Anatomy of rare semileptonic B-decays: SM and beyond

Sebastian Jaeger

University of Sussex

Workshop on B decay anomalies, CERN, 18/05/2017

Outline

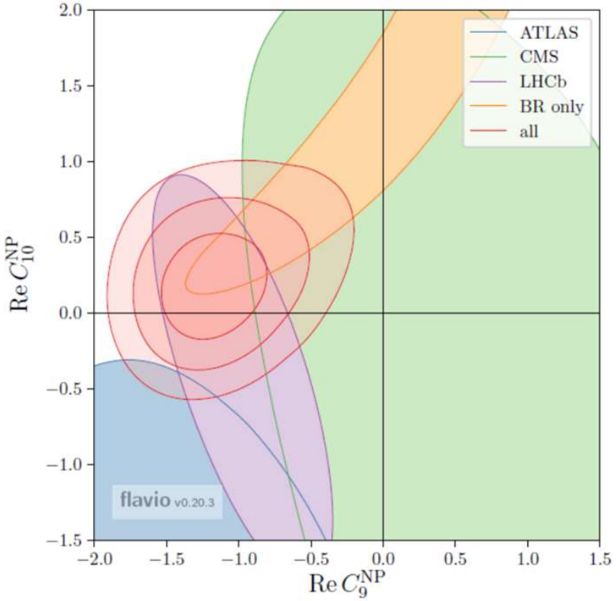
Structure of rare decay amplitudes

Anatomy of decay amplitudes, branching ratios and angular distribution

Lepton-universality ratios

Conclusions

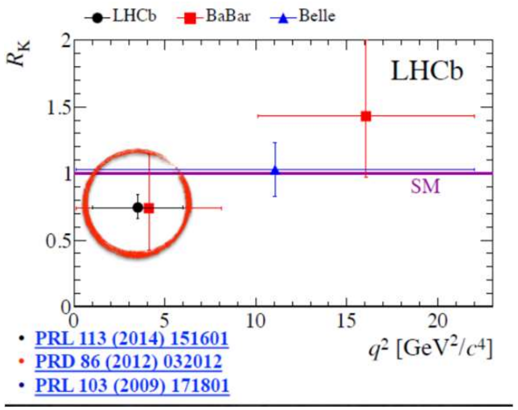
Rare B-decay Anomalies

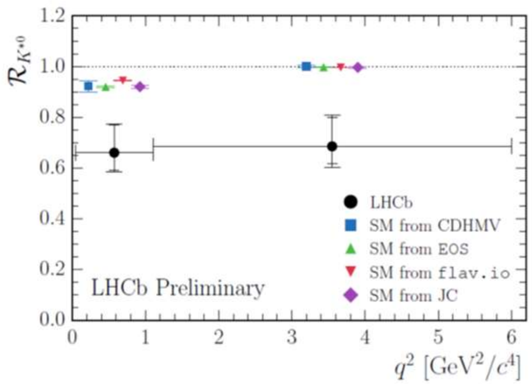


Global analysis of rare semileptonic decays (pre-RK*)

- several branching ratios seem low compared to SM expectation (orange)
- angular analysis in B->K* ll seems to disagree with SM expectations
- if SM Wilson coefficients are allowed to float, negative shift to C9 favoured

Altmannshofer et al 2017

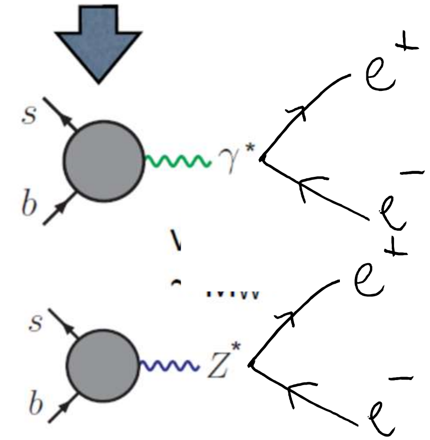




Evidence for a lepton-flavour-dependent effect in branching fractions (RK, RK*)

Weak Hamiltonian 1/2

in SM mainly



C_9 : dilepton from vector current (L=1)

$$Q_{9V} = \frac{\alpha_{\rm em}}{4\pi}(\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu l)$$

C_{10} : dilepton from axial current (L=1 or 0)

$$Q_{10A} = \frac{\alpha_{\rm em}}{4\pi}(\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu \gamma^5 l)_A$$

- both can be obtained from Z' exchanges
- or leptoquarks

Descotes-Genon et al; Altmannshofer et a
Crivellin et al; Gauld et al; ...

Alonso-Grinstein-Martin Camalich; Hiller-Schmaltz; Allanach et al; Gripajos et al; ...

C_7 : dilepton produced through photon (virtuality q^2, pole at q^2=0)

$$Q_{7\gamma} = \frac{e}{16\pi^2} m_b\,(\bar{s}\sigma_{\mu\nu} P_R b)F^{\mu\nu}$$

- strongly constrained from inclusive b->s decay

BSM: also parity-transformed operators (C_9', C_{10}', C_7')

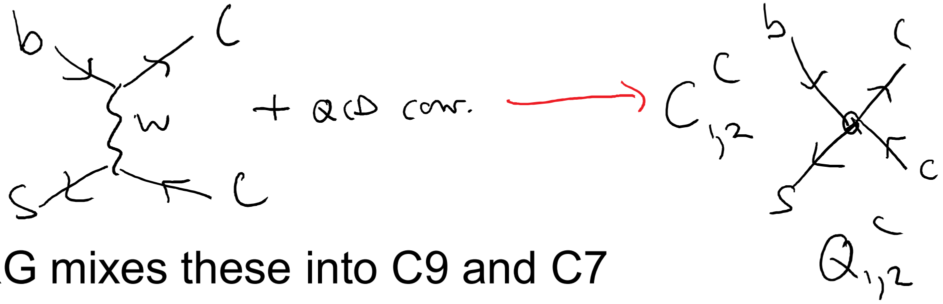
C_9, C_{10} can depend on the lepton flavour.

Universal BSM effects in C_9 mimicked by a range of SM effects

C10 effects or lepton-specific effects distinguishable from SM effects

Weak Hamiltonian 2/2

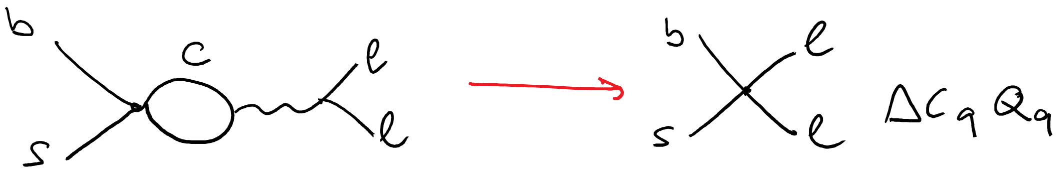
Also purely hadronic operators are important, primarily:



$$Q_1^c = (\bar{c}_L^i \gamma_\mu b_L^j)(\bar{s}_L^j \gamma^\mu c_L^i)$$

$$Q_2^c = (\bar{c}_L^i \gamma_\mu b_L^i)(\bar{s}_L^j \gamma^\mu c_L^j)$$

RG mixes these into C9 and C7



$$C_7^{\mathrm{eff}}(4.6\mathrm{GeV}) = 0.02\, C_1(M_W) - 0.19\, C_2(M_W)$$

$$C_9(4.6\mathrm{GeV}) = 8.48\, C_1(M_W) + 1.96\, C_2(M_W)$$

O(50%) of total in both cases

Induces strong scale dependence of C9 – must cancel inobservables.

At 4.6 GeV: C9(mu) ~ 4 C10 ~ -4 C7eff(mu) ~ -0.3

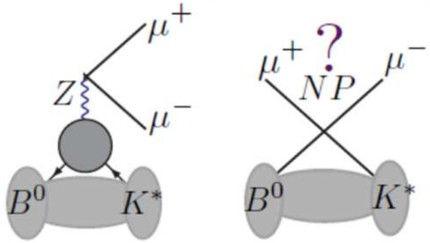
Chiral combinations: **CL = (C9-C10)/2 ~ 4** CR = (C9 + C10)/2 ~ 0

The near-vanishing of CR(4.6 GeV) is a complete numerical accident.

