$b \to s\ell\ell$ global analysis

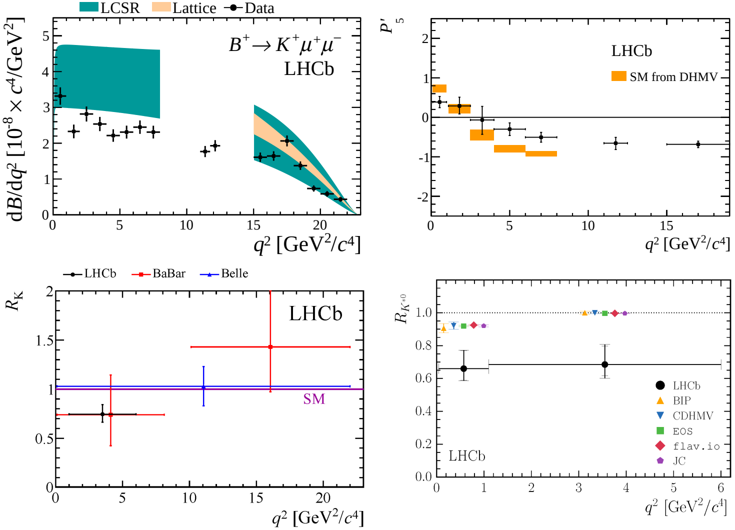
Sébastien Descotes-Genon

Laboratoire de Physique Théorique
CNRS, Univ. Paris-Sud, Université Paris-Saclay, 91405 Orsay, France

Impact of $B_s \to \mu\mu$ for New Physics searches,
PSI Villigen, Dec 18th 2017

LPT Orsay

$b \to s\ell\ell$

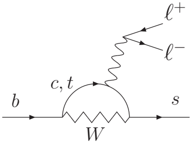


Many data, a few deviations on the way

Do these results form a consistent picture ?

Model-independent approach: $\mathcal{H}_{\rm eff}$

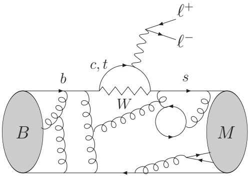
$$b \to s\gamma(^*) : \mathcal{H}^{SM}_{\Delta F=1} \propto \sum V^*_{ts} V_{tb} \mathcal{C}_i \mathcal{O}_i + \dots$$



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

Model-independent approach: $\mathcal{H}_{\rm eff}$

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

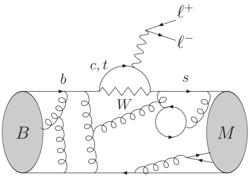


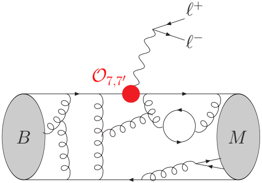
to separate short and long distances ($\mu_b = m_b$)

Model-independent approach: $\mathcal{H}_{\rm eff}$

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

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

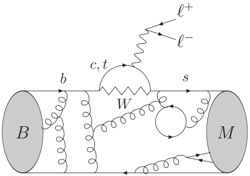


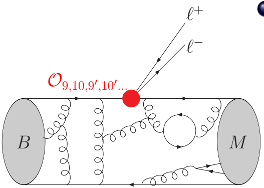


- $\mathcal{O}_7 = \frac{e}{g^2} m_b \, \bar{s}\sigma^{\mu\nu}(1+\gamma_5) F_{\mu\nu} \, b$ [real or soft photon]

Model-independent approach: $\mathcal{H}_{\rm eff}$

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





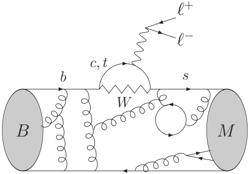
to separate short and long distances ($\mu_b = m_b$)

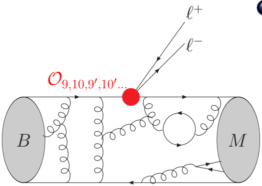
- $\mathcal{O}_7 = \frac{e}{g^2} m_b \, \bar{s}\sigma^{\mu\nu}(1+\gamma_5)F_{\mu\nu}\, b$ [real or soft photon]
- $\mathcal{O}_{9\ell} = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b \; \bar{\ell}\gamma^\mu\ell$ [$b \to s\mu\mu$ via Z/hard $\gamma\ldots$]
- $\mathcal{O}_{10\ell} = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b \; \bar{\ell}\gamma^\mu\gamma_5\ell$ [$b \to s\mu\mu$ via Z]

Model-independent approach: $\mathcal{H}_{\rm eff}$

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

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



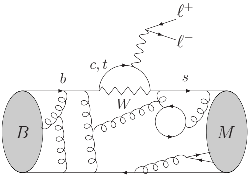


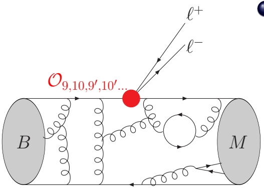
- $\mathcal{O}_7 = \frac{e}{g^2} m_b \bar{s}\sigma^{\mu\nu}(1+\gamma_5)F_{\mu\nu}\, b$ [real or soft photon]
- $\mathcal{O}_{9\ell} = \frac{e^2}{g^2}\bar{s}\gamma_\mu(1-\gamma_5)b\; \bar{\ell}\gamma^\mu \ell$ [$b \to s\mu\mu$ via Z/hard $\gamma\dots$]
- $\mathcal{O}_{10\ell} = \frac{e^2}{g^2}\bar{s}\gamma_\mu(1-\gamma_5)b\; \bar{\ell}\gamma^\mu\gamma_5 \ell$ [$b \to s\mu\mu$ via Z]

$$\mathcal{C}_7^{\rm SM} = -0.29,\ \mathcal{C}_{9\ell}^{\rm SM} = 4.1,\ \mathcal{C}_{10\ell}^{\rm SM} = -4.3$$

A= $\mathcal{C}_i$ (short dist) $\times$ Hadronic qties (long dist)

Model-independent approach: $\mathcal{H}_{\rm eff}$





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

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

- $\mathcal{O}_7 = \frac{e}{g^2} m_b \bar{s}\sigma^{\mu\nu}(1+\gamma_5)F_{\mu\nu}\, b$ [real or soft photon]
- $\mathcal{O}_{9\ell} = \frac{e^2}{g^2}\bar{s}\gamma_\mu(1-\gamma_5)b\ \bar{\ell}\gamma^\mu\ell$ [$b \to s\mu\mu$ via Z/hard $\gamma\ldots$]
- $\mathcal{O}_{10\ell} = \frac{e^2}{g^2}\bar{s}\gamma_\mu(1-\gamma_5)b\ \bar{\ell}\gamma^\mu\gamma_5\ell$ [$b \to s\mu\mu$ via Z]

$$\mathcal{C}_7^{\rm SM} = -0.29,\ \mathcal{C}_{9\ell}^{\rm SM} = 4.1,\ \mathcal{C}_{10\ell}^{\rm SM} = -4.3$$

A= $\mathcal{C}_i$ (short dist) $\times$ Hadronic qties (long dist)

NP changes short-distance $\mathcal{C}_i$ or adds new operators $\mathcal{O}_i$

- Chirally flipped ($W \to W_R$) — $\mathcal{O}_7 \to \mathcal{O}_{7'} \propto \bar{s}\sigma^{\mu\nu}(1-\gamma_5)F_{\mu\nu}\, b$
- (Pseudo)scalar ($W \to H^+$) — $\mathcal{O}_{9\ell}, \mathcal{O}_{10\ell} \to \mathcal{O}_{S\ell} \propto \bar{s}(1+\gamma_5)b\bar{\ell}\ell, \mathcal{O}_{P\ell}$
- Tensor operators ($Z \to T$) — $\mathcal{O}_{9\ell} \to \mathcal{O}_{T\ell} \propto \bar{s}\sigma_{\mu\nu}(1-\gamma_5)b\ \bar{\ell}\sigma_{\mu\nu}\ell$

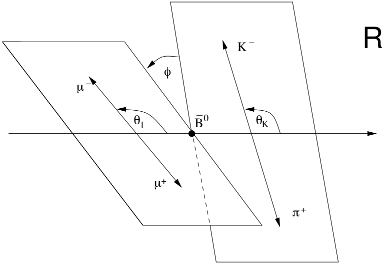
Observables

	Inclusive	Exclusive
$b \to s\gamma$	$B \to X_s\gamma$	$B_s \to \phi\gamma$, $B \to K^*\gamma$
$b \to s\ell\ell$	$B \to X_s\ell\ell$	$B_s \to \mu\mu$, $B \to K\mu\mu$, $B \to K^*\ell\ell$, $B_s \to \phi\mu\mu$
LFU		R_{K^*}, R_K, $Q_{4'}$, $Q_{5'}$

- Mostly Br, but also angular observables ($B \to K^*\ell\ell$, $B_s \to \phi\mu\mu$)
- Anomalies in
  - Br for $B \to K\mu\mu$, $B \to K^*\mu\mu$, $B_s \to \phi\mu\mu$
  - Angular observables for $B \to K^*\mu\mu$ at large K^* recoil
  - LFUV quantities: R_K, R_{K^*} (potentially $Q_i = P_i^\mu - P_i^e$)
- Combine all these observables in a statistical framework to overconstrain short-distance physics $\mathcal{C}_i$ and compare with SM

Strong impact of computation of long distances in $B \to K(^*)\ell\ell$ on the outcome of the global analyses

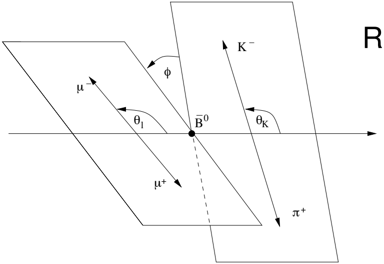
$B \to K^*(\to K\pi)\mu\mu$



Rich kinematics

- differential decay rate in terms of 12 angular coeffs $J_i(q^2)$
  with $q^2 = (p_{\ell^+} + p_{\ell^-})^2$
- interferences between 8 transversity amplitudes for $B \to K^*(\to K\pi)V^*(\to \ell\ell)$

$B \to K^*(\to K\pi)\mu\mu$

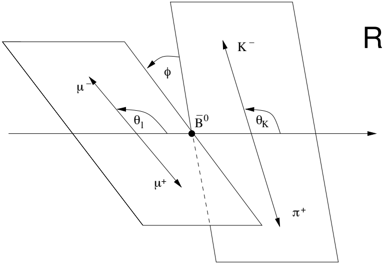


Rich kinematics

- differential decay rate in terms of 12 angular coeffs $J_i(q^2)$ with $q^2 = (p_{\ell^+} + p_{\ell^-})^2$
- interferences between 8 transversity amplitudes for $B \to K^*(\to K\pi)V^*(\to \ell\ell)$

- Transversity amplitudes (K^* polarisation, $\ell\ell$ chirality) in terms of Wilson coefficients and 7 form factors $A_{0,1,2}$, V, $T_{1,2,3}$
- EFT relations between form factors in limit $m_B \to \infty$, either when K^* very soft or very energetic (low/large-recoil)

$B \to K^*(\to K\pi)\mu\mu$



Rich kinematics

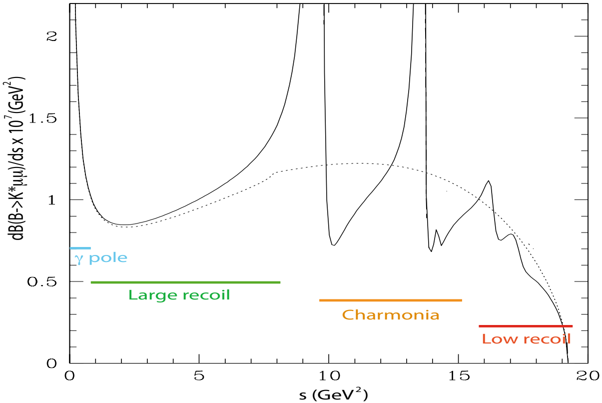
- differential decay rate in terms of 12 angular coeffs $J_i(q^2)$ with $q^2 = (p_{\ell^+} + p_{\ell^-})^2$
- interferences between 8 transversity amplitudes for $B \to K^*(\to K\pi)V^*(\to \ell\ell)$

- Transversity amplitudes (K^* polarisation, $\ell\ell$ chirality) in terms of Wilson coefficients and 7 form factors $A_{0,1,2}$, V, $T_{1,2,3}$
- EFT relations between form factors in limit $m_B \to \infty$, either when K^* very soft or very energetic (low/large-recoil)

- Optimised observables P_i with reduced hadronic uncertainties = ratios of J_i where form factors cancel in these limits
- Otherwise, averaged angular coeffs S_i with larger uncertainties

[Matias, Krüger, Becirevic, Schneider, Mescia, Virto, SDG, Ramon, Hurth; Hiller, Bobeth, Van Dyk. . .]

