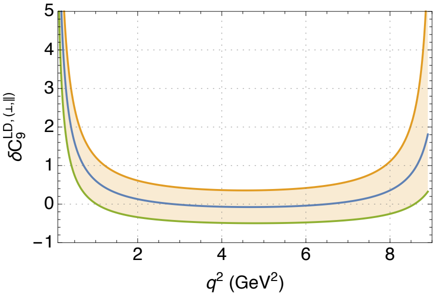
$B \to K^*\ell\bar{\ell}$: h_i : Charm – DHMV

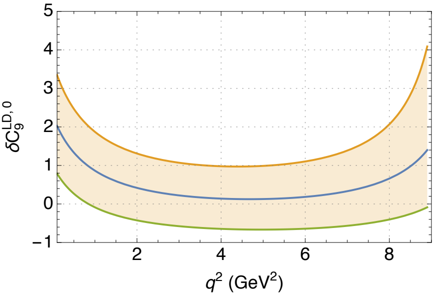
Inspired by Khodjamirian et al (KMPW): $C_9 \to C_9 + s_i\ \delta C_9^{\mathrm{LD}(i)}(q^2)$

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

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

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





$B \to K^* \ell \bar{\ell}$: h_i : large-q^2 – DHMV

- 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 (Lyon + Zwicky 2014)

Fit 1: 1D $\to$ 2D fits

	$\mathcal{C}_7^{\rm NP}$	$\mathcal{C}_9^{\rm NP}$	$\mathcal{C}_{10}^{\rm NP}$	$\mathcal{C}_{7'}^{\rm NP}$	$\mathcal{C}_{9'}^{\rm NP}$	$\mathcal{C}_{10'}^{\rm NP}$
	1.10	**4.45**	2.48	0.73	1.76	1.45
$\mathcal{C}_7^{\rm NP}$	*	0.06	0.80	1.09	1.14	1.10
$\mathcal{C}_9^{\rm NP}$	**4.31**	*	**4.01**	**4.52**	**4.58**	**4.70**
$\mathcal{C}_{10}^{\rm NP}$	2.36	1.56	*	2.39	2.01	2.02
$\mathcal{C}_{7'}^{\rm NP}$	0.71	1.07	0.30	*	0.39	0.39
$\mathcal{C}_{9'}^{\rm NP}$	1.79	2.06	1.00	1.65	*	1.04
$\mathcal{C}_{10'}^{\rm NP}$	1.44	2.10	0.04	1.31	0.25	*