Decay amplitude structure

Two mechanisms to produce dilepton in & beyond SM

- via axial lepton current (in SM: Z, boxes) C10



K* helicity

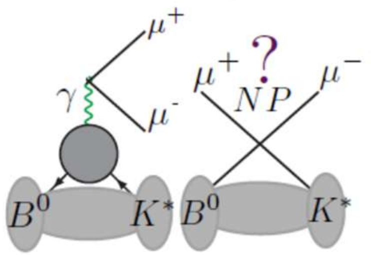
$$H_A(\lambda) \propto \boxed{\tilde{V}_\lambda(q^2)} C_{10} - V_{-\lambda}(q^2) C'_{10}$$

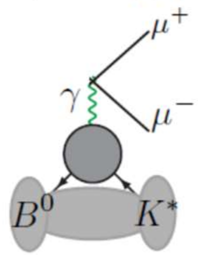
one form factor (nonperturbative) per helicity

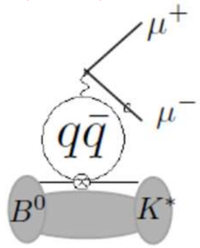
amplitudes factorize naively

[nb - one more amplitude if not neglecting lepton mass]

- via vector lepton current (in SM: (mainly) photon) C7, C9, hadronic hamiltonian







$$H_V(\lambda) \propto \tilde{V}_\lambda(q^2) C_9 - V_{-\lambda}(q^2) C'_9 + \boxed{\frac{2\, m_b m_B}{q^2}} \left(\tilde{T}_\lambda(q^2) C_7 - \tilde{T}_{-\lambda}(q^2) C'_7 \right) - \boxed{\frac{16\,\pi^2 m_B^2}{q^2}} h_\lambda(q^2)$$

photon pole at $q^2=0$

two form factors interfere for each helicity

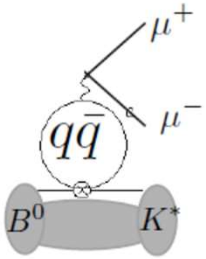
nonlocal "quark loops"
do **not** factorize naively

Natural, systematic discussion in terms of helicity amplitudes SJ, Martin Camalich 2012, 2014

Photon pole absent for helicity-0 (form factor rescaling)

Nonlocal term and heavy quark expansion

$$H_V(\lambda) \propto \tilde{V}_\lambda(q^2) C_9 - V_{-\lambda}(q^2) C_9' + \frac{2\, m_b m_B}{q^2}\left(\tilde{T}_\lambda(q^2) C_7 - \tilde{T}_{-\lambda}(q^2) C_7'\right) - \boxed{\frac{16\,\pi^2 m_B^2}{q^2}\, h_\lambda(q^2)}$$



+ strong interactions!

more properly:

$$\frac{e^2}{q^2} L_V^\mu a_\mu^{\rm had} = -i\frac{e^2}{q^2}\int d^4x e^{-iq\cdot x}\langle \ell^+\ell^-|j_\mu^{\rm em,lept}(x)|0\rangle \boxed{\int d^4y\, e^{iq\cdot y}\langle M|j^{\rm em,had,\mu}(y)\mathcal{H}_{\rm eff}^{\rm had}(0)|\bar{B}\rangle}$$

$$h_\lambda \equiv \frac{i}{m_B^2}\epsilon^{\mu *}(\lambda) a_\mu^{\rm had}$$

nonlocal, nonperturbative, large normalisation ($V_{cb}^* V_{cs}$ C_2)

traditional "ad hoc fix" : $C_9 \to C_9 + Y(q^2) = C_9^{\rm eff}(q^2)$, $C_7 \to C_7^{\rm eff}$ "taking into account the charm loop"

* for $C_7^{\rm eff}$ this seems ok at lowest order (pure UV effect; scheme independence)
* for $C_9^{\rm eff}$ amounts to factorisation of scales ~ m_b (, m_c ,q^2) and Λ (soft QCD)
* not justified in large-N limit (broken already at leading logarithmic order)
* what about QCD corrections?
* not a priori clear whether this even gets one closer to the true result!

only known justification is a heavy-quark expansion in Λ/m_b (just like inclusive decay is treated !)

Beneke, Feldmann, Seidel 2001, 2004

Nonlocal term and heavy quark expansion

traditional “ad hoc fix” : $C_9 \to C_9 + Y(q^2) = C_9^{eff}(q^2)$, $C_7 \to C_7^{eff}$

dominant effect: charm loop, proportional to ($z = 4\, m_c^2/q^2$)

$$-\frac{4}{9}\left(\ln\frac{m_q^2}{\mu^2} - \frac{2}{3} - z\right) - \frac{4}{9}(2+z)\sqrt{|z-1|}\begin{cases} \arctan\dfrac{1}{\sqrt{z-1}}, & z > 1, \\ \ln\dfrac{1+\sqrt{1-z}}{\sqrt{z}} - \dfrac{i\pi}{2}, & z \leqslant 1 \end{cases}$$

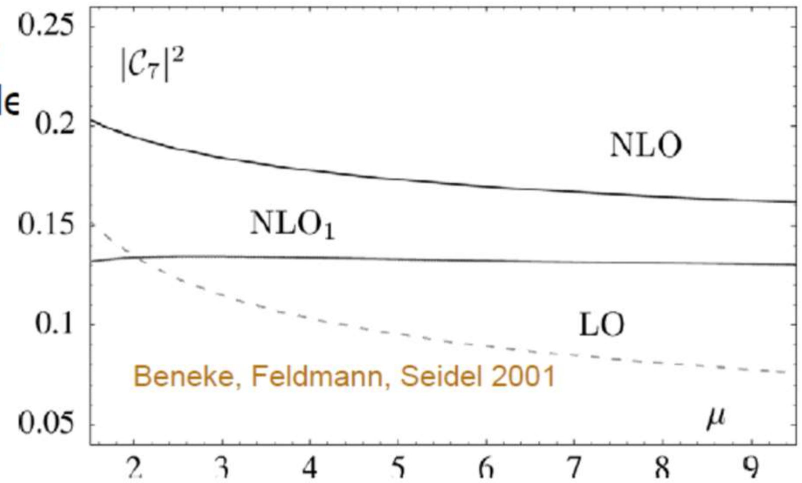
$$C_9^{\rm eff} = \begin{cases} 4.18|_{C_9} + (0.22 + 0.05i)|_Y & (m_c = m_c^{\rm pole} = 1.7{\rm GeV}) \\ 4.18|_{C_9} + (0.40 + 0.05i)|_Y & (m_c = m_c^{\overline{\rm MS}} = 1.2{\rm GeV}). \end{cases}$$

ie a 5% mass scheme ambiguity

separately, one has a residual scale ambiguity of order 30% at the level of the decay amplitude

resolved in the heavy-quark expansion (to leading power)

Beneke, Feldmann, Seidel 2001, 2004



Scalar branching ratio

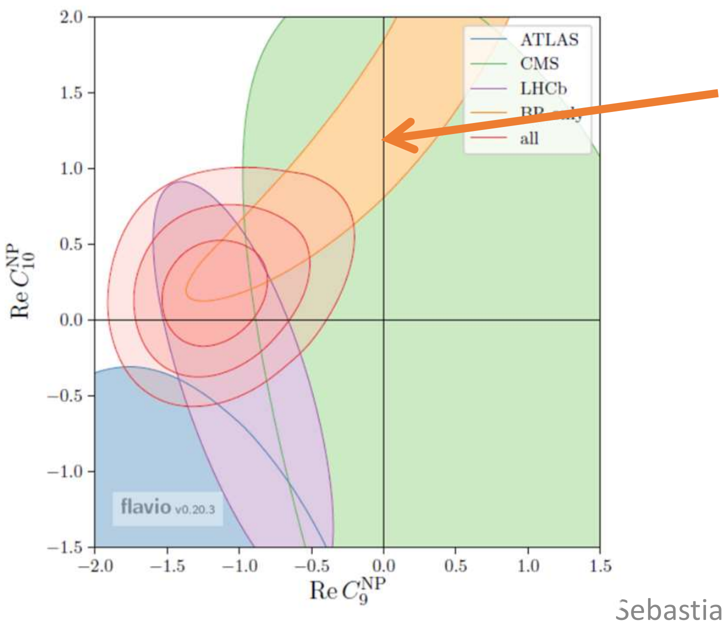
In this case only helicity zero, no photon pole, mild dilepton mass dependence

Schematically (neglecting some normalisations and small imaginary parts),

$$H_V = C_7 T + C_9 V + h \qquad\qquad H_A = C_{10} V$$

$$BR \propto (|H_V|^2 + |H_A|^2) = \frac{1}{2}(C_7 T + h_0 + 2 C_R V)^2 + \frac{1}{2}(C_7 T + h_0 + 2 C_L V)^2$$

Because C7 and CR are small in the SM, BR essentially is determined by the product CL* V. Weak sensitivity to CR (as long as small) or C7.