Kinematic regions for $B \to K^* \mu\mu$



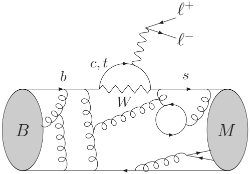
- Very large K^*-recoil ($4m_\ell^2 < q^2 < 1$ GeV^2) γ almost real
- Large K^*-recoil ($q^2 < 9$ GeV^2) energetic K^* ($E_{K^*} \gg \Lambda_{QCD}$)

  Light-Cone Sum Rules, QCD factorisation, SCET
- Charmonium region ($q^2 = m^2_{\psi,\psi'\ldots}$ between 9 and 14 GeV^2)
- Low K^*-recoil ($q^2 > 14$ GeV^2) soft K^* ($E_{K^*} \simeq \Lambda_{QCD}$)

  Lattice QCD, OPE, HQET

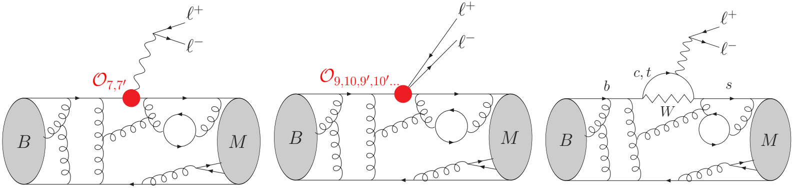
Two sources of hadronic uncertainties

$$A(B \to K^*\ell\ell) = \frac{G_F\alpha}{\sqrt{2}\pi} V_{tb}V_{ts}^*[(A_\mu + T_\mu)\bar{u}_\ell\gamma^\mu v_\ell + B_\mu \bar{u}_\ell\gamma^\mu\gamma_5 v_\ell]$$



Two sources of hadronic uncertainties

$$A(B \to K^* \ell\ell) = \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* [(A_\mu + T_\mu) \bar{u}_\ell \gamma^\mu v_\ell + B_\mu \bar{u}_\ell \gamma^\mu \gamma_5 v_\ell]$$



Form factors (local)

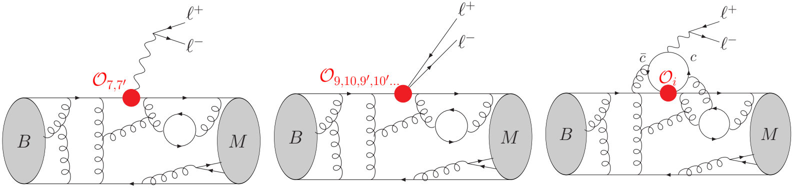
- Local contributions (more terms if NP in non-SM $\mathcal{C}_i$): 7 form factors

$$A_\mu = -\frac{2 m_b q^\nu}{q^2} \mathcal{C}_7 \langle V_\lambda | \bar{s} \sigma_{\mu\nu} P_R b | B \rangle + \mathcal{C}_{9\ell} \langle V_\lambda | \bar{s} \gamma_\mu P_L b | B \rangle$$

$$B_\mu = \mathcal{C}_{10\ell} \langle V_\lambda | \bar{s} \gamma_\mu P_L b | B \rangle \qquad \lambda : \ K^* \text{ helicity}$$

Two sources of hadronic uncertainties

$$A(B \to K^*\ell\ell) = \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* [(A_\mu + T_\mu) \bar{u}_\ell \gamma^\mu v_\ell + B_\mu \bar{u}_\ell \gamma^\mu \gamma_5 v_\ell]$$



Form factors (local) Charm loop (non-local)

- Local contributions (more terms if NP in non-SM $\mathcal{C}_i$): 7 form factors

$$A_\mu = -\frac{2m_b q^\nu}{q^2} \mathcal{C}_7 \langle V_\lambda | \bar{s}\sigma_{\mu\nu} P_R b | B\rangle + \mathcal{C}_{9\ell} \langle V_\lambda | \bar{s}\gamma_\mu P_L b | B\rangle$$

$$B_\mu = \mathcal{C}_{10\ell} \langle V_\lambda | \bar{s}\gamma_\mu P_L b | B\rangle \qquad \lambda: \ K^* \text{ helicity}$$

- Non-local contributions (charm loops): hadronic contribs.

T_μ contributes like $\mathcal{O}_{7,9\ell}$, but depends on q^2 and external states
SM contribution independent of the lepton flavour

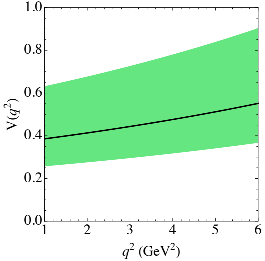
Form factors

- low K^* recoil: lattice, with correlations [Horgan, Liu, Meinel, Wingate]
- large K^* recoil: B-meson Light-Cone Sum Rule,
  - large error bars and no correlations [Khodjamirian, Mannel, Pivovarov, Wang]
  - reduce uncertainties and restore correlations among form factors using EFT correlations arising in $m_b \to \infty$, e.g., at large K^* recoil

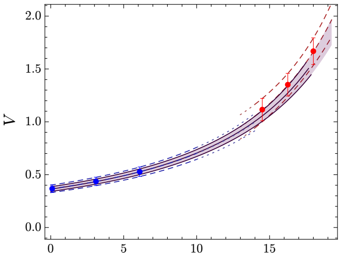
$$\xi_\perp = \frac{m_B}{m_B + m_{K^*}} V = \frac{m_B + m_{K^*}}{2E_{K^*}} A_1 = T_1 = \frac{m_B}{2E_{K^*}} T_2 \qquad + O(\alpha_s, \Lambda/m_b)$$

- all: fit to K^*-meson LCSR + lattice, small errors bars, correlations

[Bharucha, Straub, Zwicky]

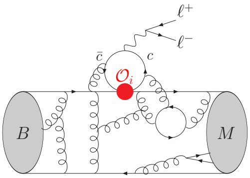


KMPW (LCSR, low q^2)



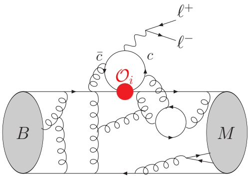
BSZ (fit LCSR + lattice)

Charm-loop contribution



- short-distance perturbatively in $\mathcal{C}_9$
- long-distance $\Delta\mathcal{C}_9^{BK^{(*)}}$ depending on q^2 and external state, includes photon pole
- can be parametrised as a polynomial in q^2 (with coefficients $O(\Lambda/m_b)$)

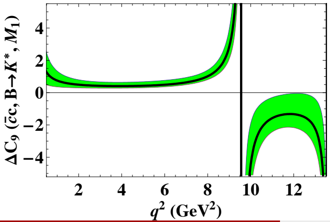
Charm-loop contribution



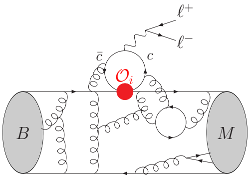
- short-distance perturbatively in $\mathcal{C}_9$
- long-distance $\Delta\mathcal{C}_9^{BK^{(*)}}$ depending on q^2 and external state, includes photon pole
- can be parametrised as a polynomial in q^2 (with coefficients $O(\Lambda/m_b)$)

- or computed using LCSR [Khodjamirian, Mannel, Pivovarov, Wang]
  - expansion in $\Lambda^2/(q^2 - 4m_c^2)$ and computation for small $q^2 < 0$
  - extrapolated through dispersion relation including J/ψ and $\psi(2S)$
  - for $B \to K^*$, partial computation yields $\Delta\mathcal{C}_9^{BK^*} > 0$
  - alternative data-driven extrapol (z-expansion) with same results

[Bobeth, Chrzaszcz, Van Dyk, Virto]



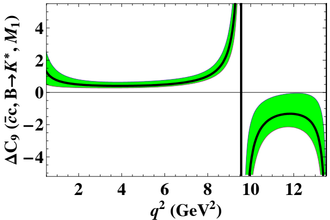
Charm-loop contribution



- short-distance perturbatively in $\mathcal{C}_9$
- long-distance $\Delta\mathcal{C}_9^{BK^{(*)}}$ depending on q^2 and external state, includes photon pole
- can be parametrised as a polynomial in q^2 (with coefficients $O(\Lambda/m_b)$)

- or computed using LCSR [Khodjamirian, Mannel, Pivovarov, Wang]
  - expansion in $\Lambda^2/(q^2-4m_c^2)$ and computation for small $q^2<0$
  - extrapolated through dispersion relation including J/ψ and $\psi(2S)$
  - for $B\to K^*$, partial computation yields $\Delta\mathcal{C}_9^{BK^*}>0$
  - alternative data-driven extrapol (z-expansion) with same results

[Bobeth, Chrzaszcz, Van Dyk, Virto]



- can be used directly:
  $\Delta\mathcal{C}_9^{BK^*,i}=\delta C^{BK^*,i}_{9,\mathrm{pert}}+\delta C^{BK^*,i}_{9,\mathrm{non\ pert}}$
- or order of magnitude
  $\Delta\mathcal{C}_9^{BK^*,i}=\delta C^{BK^*,i}_{9,\mathrm{pert}}+s_i\delta C^{BK^*,i}_{9,\mathrm{non\ pert}}$
  for $i=0,||,\perp$, $s_i=0\pm1$

General comments on fits

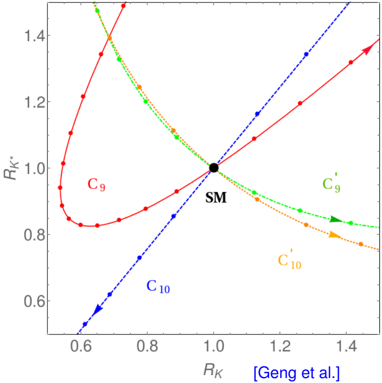
Recent global analyses with subset of $b \to s\mu\mu$ + LFUV / $b \to see$

- fit to hypothesis with some $\mathcal{C}_i^{NP}$, with χ^2 involving th. and exp. unc.
- p-value : $\chi^2_{\rm min}$ considering N_{dof} [does hyp. yield overall good fit ?]
- $\mathrm{Pull}_{\rm SM}$: $\chi^2_{min}(\mathcal{C}_i = 0) - \chi^2_{min}$ [does hyp. solve SM deviations ?]

General comments on fits

Recent global analyses with subset of $b \to s\mu\mu$ + LFUV / $b \to see$

- fit to hypothesis with some $\mathcal{C}_i^{NP}$, with χ^2 involving th. and exp. unc.
- p-value : $\chi^2_{\min}$ considering N_{dof} [does hyp. yield overall good fit ?]
- $\mathrm{Pull}_{\mathrm{SM}}$: $\chi^2_{min}(\mathcal{C}_i = 0) - \chi^2_{min}$ [does hyp. solve SM deviations ?]



[Geng et al.]

- LFUV obs with reduced hadronic unc. but degeneracy between shifts in $\mathcal{C}_{ie}^{NP}$ and $\mathcal{C}_{i\mu}^{NP}$
- other observables lift degeneracy, favour NP in $b \to s\mu\mu$, but more sensitive to hadronic unc.
- $B_s \to \mu\mu$ SM-like : scalar ops generally ignored
- CP conservation generally assumed (hence real $\mathcal{C}_i^{NP}$)

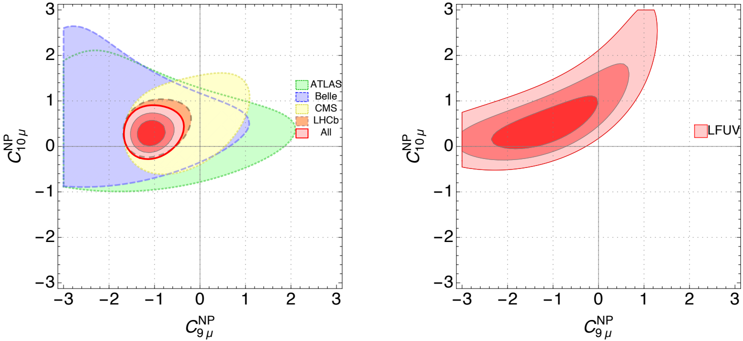
(Capdevila et al.)

- Stat approach: Frequentist
- Form factors: KMPW with EFT correlations
- LD charm: order of magnitude from KMPW, but sign left arbitrary

Two type of fits

- all obs [LHCb, Belle, ATLAS, CMS, 175 obs]
- LFUV+$b \to s\gamma$+$B_s \to \mu\mu$ [17 obs]

with SM p-value 11%/4%



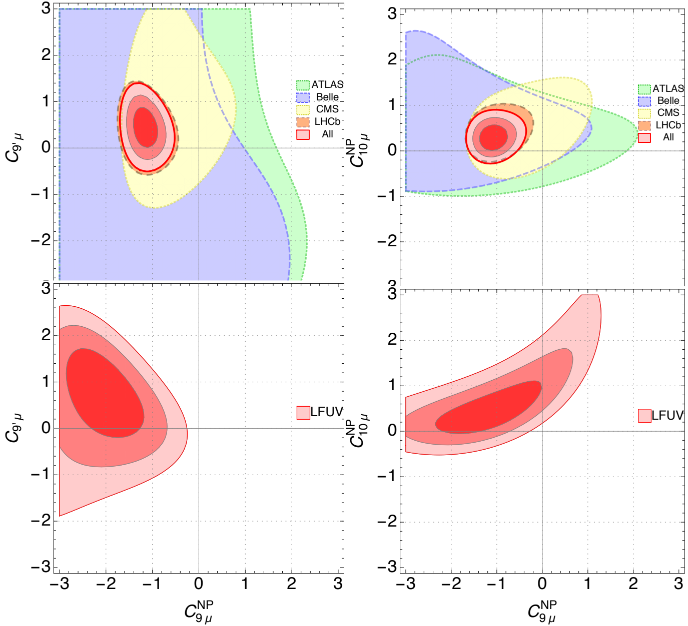
Favoured scenarios of NP in $b \to s\mu\mu$

- 1D or 2D hypotheses with shifts $\mathcal{C}_i = \mathcal{C}_i^{\rm SM} + \mathcal{C}_i^{\rm NP}$

	All			LFUV		
	Best fit	Pull(σ)	p-val(%)	Best fit	Pull(σ)	p-val(%)
$\mathcal{C}_{9\mu}^{\rm NP}$	-1.11	5.8	68	-1.76	3.9	69
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$	-0.62	5.3	58	-0.66	4.1	78
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{9\mu}'$	-1.01	5.4	61	-1.64	3.2	32
$(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_{10\mu}^{\rm NP})$	(-1.01,0.29)	5.7	72	(-1.30,0.36)	3.7	75
$(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_7')$	(-1.13,0.01)	5.5	69	(-1.85,-0.04)	3.6	66
$(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_{9'\mu})$	(-1.15,0.41)	5.6	71	(-1.99,0.93)	3.7	72
$(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_{10'\mu})$	(-1.22,-0.22)	5.7	72	(-2.22,-0.41)	3.9	85
Hyp. 1	(-1.16,0.38)	5.7	73	(-1.68,0.60)	3.8	78
Hyp. 2	(-1.15, 0.01)	5.0	57	(-2.16,0.41)	3.0	37
Hyp. 3	(-0.67,-0.10)	5.0	57	(0.61,2.48)	3.7	73
Hyp. 4	(-0.70,0.28)	5.0	57	(-0.74,0.43)	3.7	72

- hyp.1: $(\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{9'\mu}, \mathcal{C}_{10\mu}^{\rm NP} = \mathcal{C}_{10'\mu})$
- hyp.2: $(\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{9'\mu}, \mathcal{C}_{10\mu}^{\rm NP} = -\mathcal{C}_{10'\mu})$
- hyp.3: $(\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}, \mathcal{C}_{9'\mu} = \mathcal{C}_{10'\mu})$
- hyp.4: $(\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}, \mathcal{C}_{9'\mu} = -\mathcal{C}_{10'\mu})$

Consistency between fits to All and LFUV obs



Improving on the main anomalies

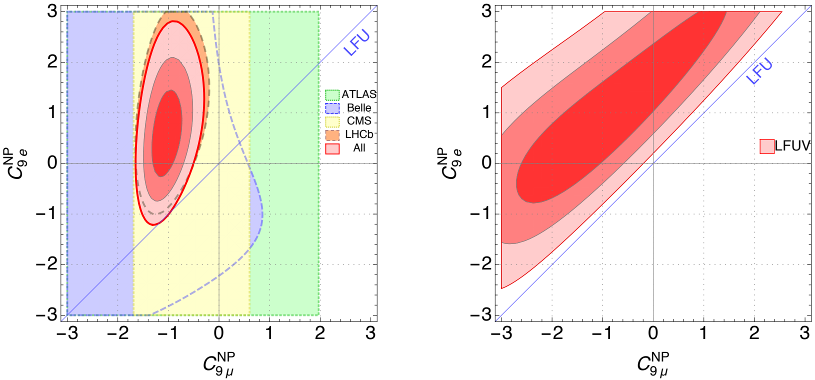
- $\mathcal{C}_{9\mu}^{NP} \simeq -1$ favoured in all "good" scenarios
- Not all anomalies "solved", but many are alleviated

Largest pulls	$\langle P'_5 \rangle^{[4,6]}$	$\langle P'_5 \rangle^{[6,8]}$	$R_K^{[1,6]}$	$R_{K^*}^{[0.045,1.1]}$
Experiment	-0.30 ± 0.16	-0.51 ± 0.12	$0.745^{+0.097}_{-0.082}$	$0.66^{+0.113}_{-0.074}$
SM pred.	-0.82 ± 0.08	-0.94 ± 0.08	1.00 ± 0.01	0.92 ± 0.02
Pull (σ)	-2.9	-2.9	+2.6	+2.3
Pred. $\mathcal{C}_{9\mu}^{\rm NP} = -1.1$	-0.50 ± 0.11	-0.73 ± 0.12	0.79 ± 0.01	0.90 ± 0.05
Pull (σ)	-1.0	-1.3	+0.4	+1.9

Largest pulls	$R_{K^*}^{[1.1,6]}$	$\mathcal{B}_{B_s \to \phi\mu^+\mu^-}^{[2,5]}$	$\mathcal{B}_{B_s \to \phi\mu^+\mu^-}^{[5,8]}$
Experiment	$0.685^{+0.122}_{-0.083}$	0.77 ± 0.14	0.96 ± 0.15
SM pred.	1.00 ± 0.01	1.55 ± 0.33	1.88 ± 0.39
Pull (σ)	+2.6	+2.2	+2.2
Pred. $\mathcal{C}_{9\mu}^{\rm NP} = -1.1$	0.87 ± 0.08	1.30 ± 0.26	1.51 ± 0.30
Pull (σ)	+1.2	+1.8	+1.6

- 6D scenario $\mathcal{C}_{7,7',9\mu,9'\mu,10\mu,10'\mu}^{NP}$ with pull reaching 5 σ

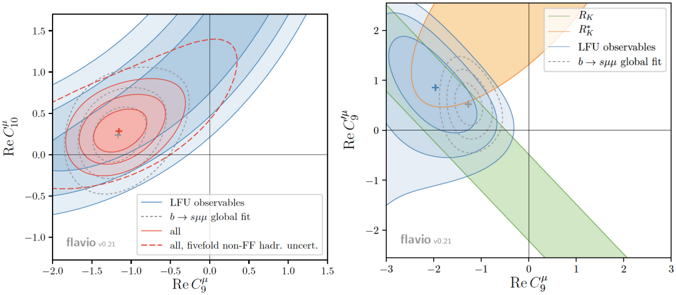
NP in both $b \to s\mu\mu$ and $b \to see$



- Up to now, only NP in $b \to s\mu\mu$, what about $b \to see$?
- Need for contribution for $\mathcal{C}_{9\mu}$ (angular obs, Br) but not for $\mathcal{C}_{9e}$
- But not forbidden either:
  - $(\mathcal{C}_{9\mu}^{NP}, \mathcal{C}_{9e}^{NP})$: best-fit point $(-1.0, 0.4)$, pull 5.5/3.5 σ, p-val 68%/65% for All/LFUV
  - $\mathcal{C}_{9\mu}^{NP} = -3\mathcal{C}_{9e}^{NP}$ good ($U(1)$ models for ν mixing [Bhatia, Chakraborty, Dighe])

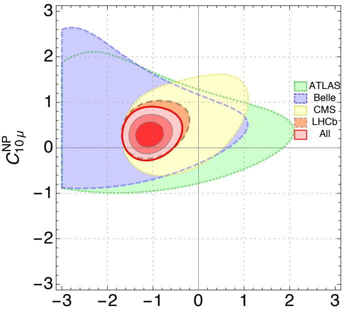
(Altmanshofer, Stangl, Straub)

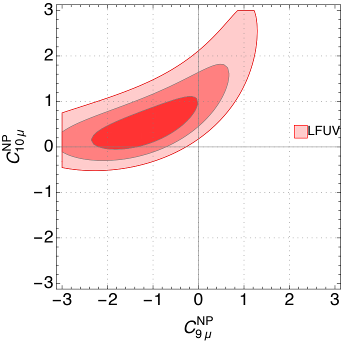
- Stat approach: Frequentist
- Form factors: BSZ
- LD charm: q^2-polynomial with order of magnitude from Λ/m_b



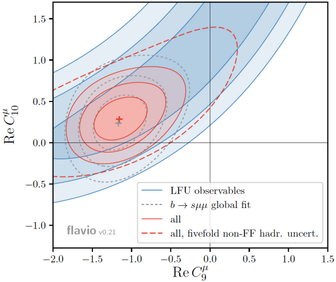
- $R_K, R_{K^*}, Q_{4'}, Q_{5'}$: flat dir $\mathcal{C}_{9\mu}^{NP} - \mathcal{C}_{9e}^{NP} - \mathcal{C}_{10\mu}^{NP} + \mathcal{C}_{10e}^{NP} \simeq -1.4$
  1D scenarios with pull around 4.3 σ
- $+\ b \to s\mu\mu$ observables, $\mathcal{C}_{9\mu} = -1.2$ with very high significance (higher than [Capdevila, Crivellin, SDG, Matias, Virto]), same 2D scenarios favoured

Consistency of the two analyses





[Capdevila, Crivellin, SDG, Matias, Virto]

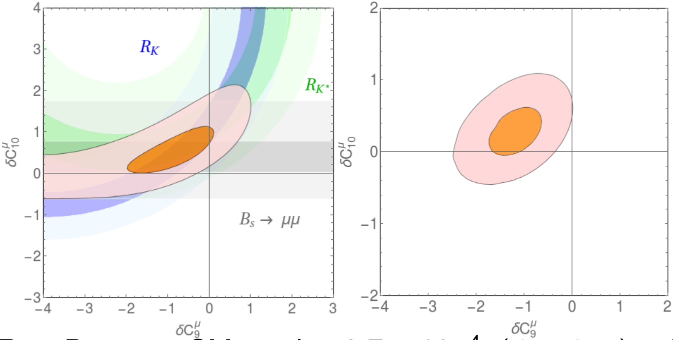


[Altmannshofer, Stangl, Straub]

- Different angular obs.
- Different form factor inputs
- Different hadronic corrections
- Same NP scenarios favoured (higher significances for [Altmannshofer, Stangl, Straub])

(Geng et al.)

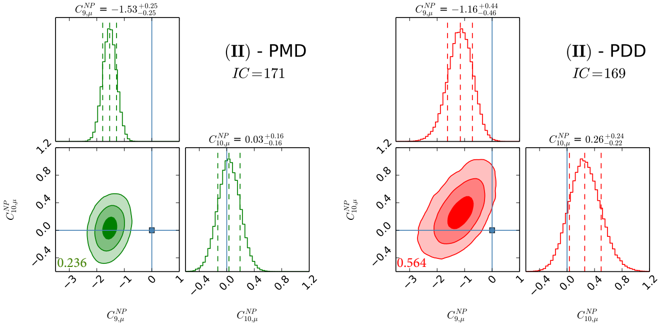
- Stat approach: Frequentist
- Form factors: LCSR & Dyson-Schwinger + EFT correlations
- LD charm: estimate proportional to C_7, magnitude from KMPW



- $R_K, R_{K^*}, B_s \to \mu\mu$, SM p-value 3.7×10^{-4}, $(\mathcal{C}_{9\mu}, \mathcal{C}_{10\mu})$ pull 3.8 σ
  same pull 3.9 σ for 1D hyp for $\mathcal{C}_{9\mu}$ or $\mathcal{C}_{10\mu}$
- $+ B \to K^*\mu\mu$ [large recoil] $+ B \to K^*\gamma$ [65 obs]
  SM p-value 0.09, $(\mathcal{C}_{9\mu}, \mathcal{C}_{10\mu})$ pull 4.2 σ

(Ciuchini et al.)

- Stat approach: Bayesian Form factors: BSZ
- LD charm: KMPW (PMD) or q^2-polynomial (16 params to fit, PDD)



- $B \to K^*\ell\ell$ [large recoil, LHCb, CMS, Belle], $B \to K^*\gamma$, $B_s \to \phi\mu\mu$, $B_s \to \phi\gamma$, $B \to K\ell\ell$, $B \to X_s\gamma$, $B_s \to \mu\mu$
- $(\mathcal{C}_{9\mu}, \mathcal{C}_{10\mu})$ pull between 3 and 4 σ (PDD) or up to 5 σ (PMD)
- alternative scenario with $\mathcal{C}^e_{10}$ and large LD charm corrections (but which dynamics to enhance these contributions ?)