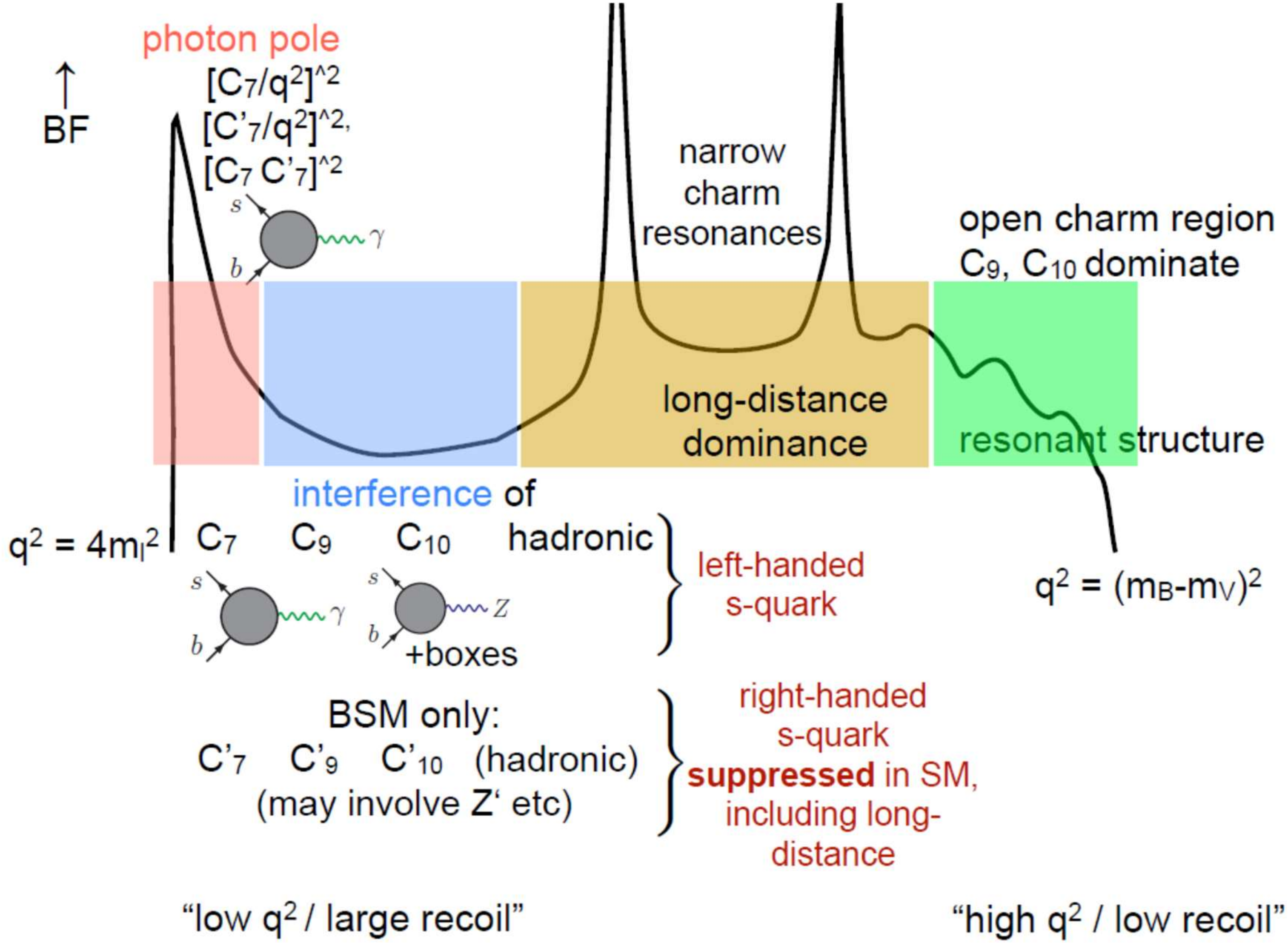


Explains the shape of the BR band: part of a circle around (-4, +4) (centre far outside plot region)

Suggests 20-25% suppression of CL w.r.t SM

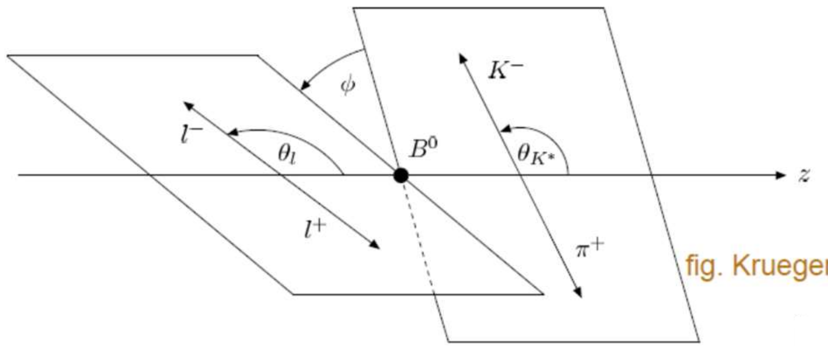
But perfectly degenerate with form factor V !
To interpret this as evidence of BSM physics need precision on V much better than 25%.
Form factor estimates from light-cone sum rules

B->V l l: rate (schematic)



B->V l l: angular distribution

Vector observed as two-particle spin-1 resonance. Six helicity amplitudes. Many angular observables



θ_K in K* rest frame

θ_l in dilepton cm frame

ϕ boost-invariant (w.r.t. z axis)

fig. Krueger, Matias 2002

$$\frac{d^{(4)}\Gamma}{dq^2\, d(\cos\theta_l) d(\cos\theta_k) d\phi} = \frac{9}{32\,\pi}$$

$$\times \Big(I_1^s \sin^2\theta_k + I_1^c \cos^2\theta_k + (I_2^s \sin^2\theta_k + I_2^c \cos^2\theta_k)\cos 2\theta_l$$
$$+ I_3 \sin^2\theta_k \sin^2\theta_l \cos 2\phi + I_4 \sin 2\theta_k \sin 2\theta_l \cos\phi$$
$$+ I_5 \sin 2\theta_k \sin\theta_l \cos\phi + (I_6^s \sin^2\theta_k + I_6^c \cos^2\theta_K)\cos\theta_l$$
$$+ I_7 \sin 2\theta_k \sin\theta_l \sin\phi + I_8 \sin 2\theta_k \sin 2\theta_l \sin\phi + I_9 \sin^2\theta_k \sin^2\theta_l \sin 2\phi \Big)$$

Angular observables

For zero mass there are the following independent observables:

$$I_2^c = -F\,\frac{\beta^2}{2}\left(|H_V^0|^2 + |H_A^0|^2\right),$$

$$I_2^s = F\,\frac{\beta^2}{8}\left(|H_V^+|^2 + |H_V^-|^2\right) + (V \to A)$$

"longitudinal" rate (sim. to scalar BR)

"transverse" rate

Usually reported as BR and FL

$$I_6^s = F\beta\,\mathrm{Re}\left[H_V^-(H_A^-)^* - H_V^+(H_A^+)^*\right]$$

Lepton forward-backward rate asymmetry

Usually reported as AFB or P2

$$I_4 = F\,\frac{\beta^2}{4}\mathrm{Re}\left[\left(H_V^- + H_V^+\right)\left(H_V^0\right)^*\right] + (V \to A).$$

$$I_5 = F\left\{\frac{\beta}{2}\mathrm{Re}\left[\left(H_V^- - H_V^+\right)\left(H_A^0\right)^*\right] + (V \leftrightarrow A)\right.$$

Often discuss P4' and P5' instead

$$I_3 = -\frac{F}{2}\mathrm{Re}\left[H_V^+(H_V^-)^*\right] + (V \to A)$$

$$I_9 = F\,\frac{\beta^2}{2}\mathrm{Im}\left[H_V^+(H_V^-)^*\right] + (V \to A)$$

Require presence of "wrong-helicity" amplitudes (suppressed in SM)

Probe right-handed currents

Forward-backward asymmetry / P2

The zero-crossing of $I_6^s = F\beta\,\mathrm{Re}\left[H_V^-(H_A^-)^* - H_V^+(H_A^+)^*\right]$ (or of AFB, or P2)

approximately coincides with that of HV-, because HV+ HA+ is doubly suppressed in the heavy-quark limit (and constrained by non-signal in I3, I9).