Other similar works

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

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

Other similar works

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

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

Consistency in the pattern of deviations from

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

Other similar works

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

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

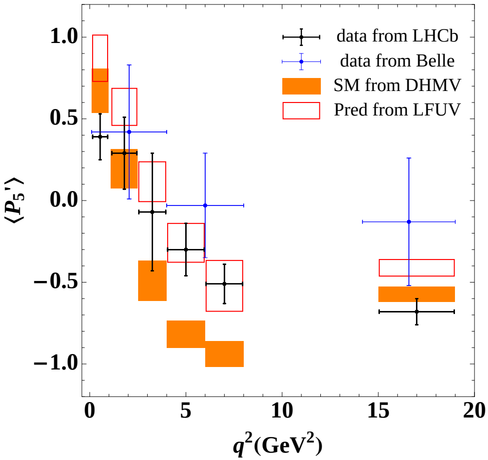
Consistency in the pattern of deviations from

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

Two types of hadronic uncertainties, but variety of approaches

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

Consistency: P_5' from LFUV obs



- Fit to LFUV obs only to determine $\mathcal{C}_{9\mu}^{NP}$
- ...then predict value of P_5'
- Confirms the very good agreement between fits to LFUV only and the other observables
- Disagreements with Standard Model in $b \to s\ell\ell$ obey a pattern
- No indication of underestimation of hadronic uncertainties

Conclusions

B physics anomalies

- $b \to s\ell^+\ell^-$ with many obs., more or less sensitive to hadronic unc.
- Interesting deviations from SM expectations + LFUV
- Global fit supports large $\mathcal{C}_{9\mu}^{NP}$ with very good consistency (Br vs angular vs LFUV, channels, recoil regions, LFUV and All obs...)
- Several NP scenarios favoured with large SM pulls and p-values
- Confirmed by many analyses with different approaches (observables, treatment of hadronic uncertainties...)

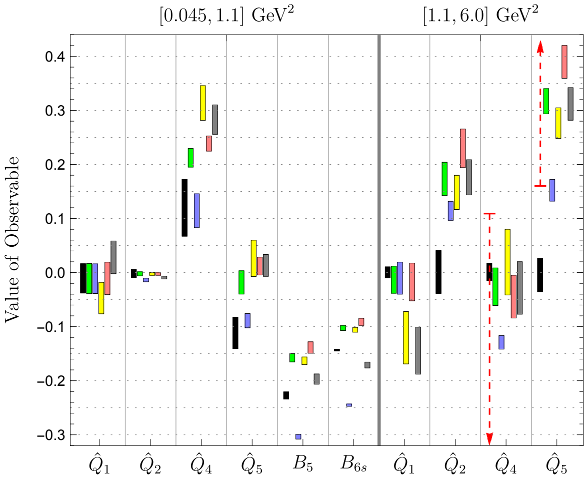
Extensions [Talks from David, Gino, Admir, Diptimoy...]

- Constraints on favoured scenarios ($B_s \to \ell\ell$ for $(\mathcal{C}_{9\mu}, \mathcal{C}_{10\mu})$)
- Wilson coefficients (scalar/pseudoscalar, imaginary part)
- Hadronic uncertainties ($b \to see$ vs $b \to s\mu\mu$)
- More LFUV observables, baryon modes, $b \to s\tau\tau$...
- Model-dependent interpretation, connection with $b \to c\ell\bar{\nu}$

Next stops: LFUV in angular observables ?

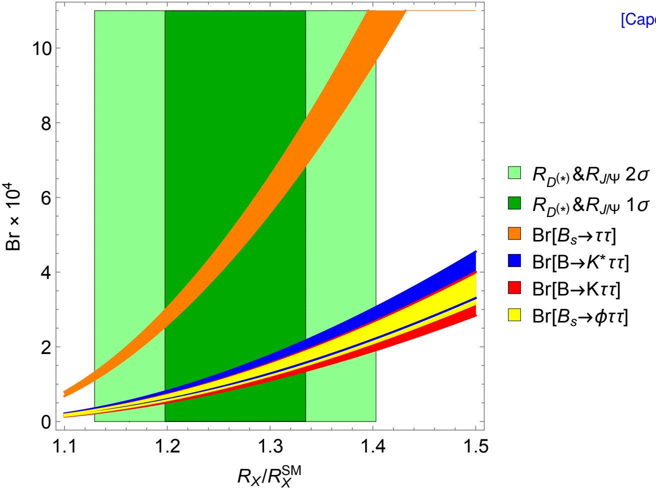
Null SM tests (up to m_ℓ effects): $Q_i = P_i^\mu - P_i^e$, $B_i = \frac{J_i^\mu}{J_i^e} - 1$

[Capdevila, Crivellin, SDG, Matias, Virto]



- Black: SM
- Green: $\mathcal{C}_{9\mu}^{NP} = -1.1$
- Blue: $\mathcal{C}_{9\mu}^{NP} = \mathcal{C}_{10\mu}^{NP} = -0.61$
- Yellow: $\mathcal{C}_{9\mu}^{NP} = \mathcal{C}_{9'\mu}^{NP} = -1.01$
- Orange: $\mathcal{C}_{9\mu}^{NP} = -3\mathcal{C}_{9e}^{NP} = -1.06$
- Gray: Best fit point for 6 dim fit

Next stops: correlating $b \to c\ell\bar{\nu}$ and $b \to s\ell\ell$?

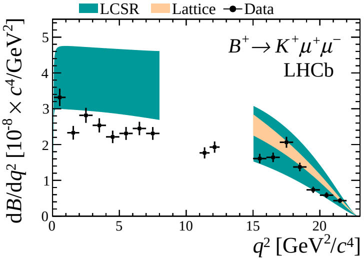


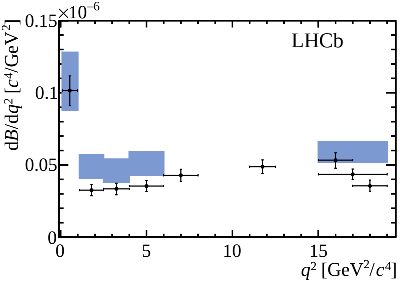
[Capdevila, Crivellin, SDG, Hofer, Matias]

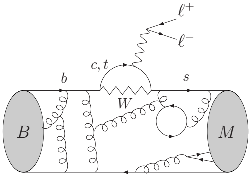
- Correlation from SMEFT ops contributing to $R(D), R(D^*), R(J/\psi)$
- Agreement with q^2-dependence of $d\Gamma/dq^2$ + bound on $b \to s\nu\bar{\nu}$
- Very large enhancement of $b \to s\tau\tau$ in this case

Thank you for your attention !

Anomalies in branching ratios

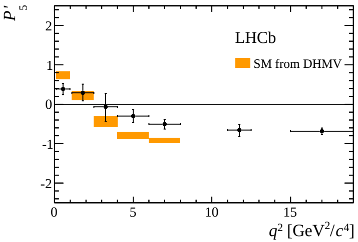






- $Br(B \to K\mu\mu)$ (up), $Br(B \to K^*\mu\mu)$ (down), $Br(B_s \to \phi\mu\mu)$ too low wrt SM
- q^2 invariant mass of $\ell\ell$ pair
- removing bins dominated by J/ψ and ψ' resonances
- large hadronic uncertainties from form factors at
  - Large-meson recoil/low q^2: light-cone sum rules
  - Low-meson recoil/large q^2: lattice QCD

Anomalies in angular observables (1)

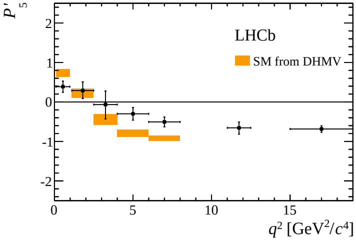


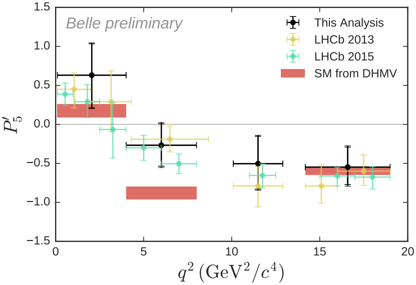
- Basis of optimised observables P_i (angular coeffs) with reduced hadronic uncertainties

  [Matias, Krüger, Becirevic, Schneider, Mescia, Virto, SDG, Ramon, Hurth; Hiller, Bobeth, Van Dyk. . .]

- Measured at LHCb with 1 fb^{-1} (2013) and 3 fb^{-1} (2015)
- Discrepancies for some (but not all) observables, in particular two bins for P'_5 deviating from SM by 2.8 σ and 3.0 σ

Anomalies in angular observables (1)

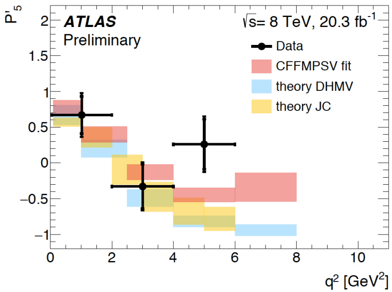


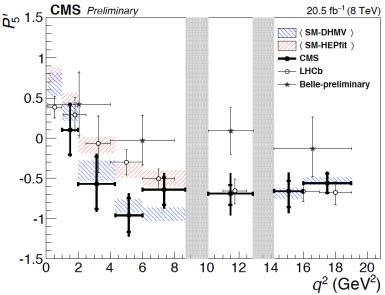


- Basis of optimised observables P_i (angular coeffs) with reduced hadronic uncertainties

  [Matias, Krüger, Becirevic, Schneider, Mescia, Virto, SDG, Ramon, Hurth; Hiller, Bobeth, Van Dyk. . .]
- Measured at LHCb with 1 fb^{-1} (2013) and 3 fb^{-1} (2015)
- Discrepancies for some (but not all) observables, in particular two bins for P'_5 deviating from SM by 2.8 σ and 3.0 σ
- . . . confirmed by Belle in 2016 (with larger uncertainties)

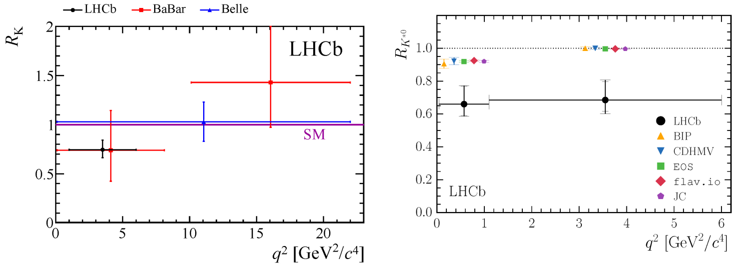
Anomalies in angular observables (2)





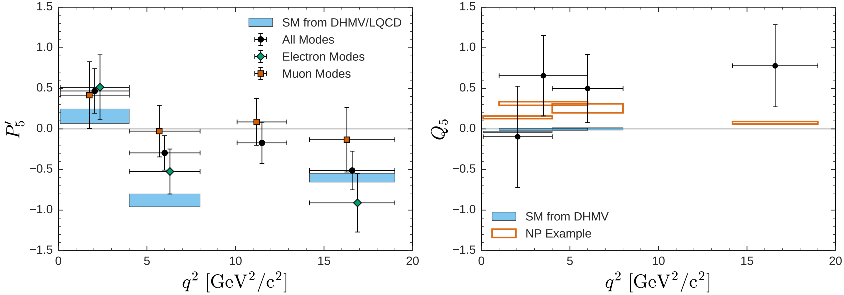
- ATLAS and CMS in 2017, but with larger uncertainties
- ATLAS: full basis, deviation in P'_5 (OK with LHCb) and P'_4 (not OK)
- CMS: only P_1 and P'_5 using input on F_L from earlier analyses (not clear why) leading to lower P'_5 than others
- There is more to $B \to K^* \mu\mu$ than just P'_5
  - P_2 also interesting deviations in LHCb 1 fb^{-1} data in [2,4] bin (but not seen at 3 fb^{-1} due to too large F_L leading to large uncert.)
  - useful that other optimised observables in agreement with SM

Anomalies in lepton flavour universality : Br



- LFU-test ratios $R_K = \frac{Br(B\to K\mu\mu)}{Br(B\to Kee)}$ and $R_{K^*} = \frac{Br(B\to K^*\mu\mu)}{Br(B\to K^*ee)}$ for LHCb
- hadronic uncertainties/effects cancel largely in the SM ($V-A$ interaction only) and for $q^2 \geq 1$ GeV^2 (m_ℓ effects negligible)
- in SM, a single form factor cancel in $R_K = 1$, but several polarisations and form factors in R_{K^*} (small q^2-dep.)
- small effects of QED radiative corrections (1-3 %)
- LHCb: 2.6 σ for $R_{K[1,6]}$, 2.3 and 2.6 σ for $R_{K^*[0.045,1.1]}$ and $R_{K^*[1.1,6]}$

Anomalies in LFU: angular observables



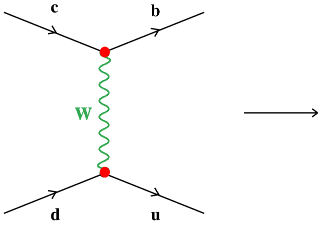
Belle also compared $b \to see$ and $b \to s\mu\mu$ in 2016

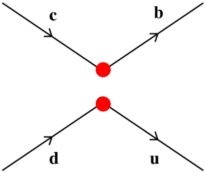
- different systematics from LHCb
- 2.6 σ deviation for $\langle P_5' \rangle^{\mu}_{[4,8]}$ versus 1.3 σ deviation for $\langle P_5' \rangle^{e}_{[4,8]}$
- same indication by looking at $Q_5 = P_5^{\mu\prime} - P_5^{e\prime}$, deviating from SM
- more data needed to confirm this hint of LFU violation (LFUV)

Effective approaches

Fermi-like approach (for decoupling th): separation of different scales

Short dist/Wilson coefficients and Long dist/local operator



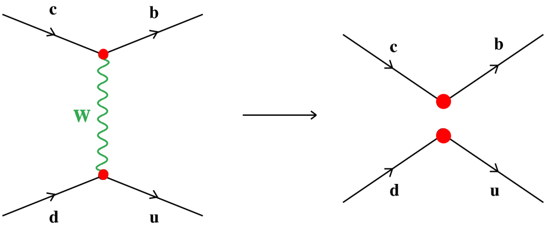


$$V_{ud} V_{cb}^* \frac{G_F}{\sqrt{2}} \frac{m_W^2}{m_W^2 - p_W^2} \; \bar{u}\gamma_\mu(1-\gamma_5)d\bar{b}\gamma^\mu(1-\gamma_5)c$$

Effective approaches

Fermi-like approach (for decoupling th): separation of different scales

Short dist/Wilson coefficients and Long dist/local operator



$$V_{ud} V_{cb}^* \frac{G_F}{\sqrt{2}} \bar{u}\gamma_\mu(1-\gamma_5)d\bar{b}\gamma^\mu(1-\gamma_5)c + O(1/M_W^2)$$

Fermi theory carries some info on the underlying (electroweak) theory

- G_F: scale of underlying physics
- $\mathcal{O}_i$: interaction with left-handed fermions, through charged spin 1
- Losing some info (gauge structure, Z^0 ...)

but a good start if no particle (=W, Z) yet seen

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

175 observables in total (no CP-violating obs) [Capdevila, Crivellin, SDG, Matias, Virto]

- $B \to K^*\mu\mu$ (Br, $P_{1,2}$, $P'_{4,5,6,8}$, F_L in large- and low-recoil bins)
- $B \to K^*ee$ ($P_{1,2,3}$, $P'_{4,5}$, F_L in large- and low-recoil bins)
- $B_s \to \phi\mu\mu$ (Br, P_1, $P'_{4,6}$, F_L in large- and low-recoil bins)
- $B \to K\mu\mu$ (Br in many bins)
- R_K, R_{K^*}, $Q_{4,5}$ (large-recoil bins)
- $B \to X_s\gamma$,$B \to X_s\mu\mu$,$B_s \to \mu\mu$,$B_s \to \phi\gamma$(Br),$B \to K^*\gamma$(Br, A_I, $S_{K^*\gamma}$)

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

175 observables in total (no CP-violating obs) [Capdevila, Crivellin, SDG, Matias, Virto]

- $B \to K^*\mu\mu$ (Br, $P_{1,2}$, $P'_{4,5,6,8}$, F_L in large- and low-recoil bins)
- $B \to K^*ee$ ($P_{1,2,3}$, $P'_{4,5}$, F_L in large- and low-recoil bins)
- $B_s \to \phi\mu\mu$ (Br, P_1, $P'_{4,6}$, F_L in large- and low-recoil bins)
- $B \to K\mu\mu$ (Br in many bins)
- R_K, R_{K^*}, $Q_{4,5}$ (large-recoil bins)
- $B \to X_s\gamma$,$B \to X_s\mu\mu$,$B_s \to \mu\mu$,$B_s \to \phi\gamma$(Br),$B \to K^*\gamma$(Br, A_I, $S_{K^*\gamma}$)

Various computational approaches

- inclusive: OPE
- excl large-meson recoil: QCD fact, Soft-collinear effective theory
- excl low-meson recoil: Heavy quark eff th, Quark-hadron duality

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

175 observables in total (no CP-violating obs) [Capdevila, Crivellin, SDG, Matias, Virto]

- $B \to K^*\mu\mu$ (Br, $P_{1,2}$, $P'_{4,5,6,8}$, F_L in large- and low-recoil bins)
- $B \to K^* ee$ ($P_{1,2,3}$, $P'_{4,5}$, F_L in large- and low-recoil bins)
- $B_s \to \phi\mu\mu$ (Br, P_1, $P'_{4,6}$, F_L in large- and low-recoil bins)
- $B \to K\mu\mu$ (Br in many bins)
- R_K, R_{K^*}, $Q_{4,5}$ (large-recoil bins)
- $B \to X_s\gamma$, $B \to X_s\mu\mu$, $B_s \to \mu\mu$, $B_s \to \phi\gamma$(Br), $B \to K^*\gamma$(Br, A_I, $S_{K^*\gamma}$)

Various computational approaches

- inclusive: OPE
- excl large-meson recoil: QCD fact, Soft-collinear effective theory
- excl low-meson recoil: Heavy quark eff th, Quark-hadron duality

Frequentist analysis

- $\mathcal{C}_i(\mu_{ref}) = \mathcal{C}_i^{SM} + \mathcal{C}_i^{NP}$, with $\mathcal{C}_i^{NP}$ assumed to be real (no CPV)
- Experimental correlation matrices provided (from all exp)
- Theoretical inputs (form factors. . .) with correlation matrix computed treating all theo errors as Gaussian random variables

$b \to s\mu\mu$: 6D hypothesis

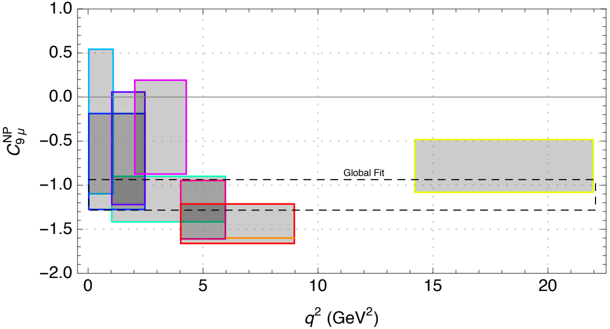
Letting all 6 Wilson coefficients for muons vary (but only real)

	Best fit	1 σ	2 σ
$\mathcal{C}_7^{\rm NP}$	+0.03	$[-0.01, +0.05]$	$[-0.03, +0.07]$
$\mathcal{C}_{9\mu}^{\rm NP}$	-1.12	$[-1.34, -0.88]$	$[-1.54, -0.63]$
$\mathcal{C}_{10\mu}^{\rm NP}$	+0.31	$[+0.10, +0.57]$	$[-0.08, +0.84]$
$\mathcal{C}_{7'}$	+0.03	$[+0.00, +0.06]$	$[-0.02, +0.08]$
$\mathcal{C}_{9'\mu}$	+0.38	$[-0.17, +1.04]$	$[-0.59, +1.58]$
$\mathcal{C}_{10'\mu}$	+0.02	$[-0.28, +0.36]$	$[-0.54, +0.68]$

- Pattern: $\mathcal{C}_7^{\rm NP} \gtrsim 0$, $\mathcal{C}_{9\mu}^{\rm NP} < 0$, $\mathcal{C}_{10\mu}^{\rm NP} > 0$, $\mathcal{C}_7' \gtrsim 0$, $\mathcal{C}_{9\mu}' > 0$, $\mathcal{C}_{10\mu}' \gtrsim 0$
- $\mathcal{C}_9$ is consistent with SM only above 3σ
- All others are consistent with zero at 1σ except for $\mathcal{C}_{10}$ at 2 σ
- $\text{Pull}_{\rm SM}$ for the 6D fit is 5.0σ (used to be 3.6 σ)

Other recent analyses (smaller sets of data/other approaches) : same patterns, different significances [Altmannshofer, Stangl, Straub; Ciuchini, Coutinho, Fedele, Franco, Paul, Silvestrini, Valli; Geng, Grinstein, Jäger, Camalich, Ren, Shi; Hurth, Mahmoudi, Martinez Santos, Neshatpour...]

Cross-check: q^2-dependence of $\mathcal{C}_9$

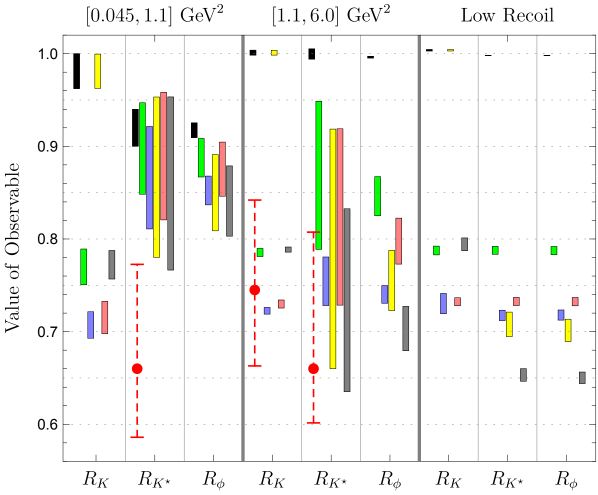


[Capdevila, Crivellin, Matias, Virto, SDG]

- Fit to $\mathcal{C}_9^{NP}$ from individual bins of $b \to s\mu\mu$ data (NP only in $\mathcal{C}_{9\mu}$)
  - NP in $\mathcal{C}_9$ from short distances, q^2-independent
  - Hadronic physics in $\mathcal{C}_9$ related to $c\bar{c}$ dynamics, (likely) q^2-dependent
- No indication of additional q^2-dependence missed by the fit
- Can be checked for other NP scenarios
- In agreement with other analyses [Altmanshoffer, Straub]
- Further estimates from LHCb data-driven analyses (D. Van Dyk's talk)

LFUV in branching ratios

[Capdevila, Crivellin, SDG, Matias, Virto]



- Black: SM
- Green: $\mathcal{C}_{9\mu}^{NP} = -1.1$
- Blue: $\mathcal{C}_{9\mu}^{NP} = \mathcal{C}_{10\mu}^{NP} = -0.61$
- Yellow: $\mathcal{C}_{9\mu}^{NP} = \mathcal{C}_{9'\mu}^{NP} = -1.01$
- Orange: $\mathcal{C}_{9\mu}^{NP} = -3\mathcal{C}_{9e}^{NP} = -1.06$
- Gray: Best fit point for 6 dim fit

R_{K^*} with conservative [Khodjamirian et al] but R_ϕ computed with [Bharucha et al]

LFUV in angular observables: Q_i, B_i, M

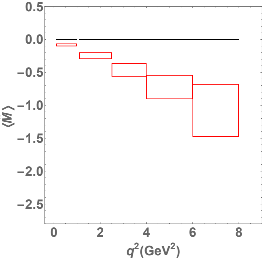
[Capdevilla, Matias, Virto, SDG]

Expecting measurements of BR and angular coefficients for $B \to K^* ee$

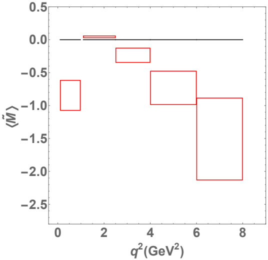
- null SM tests (up to m_ℓ effects): $Q_i = P_i^\mu - P_i^e\,, \quad B_i = \frac{J_i^\mu}{J_i^e} - 1$
- angular coeffs J_5 and J_{6s} with only a linear dependence on $\mathcal{C}_9$

$$M = (J_5^\mu - J_5^e)(J_{6s}^\mu - J_{6s}^e)/(J_{6s}^\mu J_5^e - J_{6s}^e J_5^\mu)$$

  - cancellation of hadronic contribs in $\mathcal{C}_9$ if NP in $\mathcal{C}_{9\mu}$ only
  - different sensitivity to NP scenarios compared to $R_{K^{(*)}}$



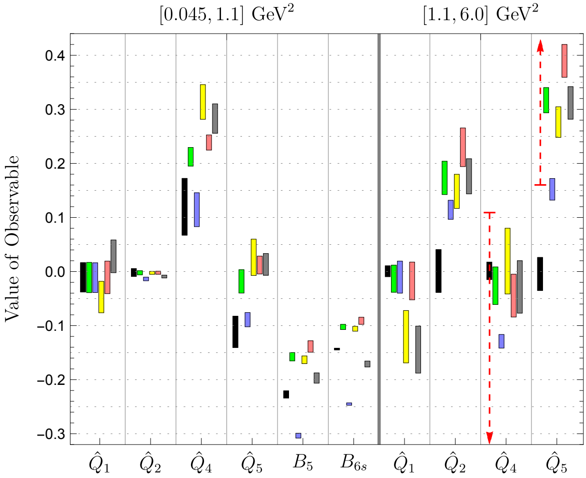
$\mathcal{C}_{9\mu}^{\rm NP} = -1.1, \mathcal{C}_{ie}^{\rm NP} = 0$



$\mathcal{C}_{9\mu}^{\rm NP} = \mathcal{C}_{10\mu}^{\rm NP} = -0.65, \mathcal{C}_{ie}^{\rm NP} = 0$

LFUV in angular observables: Q_i, B_i

[Capdevila, Crivellin, SDG, Matias, Virto]

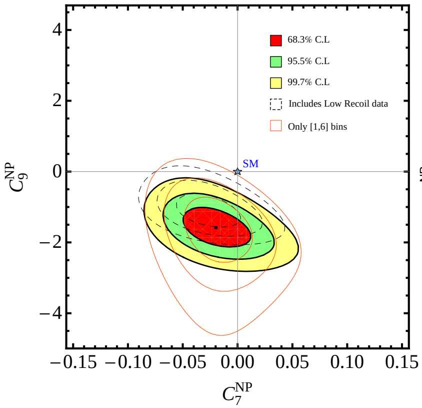


- Black: SM
- Green: $\mathcal{C}_{9\mu}^{NP} = -1.1$
- Blue: $\mathcal{C}_{9\mu}^{NP} = \mathcal{C}_{10\mu}^{NP} = -0.61$
- Yellow: $\mathcal{C}_{9\mu}^{NP} = \mathcal{C}_{9'\mu}^{NP} = -1.01$
- Orange: $\mathcal{C}_{9\mu}^{NP} = -3\mathcal{C}_{9e}^{NP} = -1.06$
- Gray: Best fit point for 6 dim fit

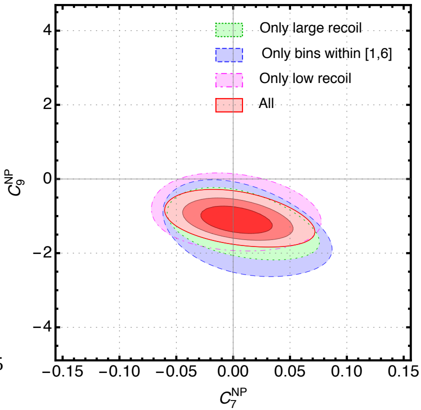
- Precise measurement of Q_5 in [1,6] can discard $\mathcal{C}_{9\mu}^{NP} = -\mathcal{C}_{10\mu}^{NP}$
- Other obs. useful to separate various scenarios

From 2013 to 2016

Many improvements from experiment and theory, but. . .