Have

$$H_V^- \propto \frac{2m_b^2}{q^2} C_7 T_- + C_9 V_- + h_-$$

Zero depends on form factor ratio T-/V- (besides on nonlocal term h-).
This ratio is calculable in the heavy-quark limit (in terms of meson LCDA's).

Charles et al 1999
Beneke, Feldmann 2000
...

Forms the basis for the 'optimised observables' (P2, P5', etc)

Descotes-Genon, Hofer, Matias, Virto

HQ limit: $T_-(0)/V_-(0) \sim 1.05 > 1$

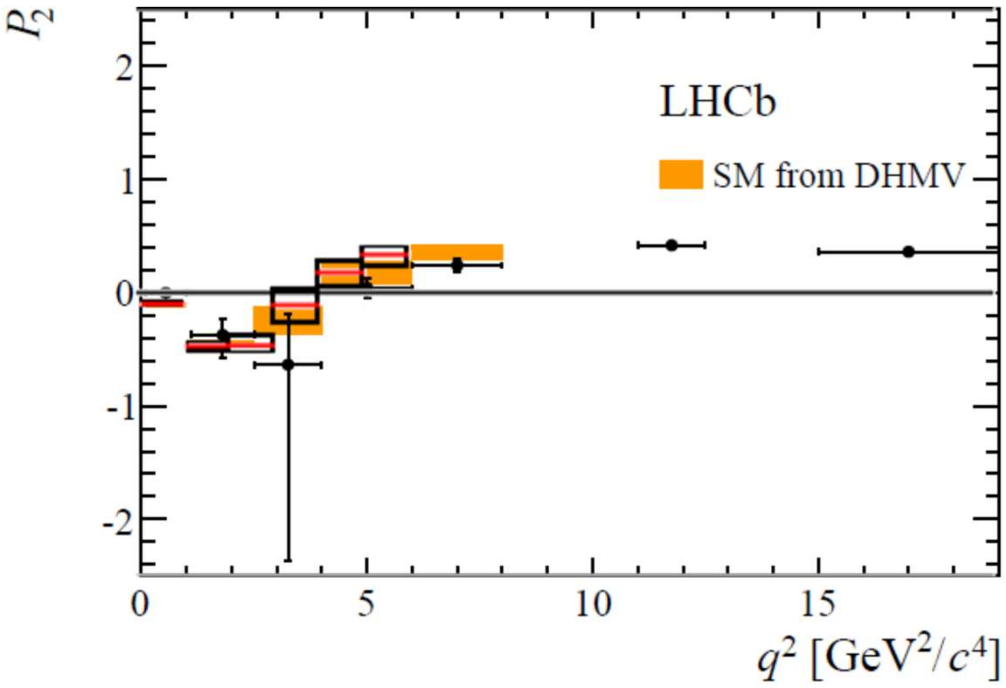
compare to: $T_-(0)/V_-(0) = 0.94 \pm 0.04$

[D Straub, priv comm based on Bharucha, Straub, Zwicky 1503.05534]

LCSR computation with correlated parameter variations.

Size consistent with a power correction; 5% uncertainty estimate.

P2 – theory vs data



arXiv:1512.04442 (LHCb)

Boxes – predictions from SJ, Martin Camalich 2014

(pure heavy-quark limit, general power correction parameterisation, varying in 10% range, Gaussian error combination)

Good agreement with data, even for pure heavy-quark limit with no power corrections (red lines)

P5'

Defined through $$P_5' = \frac{I_5}{\sqrt{-I_{2s}I_{2c}}}$$ Descotes-Genon, Hofer, Matias, Virto

$$I_5 = F\left\{\frac{\beta}{2}\mathrm{Re}\left[\left(H_V^- - H_V^+\right)\left(H_A^0\right)^*\right] + (V \leftrightarrow A)\right.$$

Approximately:

suppressed at 3-6 GeV2 (AFB zero)

proportional to C10

proportional to C9 x C10

$$I_2^c = -F\,\frac{\beta^2}{2}\left(|H_V^0|^2 + |H_A^0|^2\right),$$

Proportional to CL^2

$$I_2^s = F\,\frac{\beta^2}{8}\left(|H_V^+|^2 + |H_V^-|^2\right) + (V \to A)$$

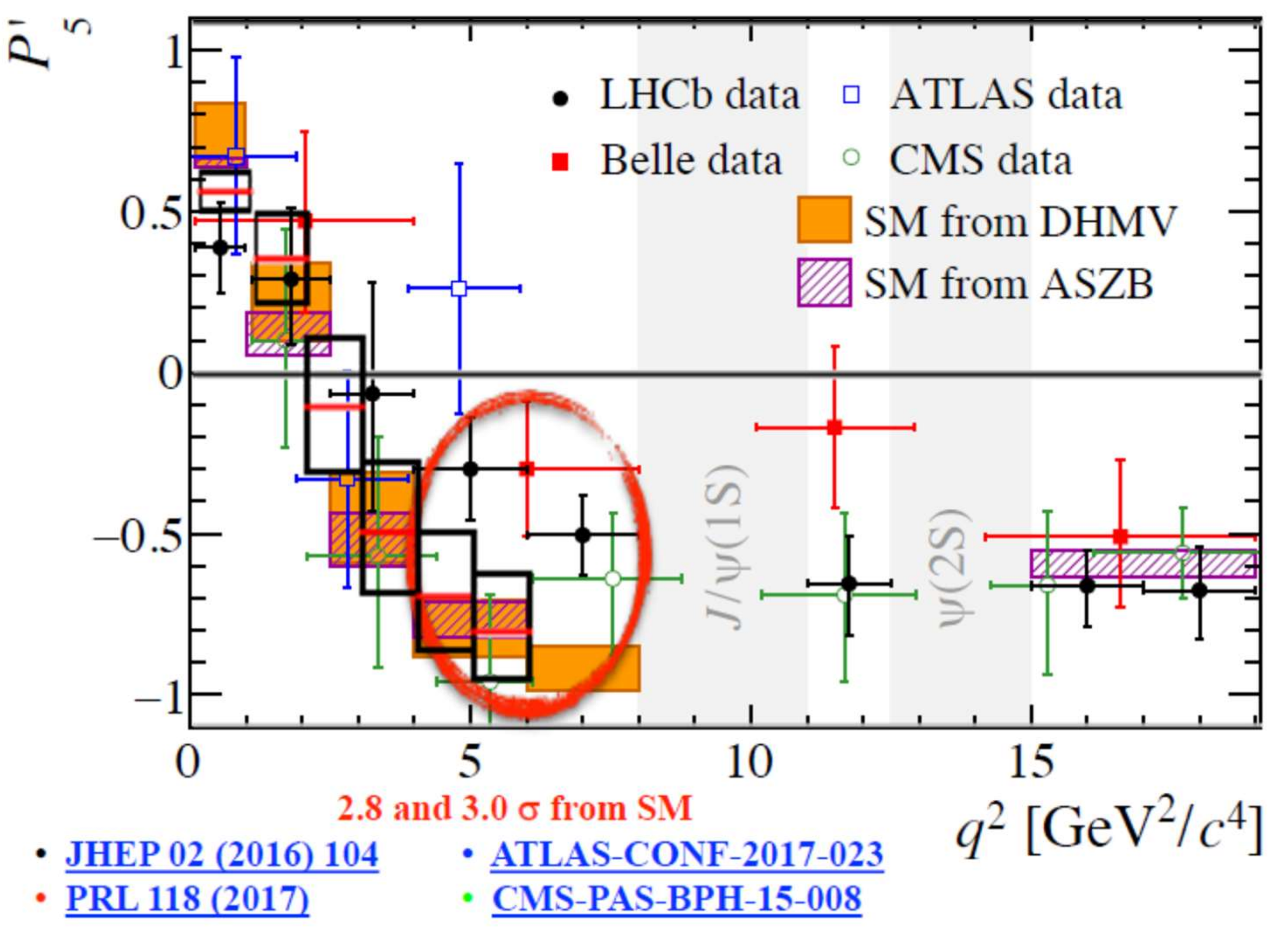
Dominated by axial amplitude

As a result, the C10 (as well as form factor) dependence largely cancels, and the observable is strongly dependent on C9 (very roughly proportional)