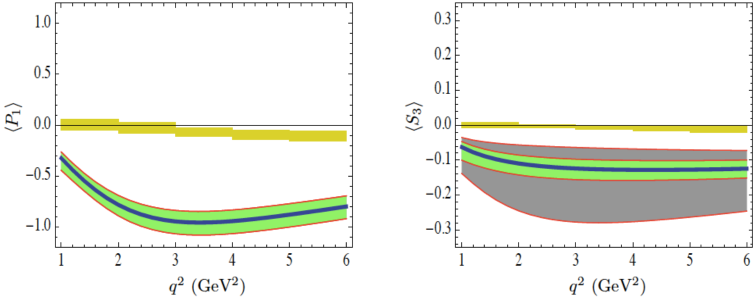


[SDG, J. Matias, Virto] (2013)



[SDG, L. Hofer J. Matias, Virto] (2016)

Sensitivity of observables to form factors



- P_i designed to have limited sensitivity to form factors
- S_i CP-averaged version of J_i

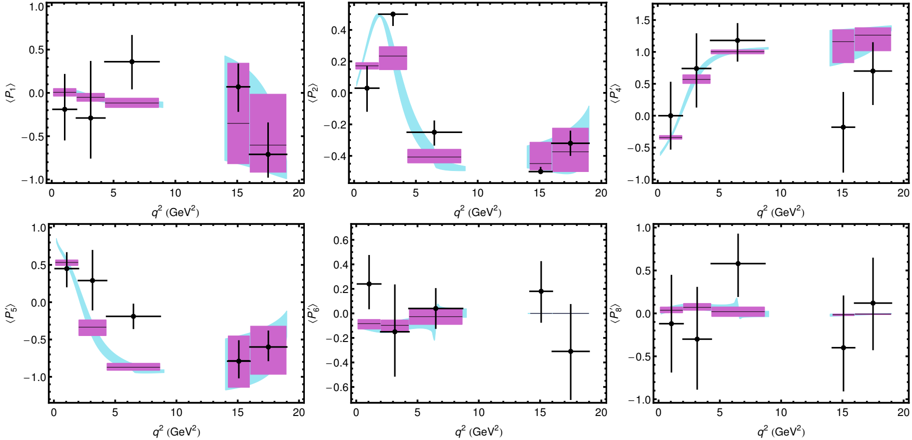
$$P_1 = \frac{2S_3}{1-F_L} \qquad F_L = \frac{J_{1c}+\bar{J}_{1c}}{\Gamma+\bar{\Gamma}} \qquad S_3 = \frac{J_3+\bar{J}_3}{\Gamma+\bar{\Gamma}}$$

Illustration for arbitrary NP point for two sets of LCSR form factors:

green [Ball, Zwicky] versus gray [Khodjamirian et al.]

more or less easy to discriminate against yellow (SM prediction)

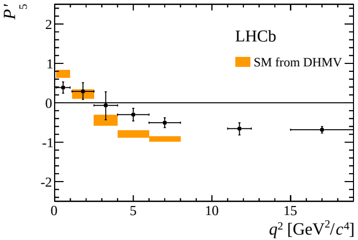
SM predictions and LHCb results at 1 fb^{-1}



Meaning of the discrepancy in P_2 and P_5' ? [SDG, Matias, Virto]

- P_2 same zero as A_{FB}, related to $\mathcal{C}_9/C_7$
- $P_{5'} \to -1$ as q^2 grows due to $A^R_{\perp,||} \ll A^L_{\perp,||}$ for $\mathcal{C}_9^{SM} \simeq -\mathcal{C}_{10}^{SM}$
- A negative shift in C_7 and $\mathcal{C}_9$ can move them in the right direction

Focus on P_5'



[SDG, J. Matias, M. Ramon, J. Virto]

$B \to K^* \mu\mu$ with $A^{\ell\ell\ \text{chirality}}_{\text{transversity}}$

$$P_5' = \sqrt{2}\frac{\mathrm{Re}(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*})}{\sqrt{|A_0|^2(|A_\perp|^2 + |A_{||}|^2)}}$$

LHCb measurements (crosses) significantly away from SM (boxes) in the large-recoil region

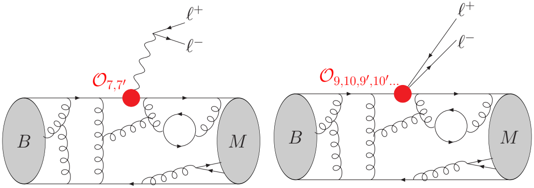
In large recoil limit with no right-handed current, with $\xi_{\perp,||}$ ffs

$$A^L_{\perp,||} \propto \pm\left[\mathcal{C}_9 - \mathcal{C}_{10} + 2\frac{m_b}{s}\mathcal{C}_7\right]\xi_\perp(s) \qquad A^R_{\perp,||} \propto \pm\left[\mathcal{C}_9 + \mathcal{C}_{10} + 2\frac{m_b}{s}\mathcal{C}_7\right]\xi_\perp(s)$$

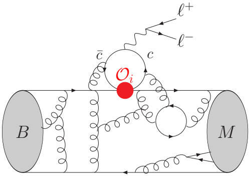
$$A^L_0 \propto -\left[\mathcal{C}_9 - \mathcal{C}_{10} + 2\frac{m_b}{m_B}\mathcal{C}_7\right]\xi_{||}(s) \qquad A^R_0 \propto -\left[\mathcal{C}_9 + \mathcal{C}_{10} + 2\frac{m_b}{m_B}\mathcal{C}_7\right]\xi_{||}(s)$$

- In SM, $\mathcal{C}_9 \simeq -\mathcal{C}_{10}$ leading to $|A^R_{\perp,||}| \ll |A^L_{\perp,||}|$
- If $\mathcal{C}_9^{\mathrm{NP}} < 0$, $|A^R_{0,||,\perp}|$ increases, $|A^L_{0,||,\perp}|$ decreases, $|P_5'|$ gets lower
- For P_4', sum with $A_{0,||}$, so not sensitive to $\mathcal{C}_9$ in the same way

Form factors and power corrections

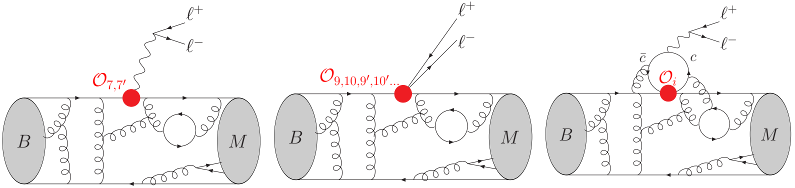


Form factors (local)



Charm loop (non-local)

Form factors and power corrections

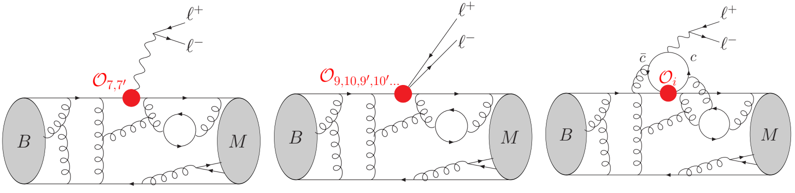


Form factors (local) Charm loop (non-local)

Uncertainties in form factors ?

- form factor inputs + correlations from EFT with limit $m_b \to \infty$
  but $O(\Lambda/m_b)$ power corrections to this limit
- Power corrs: large impact on optimised obs. like $P_{5'}$? [Camalich, Jäger]

Form factors and power corrections

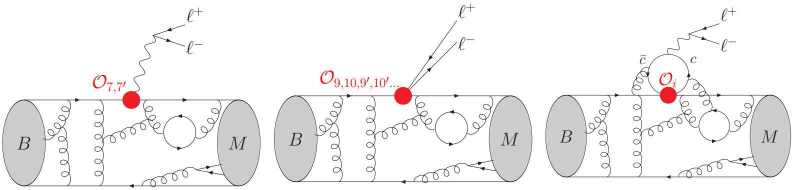


Form factors (local) Charm loop (non-local)

Uncertainties in form factors ?

- form factor inputs + correlations from EFT with limit $m_b \to \infty$ but $O(\Lambda/m_b)$ power corrections to this limit
- Power corrs: large impact on optimised obs. like $P_{5'}$? [Camalich, Jäger]
- No, but accurate predictions require [Matias, Virto, Hofer, Capdevilla, SDG]
  - appropriate def of soft form factors $\xi_{\perp,||}$ in $m_b \to \infty$ limit (scheme)
  - correlations from EFT (heavy-quark sym.) among form factors
  - power corrs varied in agreement with form factor inputs

Form factors and power corrections



Form factors (local) Charm loop (non-local)

Uncertainties in form factors ?

- form factor inputs + correlations from EFT with limit $m_b \to \infty$ but $O(\Lambda/m_b)$ power corrections to this limit
- Power corrs: large impact on optimised obs. like $P_{5'}$? [Camalich, Jäger]
- No, but accurate predictions require [Matias, Virto, Hofer, Capdevilla, SDG]
  - appropriate def of soft form factors $\xi_{\perp,||}$ in $m_b \to \infty$ limit (scheme)
  - correlations from EFT (heavy-quark sym.) among form factors
  - power corrs varied in agreement with form factor inputs
- [Camalich, Jäger] artefacts from non-optimal scheme/variation for pcs

Power corrections

- Factorisable power corrections (form factors)
  - Parametrize power corrections to form factors (at large recoil):

$$F(q^2) = F^{\rm soft}(\xi_{\perp,\|}(q^2)) + \Delta F^{\alpha_s}(q^2) + a_F + b_F \frac{q^2}{m_B^2} + \ldots$$

  - Fit $a_F, b_F, \ldots$ to the full form factor F (taken e.g. from LCSR)
    - Respect correlations among $a_{F_i}, b_{F_i}, \ldots$ and kinematic relations
    - Choose appropriate definition of $\xi_{||,\perp}$ from form factors (scheme) or take into account correlations among form factors
  - Vary power corrections as 10% of the total form factor around the central values obtained for $a_F, b_F \ldots$

Power corrections

- Factorisable power corrections (form factors)
  - Parametrize power corrections to form factors (at large recoil):

$$F(q^2) = F^{\rm soft}(\xi_{\perp,\|}(q^2)) + \Delta F^{\alpha_s}(q^2) + a_F + b_F \frac{q^2}{m_B^2} + \ldots$$

  - Fit $a_F, b_F, \ldots$ to the full form factor F (taken e.g. from LCSR)
    - Respect correlations among $a_{F_i}, b_{F_i}, \ldots$ and kinematic relations
    - Choose appropriate definition of $\xi_{||,\perp}$ from form factors (scheme) or take into account correlations among form factors
  - Vary power corrections as 10% of the total form factor around the central values obtained for $a_F, b_F \ldots$

- Nonfactorisable power corrections (extra part from amplitudes)
  - Extract from $\langle K^*\gamma^*|H_{eff}|B\rangle$ the part not associated to form factors
  - Multiply each of them with a complex q^2-dependent factor

$$\mathcal{T}_i^{\rm had} \to (1 + r_i(q^2))\mathcal{T}_i^{\rm had}, \quad r_i(s) = r_i^a e^{i\phi_i^a} + r_i^b e^{i\phi_i^b}(s/m_B^2) + r_i^c e^{i\phi_i^c}(s/m_B^2)^2.$$

  - Vary $r_i^{a,b,c} = 0 \pm 0.1$ and phase $\phi_i^{a,b,c}$ free for $i = 0, \perp, ||$

Very large power corrections ? (1)

- Scheme: choice of definition for the two soft form factors (all equivalent for $m_B \to \infty$)

$$\{\xi_\perp, \xi_{||}\} = \{V, \alpha A_1 + \beta A_2\}, \{T_1, A_0\}, \ldots$$

- Power corrections for the other form factors from dimensional estimates or fit to available determinations (LCSR)

$$F(q^2) = F^{\rm soft}(\xi_{\perp,||}(q^2)) + \Delta F^{\alpha_s}(q^2) + a_F + b_F \frac{q^2}{m_B^2} + \ldots$$

- For some schemes, large(r) uncertainties found for some optimised observables [Camalich, Jäger]

Very large power corrections ? (1)

- Scheme: choice of definition for the two soft form factors (all equivalent for $m_B \to \infty$)

$$\{\xi_\perp, \xi_{||}\} = \{V, \alpha A_1 + \beta A_2\}, \{T_1, A_0\}, \ldots$$

- Power corrections for the other form factors from dimensional estimates or fit to available determinations (LCSR)

$$F(q^2) = F^{\rm soft}(\xi_{\perp,||}(q^2)) + \Delta F^{\alpha_s}(q^2) + a_F + b_F \frac{q^2}{m_B^2} + \ldots$$

- For some schemes, large(r) uncertainties found for some optimised observables [Camalich, Jäger]

Observables are scheme independent, but
procedure to compute them can be either scheme dependent or not

a) Include all correlations among uncertainties for power corr
more accurate, but hinges on detail of ff determination

b) Assign 10% uncorrelated uncertainties for power corrs a_F, b_F
depends on scheme (setting $a_F = b_F = 0$ for two form factors)

Very large power corrections ? (2)

Model independent ⟷ Full LCSR information

1

- ★ $\Delta F^{\rm PC} = F \times \mathcal{O}(\Lambda/m_B) \sim F \times 10\%$
- ★ correlations from large-recoil sym. $\rightarrow \xi_{\perp,\parallel}, \Delta F^{\rm PC}$ uncorr.

2

- ★ $\Delta F^{\rm PC}$ from fit to LCSR
- ★ correlations from large-recoil sym. $\rightarrow \xi_{\perp,\parallel}, \Delta F^{\rm PC}$ uncorr.

3

- ★ $\Delta F^{\rm PC}$from fit to LCSR
- ★ correlations from LCSR $\rightarrow \xi_{\perp,\parallel}, \Delta F^{\rm PC}$ corr.

Very large power corrections ? (2)

Model independent ⟷ Full LCSR information

1

- ★ $\Delta F^{\rm PC} = F \times \mathcal{O}(\Lambda/m_B) \sim F \times 10\%$
- ★ correlations from large-recoil sym. $\to \xi_{\perp,\parallel}, \Delta F^{\rm PC}$ uncorr.

2

- ★ $\Delta F^{\rm PC}$ from fit to LCSR
- ★ correlations from large-recoil sym. $\to \xi_{\perp,\parallel}, \Delta F^{\rm PC}$ uncorr.

3

- ★ $\Delta F^{\rm PC}$from fit to LCSR
- ★ correlations from LCSR $\to \xi_{\perp,\parallel}, \Delta F^{\rm PC}$ corr.

$P_5'[4.0, 6.0]$	scheme 1	scheme 2
1	-0.72 ± 0.05	-0.72 ± 0.12
2	-0.72 ± 0.03	-0.72 ± 0.03
3	-0.72 ± 0.03	-0.72 ± 0.03
full BSZ	-0.72 ± 0.03	

errors only from pc with BSZ form factors

[Capdevilla,SDG, Hofer, Matias]

- [Bharucha, Straub, Zwicky] as example (correl provided)
- scheme indep. restored if $\Delta F^{\rm PC}$ from fit to LCSR, with expected magnitude
- sensitivity to scheme can be understood analytically
- no uncontrolled large power corrections for $P_{5'}$

Scheme dependence of observables

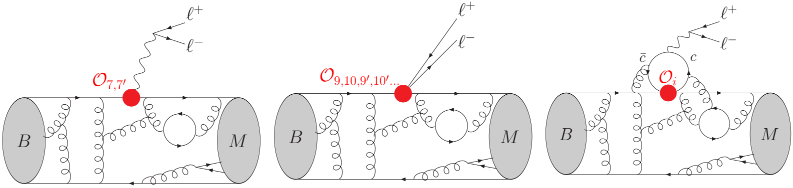
Using the connection between full and soft form factors at large recoil, keeping power corrections

$$P_5'(6\,\mathrm{GeV}^2) = P_5'|_\infty(6\,\mathrm{GeV}^2)\left(1 + 0.18\frac{2a_{V_-} - 2a_{T_-}}{\xi_\perp} - 0.73\frac{2a_{V_+}}{\xi_\perp} + 0.02\frac{2a_{V_0} - 2a_{T_0}}{\tilde{\xi}_\parallel} + \text{nonlocal terms}\right) + O\left(\frac{m_{K^*}}{m_B}, \frac{\Lambda^2}{m_B^2}, \frac{q^2}{m_B^2}\right).$$

$$P_1(6\,\mathrm{GeV}^2) = -1.21\frac{2a_{V_+}}{\xi_\perp} + 0.05\frac{2b_{T_+}}{\xi_\perp} + \text{nonlocal terms} + O\left(\frac{m_{K^*}}{m_B}, \frac{\Lambda^2}{m_B^2}, \frac{q^2}{m_B^2}\right),$$

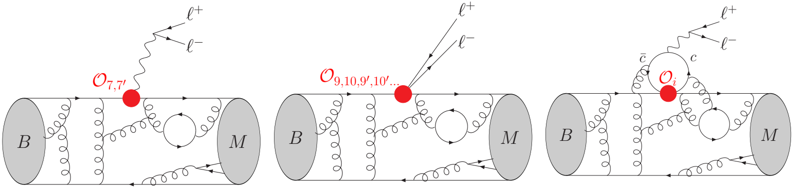
- scheme dependence of P_5' not fully taken into account in [Camalich,Jäger]
- allows one to understand the scheme dependence of P_i
- P_5' and P_1 with reduced unc. if $\xi_\perp$ defined from V ($a_{V_+} = 0$)

Charm-loop contribution



Form factors (local) Charm loop (non-local)

Charm-loop contribution

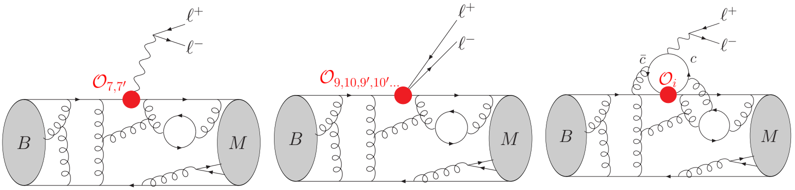


Form factors (local) Charm loop (non-local)

Uncertainties from charm loops ? [Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli]

- Effect well-known (loop process, charmonium resonances)
- Yields q^2- and hadron-dependent contrib with $\mathcal{O}_{7,9}$-like structures
  - Contribution $\Delta\mathcal{C}_9^{BK^{(*)}}$ from LCSR computation [Khodjamirian, Mannel et al.]
  - Global fits use this result as order of magn, or $O(\Lambda/m_b)$ estimates

Charm-loop contribution



Form factors (local) Charm loop (non-local)

Uncertainties from charm loops ? [Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli]

- Effect well-known (loop process, charmonium resonances)
- Yields q^2- and hadron-dependent contrib with $\mathcal{O}_{7,9}$-like structures
  - Contribution $\Delta\mathcal{C}_9^{BK^{(*)}}$ from LCSR computation [Khodjamirian, Mannel et al.]
  - Global fits use this result as order of magn, or $O(\Lambda/m_b)$ estimates
- Bayesian extraction from $B \to K^*\mu\mu$ performed by [Ciuchini et al.]
  - q^2 dependence in agreement with $\Delta\mathcal{C}_9^{BK^*;KMPW}$ + constant $\mathcal{C}_9^{\rm NP}$
  - no need for extra q^2-dep. contribution (no missed hadronic contrib)
  - actually not contradicting results of global fits, though less precise

[Matias, Virto, Hofer, Capdevilla, SDG; Hurth, Mahmoudi, Neshatpour]

Data-driven charm loop contribution (1)

[Bobeth, Chrzaszcz, Van Dyk, Virto]

Rather than fitting unphysical polynomial with arbitray coefficients

- Known analytic structure of charm loop contribution
  - Analytical up to poles and a cut starting $q^2 = 4M_D^2$
  - Inherit all singularities from form factors (M_{B_s} pole for instance)
- Appropriate parametrisation valid up to cut
  - z-expansion (better conv below cut, mapped into disc $|z| \leq 1$)
  - Poles for J/ψ ans ψ' and good asymptotic behaviour

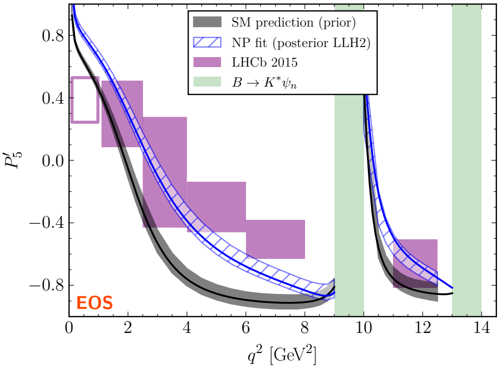
$$\eta_\alpha^* \mathcal{H}^{\alpha\mu} = i \int d^4x\, e^{iq\cdot x} \langle \bar{K}^*(k,\eta) | T\{j^\mu_{\rm em}(x), \mathcal{C}_2\mathcal{O}_2(y)\} | \bar{B}(p)\rangle$$

$$z(q^2) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}, \quad t_+ = 4M_D^2, \quad t_0 = t_+ - \sqrt{t_+(t_+ - M^2_{\psi(2S)})}$$

$$\mathcal{H}_\lambda(z) = \frac{1 - z\, z^*_{J/\psi}}{z - z_{J/\psi}} \frac{1 - z\, z^*_{\psi(2S)}}{z - z_{\psi(2S)}} \left[\sum_{k=0}^{K} \alpha_k^{(\lambda)} z^k\right] \mathcal{F}_\lambda(z)$$

Data-driven charm loop contribution (2)

[Bobeth, Chrzaszcz, Van Dyk, Virto]

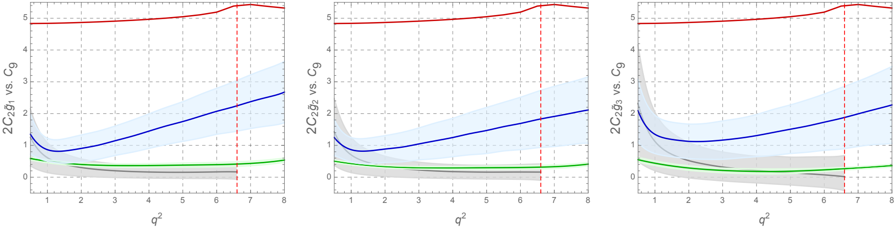


- Exploit info to determine the coefficients
    - Experimental info: discarded LHCb bins to fix J/ψ ans ψ' residues
    - Theoretical info: LCSR for $q^2 \leq 0$ (most accurate)

- Compute the observables
    - $c\bar{c}$ contribution in agreement with earlier estimates
    - P_5' for SM in disagreement with LHCb data
    - Agreement if $\mathcal{C}_9^{NP} \simeq -1.1$
    - Access to intermediate region between J/ψ and ψ'
    - Extension possible to other $b \to s\ell\ell$ modes

Charm-loop fit to $B \to K^* \ell\ell$ (1)

- $c\bar{c}$ contributions to 3 K^* helicity amplitudes $g_{1,2,3}$ as q^2-polynomial
- params from Bayesian fit to data [Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli]

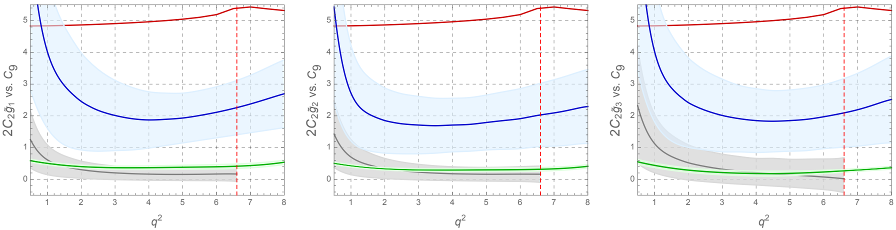


In units of $\mathcal{C}_9$: Short-Dist, QCDF, fit, KMPW $\Delta\mathcal{C}_9^{BK^*}$

- constrained fit: imposing SM + $\Delta\mathcal{C}_9^{BK^*}$ [Khodjamirian et al.] at $q^2 < 1$ GeV^2 yields q^2-dependent $c\bar{c}$ contribution, with "large" coefs for q^4

Charm-loop fit to $B \to K^* \ell\ell$ (1)