However, the number of independent hadronic inputs (for which power corrections must be estimated, LCSRs used, etc) is larger, because both transverse and longitudinal helicities enter.

Emphatic claims in literature that this does not matter Descotes-Genon et al; Capdevila et al

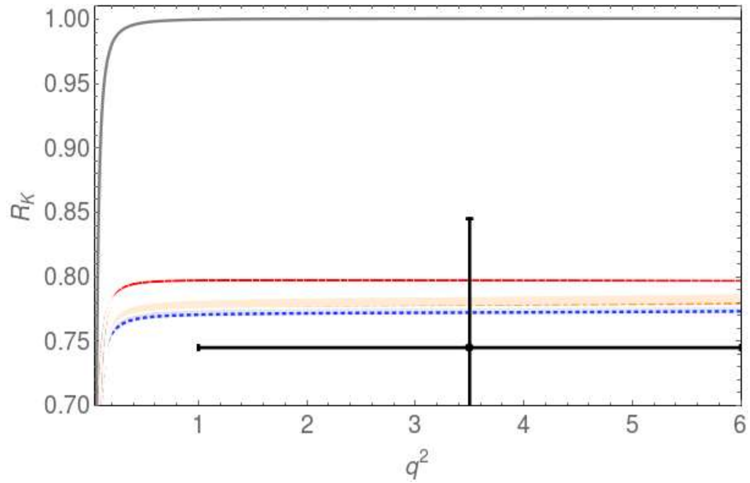
P5’

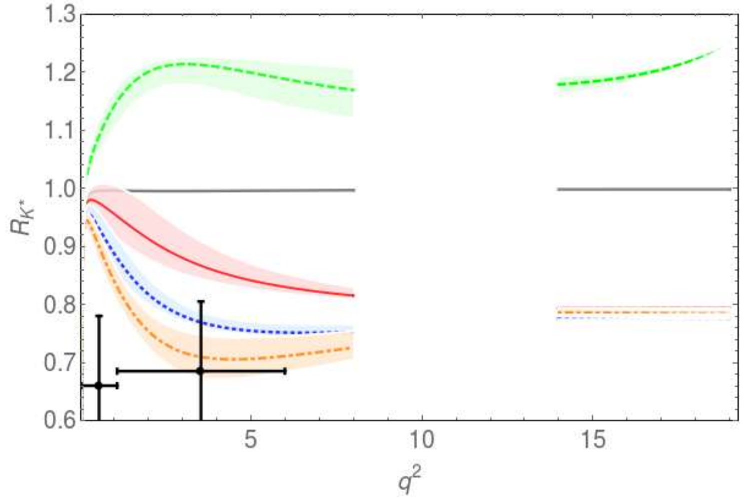


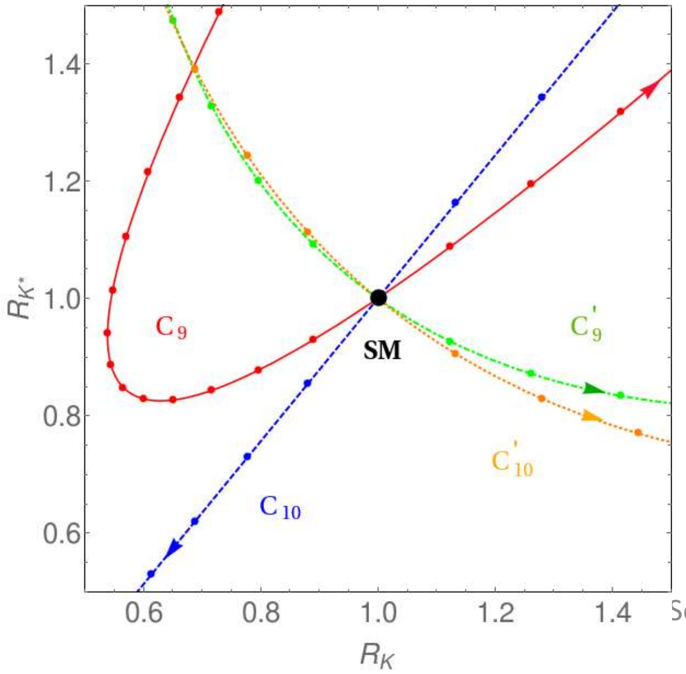
Simone Bifani, seminar at CERN (overlaid predictions from SJ&Martin Camalich 2014)

Modest discrepancy around 4-6 GeV, consistent with reduced C9

LUV measurements vs theory







Geng, Grinstein, SJ, Martin Camalich, Ren, Shi arxiv:1704.05446

Theory uncertainties completely negligible relative to experimental ones.

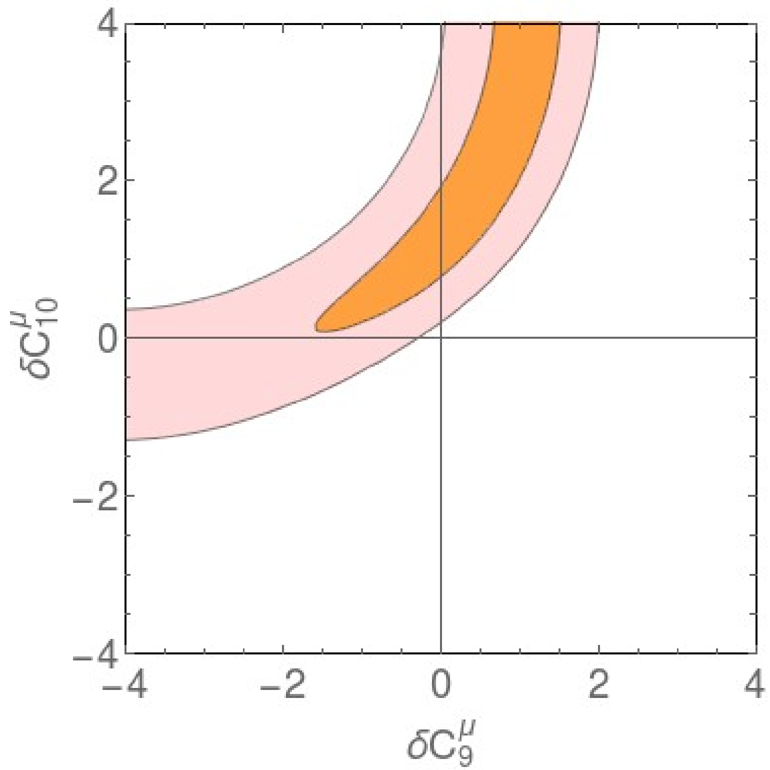
p(SM) = 2.1 x 10^-4 (3.7)

Suggests nonzero C10(BSM)

Pure LUV fit

Geng, Grinstein, SJ, Martin Camalich, Ren, Shi arxiv:1704.05446
Also Capdevila et al, Ciuchini et al, Altmannshofer et al, D'Amico et al, Hiller & Nisandzic

Obs.	Expt.	SM	$\delta C_L^\mu = -0.5$	$\delta C_9^\mu = -1$	$\delta C_{10}^\mu = 1$	$\delta C_9'^\mu = -1$
R_K [1, 6] GeV^2	0.745 ± 0.090	$1.0004^{+0.0008}_{-0.0007}$	$0.773^{+0.003}_{-0.003}$	$0.797^{+0.002}_{-0.002}$	$0.778^{+0.007}_{-0.007}$	$0.796^{+0.002}_{-0.002}$
R_{K^*} [0.045, 1.1] GeV^2	0.66 ± 0.12	$0.920^{+0.007}_{-0.006}$	$0.88^{+0.01}_{-0.02}$	$0.91^{+0.01}_{-0.02}$	$0.862^{+0.016}_{-0.011}$	$0.98^{+0.03}_{-0.03}$
R_{K^*} [1.1, 6] GeV^2	0.685 ± 0.120	$0.996^{+0.002}_{-0.002}$	$0.78^{+0.02}_{-0.01}$	$0.87^{+0.04}_{-0.03}$	$0.73^{+0.03}_{-0.04}$	$1.20^{+0.02}_{-0.03}$
R_{K^*} [15, 19] GeV^2	–	$0.998^{+0.001}_{-0.001}$	$0.776^{+0.002}_{-0.002}$	$0.793^{+0.001}_{-0.001}$	$0.787^{+0.004}_{-0.004}$	$1.204^{+0.007}_{-0.008}$



Theory uncertainties negligible.

1sigma and 3sigma confidence regions

C10(BSM)>0 favoured

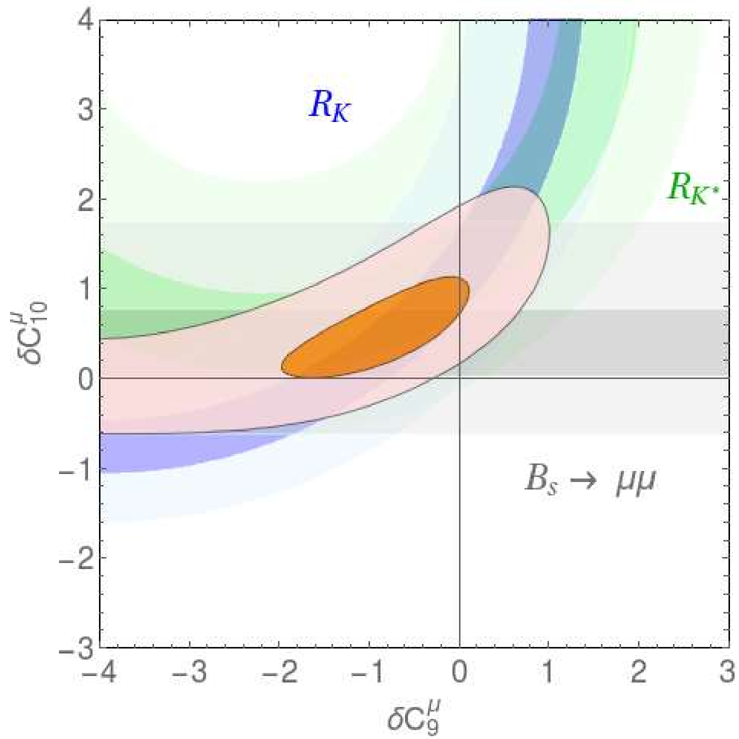
p = 0.158

SM pull 3.78 sigma

Considerable degeneracy (flat direction in chi2)

Adding Bs->mu mu

Geng, Grinstein, SJ, Martin Camalich, Ren, Shi arxiv:1704.05446



Selective probe of C10 (and C10')

Theory error negligible relative to exp (will hold till the end of HL-LHC !)

Considerably narrows the allowed fit region

p = 0.191

SM pull 3.76 sigma

Fit prefers nonzero CL = (C9-C10)/2

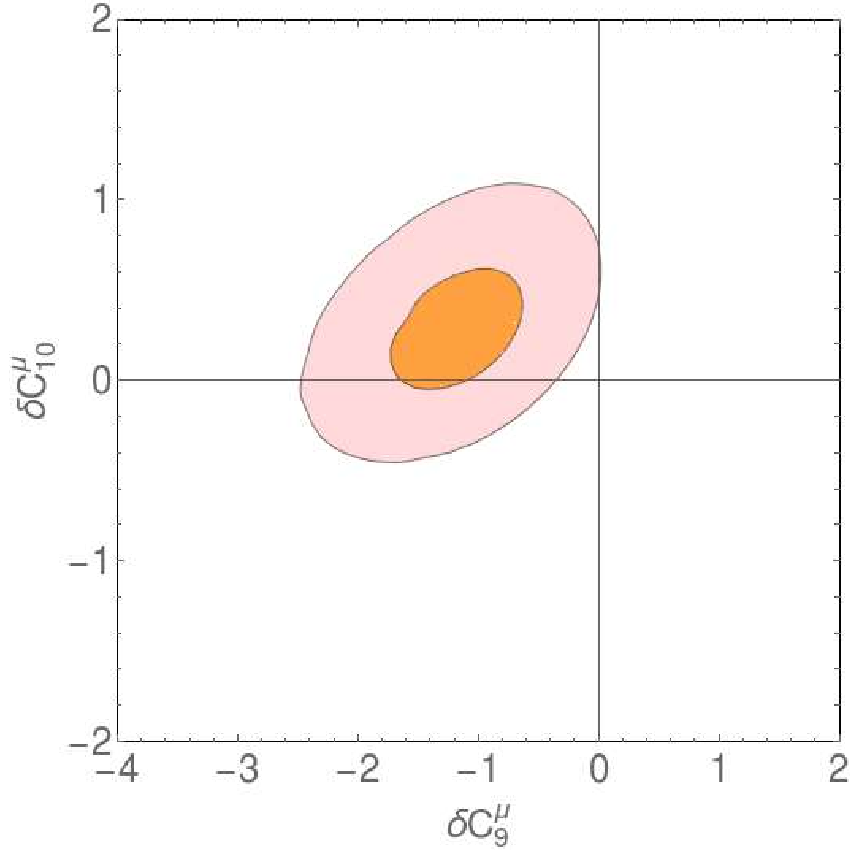
CR = (C9+C10)/2 not well constrained and consistent with zero

1-parameter CL fit: besf fit -0.61. 1sigma [-0.78, -0.41], p = 0.339

SM point (origin) excluded at 4.16 sigma

Adding B->K*mu mu angular

Geng, Grinstein, SJ, Martin Camalich, Ren, Shi arxiv:1704.05446



Serves to determine best-fit region even better.

SM pull 4.17 sigma

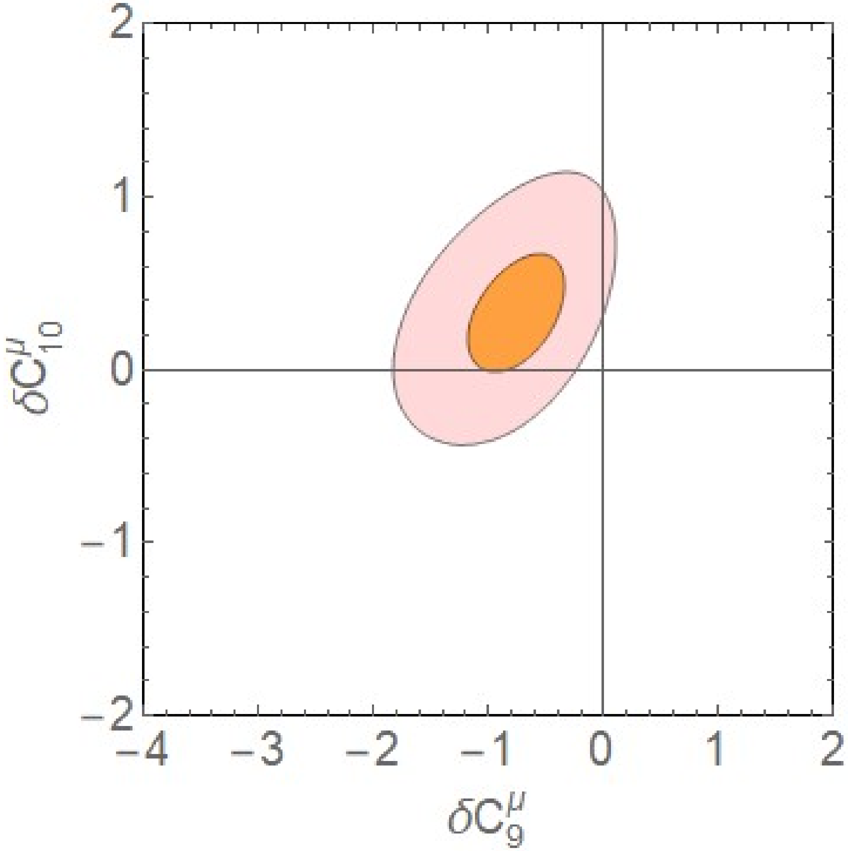
p = 0.572

(but p(SM) now up to to 0.086)

Wilson coefficient value CL=0 again excluded at high confidence.