- $c\bar{c}$ contributions to 3 K^* helicity amplitudes $g_{1,2,3}$ as q^2-polynomial
- params from Bayesian fit to data [Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli]

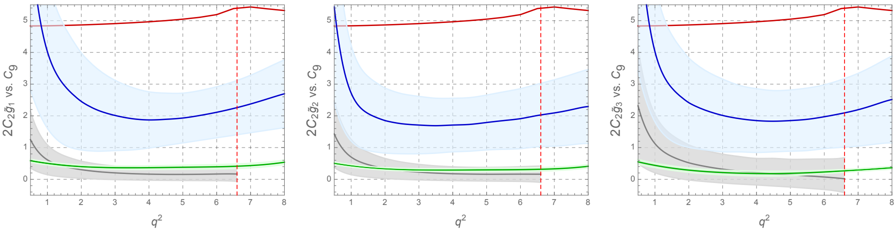


In units of $\mathcal{C}_9$: Short-Dist, QCDF, fit, KMPW $\Delta\mathcal{C}_9^{BK^*}$

- constrained fit: imposing SM + $\Delta\mathcal{C}_9^{BK^*}$ [Khodjamirian et al.] at $q^2 < 1$ GeV^2 yields q^2-dependent $c\bar{c}$ contribution, with "large" coefs for q^4
- unconstrained fit: polynomial agrees with $\Delta\mathcal{C}_9^{BK^*}$ + large cst $\mathcal{C}_9^{\rm NP}$ identical for all 3 helicity amplitudes

Charm-loop fit to $B \to K^*\ell\ell$ (1)

- $c\bar{c}$ contributions to 3 K^* helicity amplitudes $g_{1,2,3}$ as q^2-polynomial
- params from Bayesian fit to data [Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli]

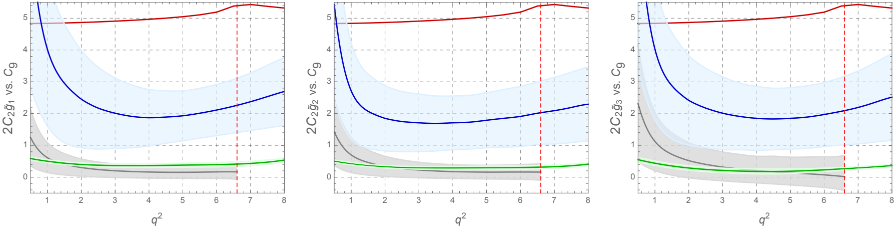


In units of $\mathcal{C}_9$: Short-Dist, QCDF, fit, KMPW $\Delta\mathcal{C}_9^{BK^*}$

- constrained fit: imposing SM + $\Delta\mathcal{C}_9^{BK^*}$ [Khodjamirian et al.] at $q^2 < 1$ GeV^2 yields q^2-dependent $c\bar{c}$ contribution, with "large" coefs for q^4
- unconstrained fit: polynomial agrees with $\Delta\mathcal{C}_9^{BK^*}$ + large cst $\mathcal{C}_9^{\rm NP}$ identical for all 3 helicity amplitudes
- constrained fit forced at low q^2, compensation skewing high q^2

Charm-loop fit to $B \to K^*\ell\ell$ (1)

- $c\bar{c}$ contributions to 3 K^* helicity amplitudes $g_{1,2,3}$ as q^2-polynomial
- params from Bayesian fit to data [Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli]



In units of $\mathcal{C}_9$: Short-Dist, QCDF, fit, KMPW $\Delta\mathcal{C}_9^{BK^*}$

- constrained fit: imposing SM + $\Delta\mathcal{C}_9^{BK^*}$ [Khodjamirian et al.] at $q^2 < 1$ GeV^2 yields q^2-dependent $c\bar{c}$ contribution, with "large" coefs for q^4
- unconstrained fit: polynomial agrees with $\Delta\mathcal{C}_9^{BK^*}$ + large cst $\mathcal{C}_9^{\rm NP}$ identical for all 3 helicity amplitudes
- constrained fit forced at low q^2, compensation skewing high q^2
- no dynamical hadronic explanation for enhancement at high q^2

Charm-loop fit to $B \to K^* \ell\ell$ (2)

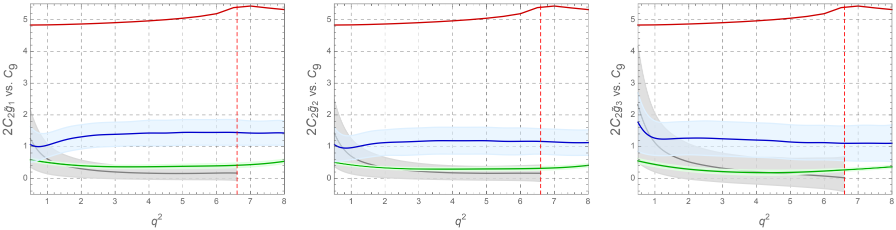
Problem related to q^4 contribution ? [Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli]

- strong q^2 dependence due to hadronic, not NP ?
- not clear: q^4 dependence already from $\mathcal{C}_i \times FF(q^2)$

Charm-loop fit to $B \to K^*\ell\ell$ (2)

Problem related to q^4 contribution ? [Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli]

- strong q^2 dependence due to hadronic, not NP ?
- not clear: q^4 dependence already from $\mathcal{C}_i \times FF(q^2)$



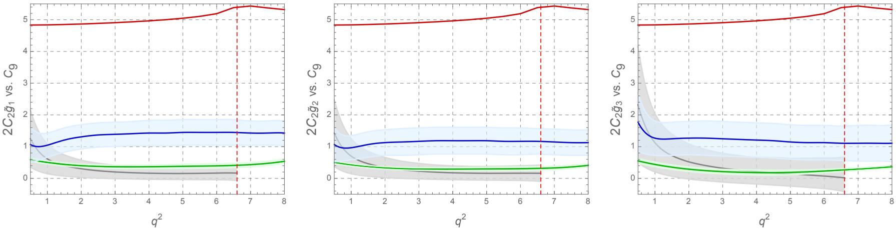
In units of $\mathcal{C}_9$: Short-Dist, QCDF, fit, KMPW $\Delta\mathcal{C}_9^{BK^*}$

- Bayesian fit without q^4 need same $\mathcal{C}_9^{\rm NP}$ in all three K^* helicities

Charm-loop fit to $B \to K^*\ell\ell$ (2)

Problem related to q^4 contribution ? [Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli]

- strong q^2 dependence due to hadronic, not NP ?
- not clear: q^4 dependence already from $\mathcal{C}_i \times FF(q^2)$



In units of $\mathcal{C}_9$: Short-Dist, QCDF, fit, KMPW $\Delta\mathcal{C}_9^{BK^*}$

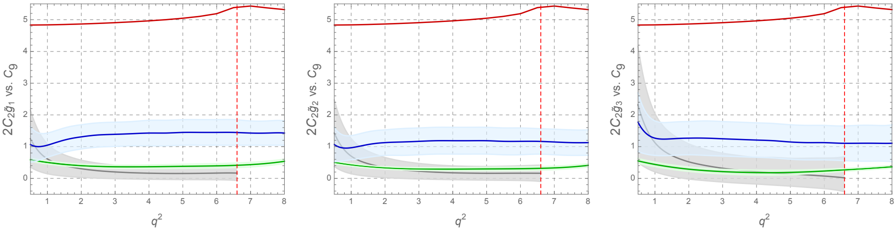
- Bayesian fit without q^4 need same $\mathcal{C}_9^{\rm NP}$ in all three K^* helicities
- Frequentist fits indicate no improvement by adding q^4 term, and adding $\mathcal{C}_9$ better pull than 12 independent coefficients

[Capdevila, Hofer, Matias, SDG; Hurth, Mahmoudi, Neshatpour]

Charm-loop fit to $B \to K^*\ell\ell$ (2)

Problem related to q^4 contribution ? [Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli]

- strong q^2 dependence due to hadronic, not NP ?
- not clear: q^4 dependence already from $\mathcal{C}_i \times FF(q^2)$



In units of $\mathcal{C}_9$: Short-Dist, QCDF, fit, KMPW $\Delta\mathcal{C}_9^{BK^*}$

- Bayesian fit without q^4 need same $\mathcal{C}_9^{\rm NP}$ in all three K^* helicities
- Frequentist fits indicate no improvement by adding q^4 term, and adding $\mathcal{C}_9$ better pull than 12 independent coefficients

[Capdevila, Hofer, Matias, SDG; Hurth, Mahmoudi, Neshatpour]

- if $c\bar{c}$, why same constant $\mathcal{C}_9^{\rm NP}$ for all mesons and helicities, which explanation for $R_{K^{(*)}}$, what causes deviations in low-recoil BRs ?

Charm-loop fit to $B \to K^*\ell\ell$ (3)

(Capdevila, Hofer, Matias, SDG)

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

- $s_i = 0$ means no contrib from long-distance $c\bar{c}$
- n order of the polynomial added, coeffs fit in frequentist framework
- testing nested hyp: pull from $\chi^{2(n-1)}_{\mathrm{min}} - \chi^{2(n)}_{\mathrm{min}}$ $\quad (\chi^{2(-1)}_{\mathrm{min}} = \mathrm{SM})$

n	0		1		2		3	
$B \to K^*\mu\mu$, $\mathcal{C}_9^{\mu,\mathrm{NP}} = 0$	2.88	(0.8 σ)	17.90	(3.5 σ)	0.08	(0.0 σ)	0.34	(0.1 σ)
$B \to K^*\mu\mu$, $\mathcal{C}_9^{\mu,\mathrm{NP}} = -1.1$	4.79	(1.3 σ)	9.73	(2.3 σ)	0.20	(0.0 σ)	0.39	(0.1 σ)
$b \to s\ell\ell$, $\mathcal{C}_9^{\mu,\mathrm{NP}} = 0$	1.55	(0.4 σ)	21.40	(3.9 σ)	0.61	(0.1 σ)		

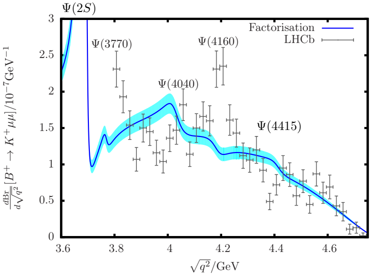
No need for high-order polyn or strong q^2-dep impossible with short distance contrib, contrary to claims by [Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli]

Charm-loop effects : resonances (1)

- 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]

Charm-loop effects : resonances (1)

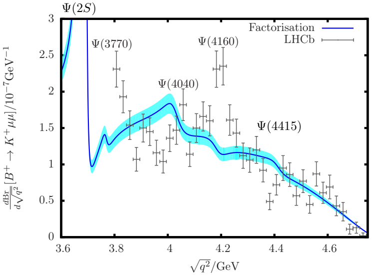
- Low recoil: quark-hadron duality
  - Average “enough” resonances to equate quark and hadron levels
  - Model estimate yield a few % for $BR(B \to K\mu\mu)$ [Beylich, Buchalla, Feldmann]



- 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]

Charm-loop effects : resonances (1)

- 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]

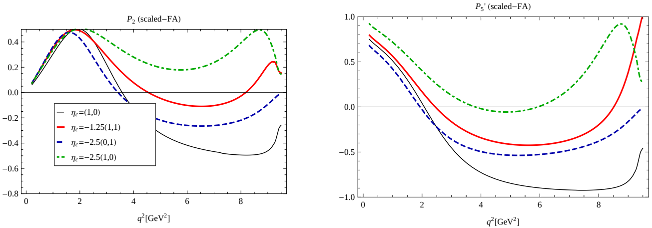
- Large recoil
  - $q^2 \leq$ 7-8 GeV^2 to limit the impact of J/ψ tail
  - Still need to include the effect of $c\bar{c}$ loop (tail of resonances + nonresonant)
  - LHCb on $B \to K\mu\mu$: resonance tails have very limited impact

Charm-loop effects : resonances (2)

On the basis of a model for $c\bar{c}$ resonances for low-recoil $B \to K\mu\mu$
[Zwicky and Lyon] proposed very large $c\bar{c}$ contrib for large-recoil $B \to K^*\mu\mu$

$$\mathcal{C}_9^{\rm eff} = \mathcal{C}_9^{SM} + \mathcal{C}_9^{\rm NP} + \eta h(q^2) \text{ and } \mathcal{C}_{9'} = \mathcal{C}_{9'}^{NP} + \eta' h(q^2)$$

where $\eta + \eta' = -2.5$ where conventional expectations are $\eta = 1, \eta' = 0$



- P_2 and P_5' could have more zeroes for $4 \le q^2 \le 9$ GeV^2
- $P'_{5[6,8]}$ would be above or equal to $P'_{5[4,6]}$, whereas global effects (like $\mathcal{C}_9^{\rm NP}$) predicts $P'_{5[6,8]} < P'_{5[4,6]}$ in agreement with experiment
- Not in agreement with LHCb findings for $B \to K\ell\ell$
- R_K and R_{K^*} unexplained since it would affect identically $\ell = e, \mu$