Adding B->K*e e BR & angular

Geng, Grinstein, SJ, Martin Camalich, Ren, Shi arxiv:1704.05446



(preliminary)

Serves to determine best-fit region even better.

Similar significance and pull as before

Wilson coefficient value CL=0 again excluded at high confidence.

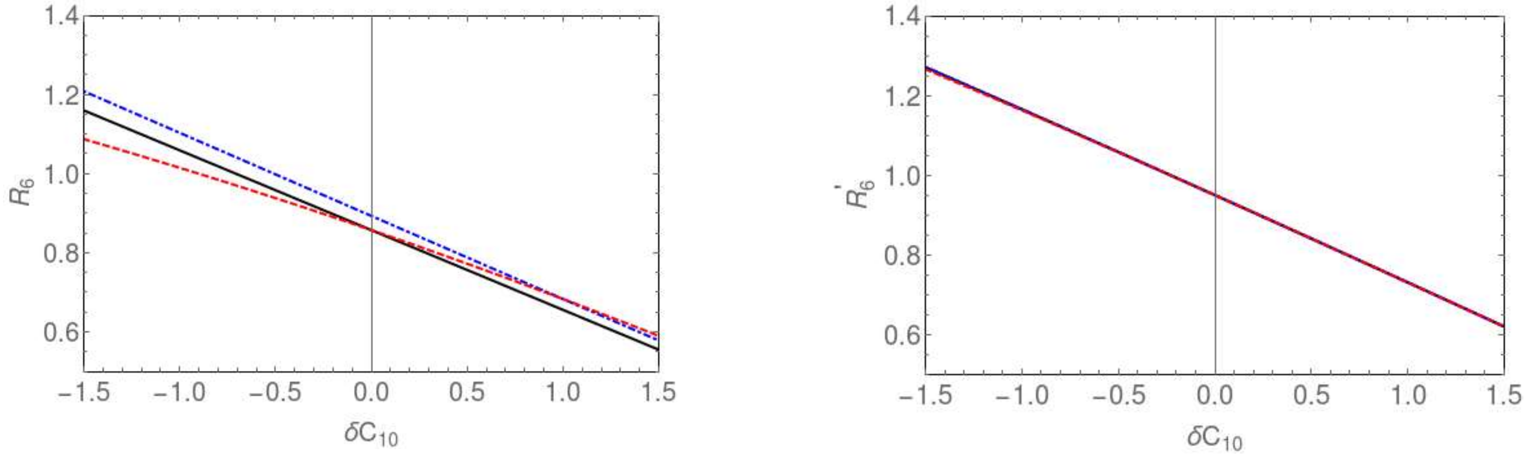
Determining CR (break C9/C10 degeneracy)

Geng, Grinstein, SJ, Martin Camalich, Ren, Shi arxiv:1704.05446

Propose to measure observable

$$R_6[a,b] = \frac{\int_a^b \Sigma_6^\mu dq^2}{\int_a^b \Sigma_6^e dq^2} \approx \frac{C_{10}^\mu}{C_{10}^e} \times \frac{\int_a^b |\vec{k}|q^2\beta_\mu^2\,\mathrm{Re}[H_{V-}^{(\mu)}(q^2)]V_-(q^2)}{\int_a^b |\vec{k}|q^2\,\mathrm{Re}[H_{V-}^{(e)}(q^2)]V_-(q^2)}$$

and/or $R_6' = \langle P_2^{(\mu)}\rangle / \langle P_2^{(e)}\rangle$

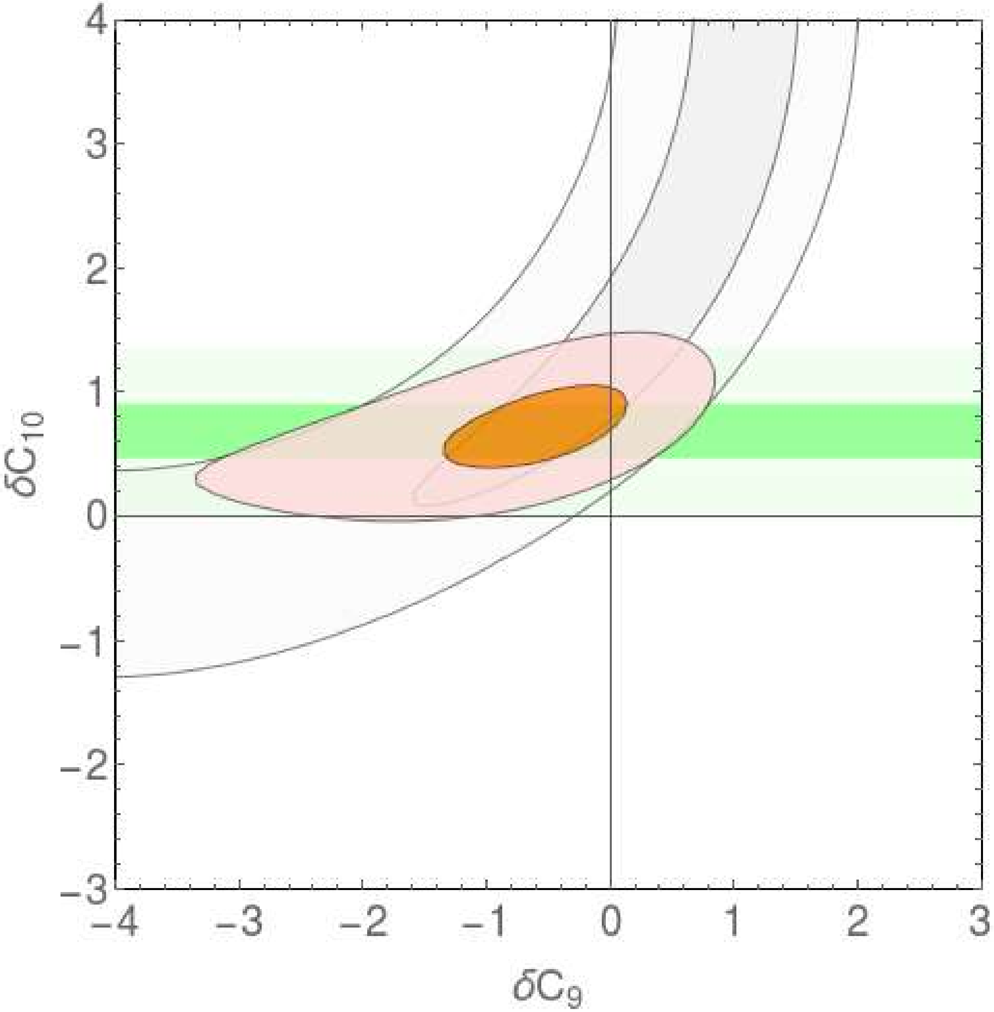


Remains very clean in presence of new physics.
Probes a LUV C10 precisely, irrespective of values of C9e, C9mu

Prospective fit with LUV obs. only

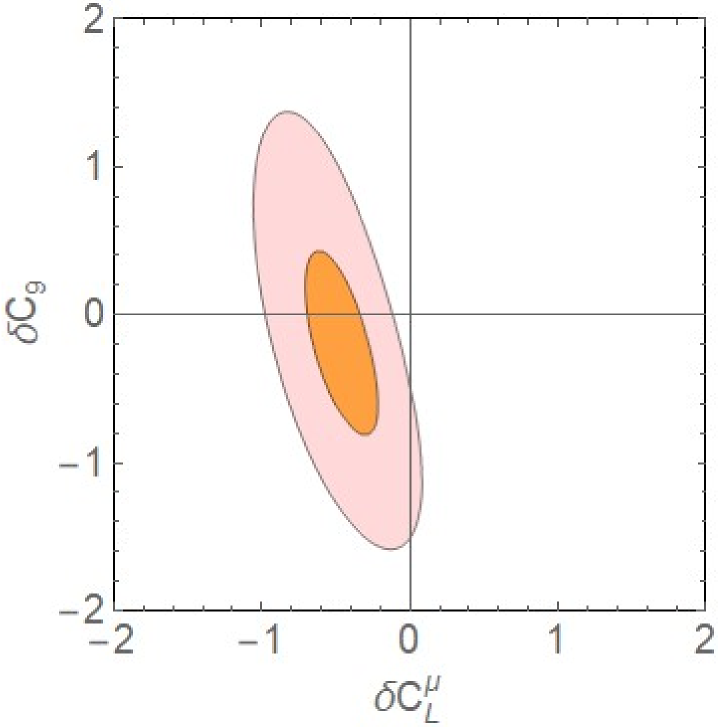
Geng, Grinstein, SJ, Martin Camalich, Ren, Shi arxiv:1704.05446

Consider a hypothetical experimental result R6' = 0.80(5)



Must C9 show LUV ?

Geng, Grinstein, SJ, Martin Camalich, Ren, Shi arxiv:1704.05446



Modified C10 needed to suppress RK* (both bins)

Preference for modified C9 (over C10) is due to angular observables in B->K* mu mu

This means a model with (for example) nonzero CLmu and in addition an ordinary, **lepton-flavour-universal, C9**, can describe the data similarly well or better

Eg. ‘charming BSM’ scenario

SJ, Kirk, Lenz, Leslie arXiv:1701.09183

Conclusions

Rare B-decays show numerous intriguing anomalies.

Branching ratios and angular distribution very sensitive to specific BSM Wilson coefficient combinations; but require precise control over weak decay form factors and non-factorizable corrections ("charm loop," …)

Significance of the SM exclusion in the global fit depends quite sensitively on what is assumed.

Lepton-universality ratios provide theoretically unassailable probes of new physics. Current data disagrees with SM at ca 4 sigma significance. Favours coupling to left-handed muons. Disentangling C9 from C10 may be possible with future angular measurements at LHCb (and beyond)

Backup

Form factors

Helicity amplitudes naturally involve "helicity" form factors

$$-im_B\tilde{V}_{L(R)\lambda}(q^2) = \langle M(\lambda)|\bar{s}\not{\epsilon}^*(\lambda)P_{L(R)}b|\bar{B}\rangle,$$
$$m_B^2\tilde{T}_{L(R)\lambda}(q^2) = \epsilon^{*\mu}(\lambda)q^\nu\langle M(\lambda)|\bar{s}\sigma_{\mu\nu}P_{R(L)}b|\bar{B}\rangle$$
$$im_B\tilde{S}_{L(R)}(q^2) = \langle M(\lambda=0)|\bar{s}P_{R(L)}b|\bar{B}\rangle.$$

~ Bharucha/Feldmann/Wick 2010

definitions here:
SJ, Martin Camalich 2012

- can be expressed as linear combinations of traditional "transversity" FFs, bringing in dependence on q^2 and meson masses - intransparent.
(However S is essentially A_0 in the traditional nomenclature.)

- **directly relevant** to B->V l l including the LHCb anomaly
in particular, **V_-/T_- determines of the zero crossing of both A_{FB} and of S_5/P_5', as far as form factors are concerned**

(Burdman; Beneke/Feldmann/Seidel)
SJ, Martin Camalich 2012,2014, this talk and WIP

- helicity+ vanishes at q^2=0, in particular
$$T_+(q^2=0)=0$$
implying several clean null tests of the SM

Burdman, Hiller 2000
SJ, Martin Camalich 2012

difficult to calculate - lattice cannot cover small q^2 (plus other issues)
best shot: light-cone sum rules with continuum subtractions

Form factor relations

At most 1-2% over entire 0..6 GeV^2 range -> ignore

$$F(q^2) = F^\infty(q^2) + a_F + b_F q^2/m_B^2 + \mathcal{O}([q^2/m_B^2]^2)$$

heavy quark limit

Power corrections - parameterise

$$F^\infty(q^2) = F^\infty(0)/(1 - q^2/m_B^2)^p + \Delta_F(\alpha_s; q^2)$$

(Charles et al) (Beneke, Feldmann)

q^2 dependence in heavy-quark limit not known (model by a power p, and/or a pole model)

$V_+^\infty(0) = 0$ $T_+^\infty(0)=0$
$V_-^\infty(0) = T_-^\infty(0)$
$V_0^\infty(0) = T_0^\infty(0)$

from heavy-quark/ large energy symmetry

Corrections are calculable in terms of perturbation theory, decay constants, light cone distribution amplitudes

$V_+^\infty(q^2) = 0$ $T_+^\infty(q^2)=0$

hence

$$\begin{aligned} T_+(q^2) &= \mathcal{O}(q^2) \times \mathcal{O}(\Lambda/m_b) \\ V_+(q^2) &= \mathcal{O}(\Lambda/m_b). \end{aligned}$$

- **"naively factorizing" part of the helicity amplitudes $H_{V,A}^+$ strongly suppressed** as a consequence of chiral SM weak interactions
- We see the suppression is **particularly strong** near low-q^2 endpoint
- Form factor relations imply reduced uncertainties in suitable observables

Burdman, Hiller 1999 (quark picture)

Beneke, Feldmann, Seidel 2001 (QCDF)

Power corrections

SJ, Martin Camalich 1412.3183

Compare

$$P_5' = P_5'|_\infty \left(1 + \frac{a_{V_-} - a_{T_-}}{\xi_\perp} \frac{m_B}{|\vec{k}|} \frac{m_B^2}{q^2} C_7^{\rm eff} \frac{C_{9,\perp} C_{9,\|} - C_{10}^2}{(C_{9,\perp}^2 + C_{10}^2)(C_{9,\perp} + C_{9,\|})} \right.$$
$$+ \frac{a_{V_0} - a_{T_0}}{\xi_\|} 2\, C_7^{\rm eff} \frac{C_{9,\perp} C_{9,\|} - C_{10}^2}{(C_{9,\|}^2 + C_{10}^2)(C_{9,\perp} + C_{9,\|})}$$
$$\left. + 8\pi^2 \frac{\tilde{h}_-}{\xi_\perp} \frac{m_B}{|\vec{k}|} \frac{m_B^2}{q^2} \frac{C_{9,\perp} C_{9,\|} - C_{10}^2}{C_{9,\perp} + C_{9,\|}} + \text{further terms} \right) + \mathcal{O}(\Lambda^2/m_B^2)$$

(truncated after 3 out of 11 independent power-correction terms!)
also, dependence on soft form factors reappears at PC level

and

$$P_1 = \frac{1}{C_{9,\perp}^2 + C_{10}^2} \frac{m_B}{|\vec{k}|} \left(-\frac{a_{T_+}}{\xi_\perp} \frac{2\, m_B^2}{q^2} C_7^{\rm eff} C_{9,\perp} - \frac{a_{V_+}}{\xi_\perp} (C_{9,\perp} C_9^{\rm eff} + C_{10}^2) - \frac{b_{T_+}}{\xi_\perp} 2 C_7^{\rm eff} C_{9,\perp} \right.$$
$$\left. - \frac{b_{V_+}}{\xi_\perp} \frac{q^2}{m_B^2} (C_{9,\perp} C_9^{\rm eff} + C_{10}^2) + 16\pi^2 \frac{h_+}{\xi_\perp} \frac{m_B^2}{q^2} C_{9,\perp} \right) + \mathcal{O}(\Lambda^2/m_B^2).$$

(complete expression)

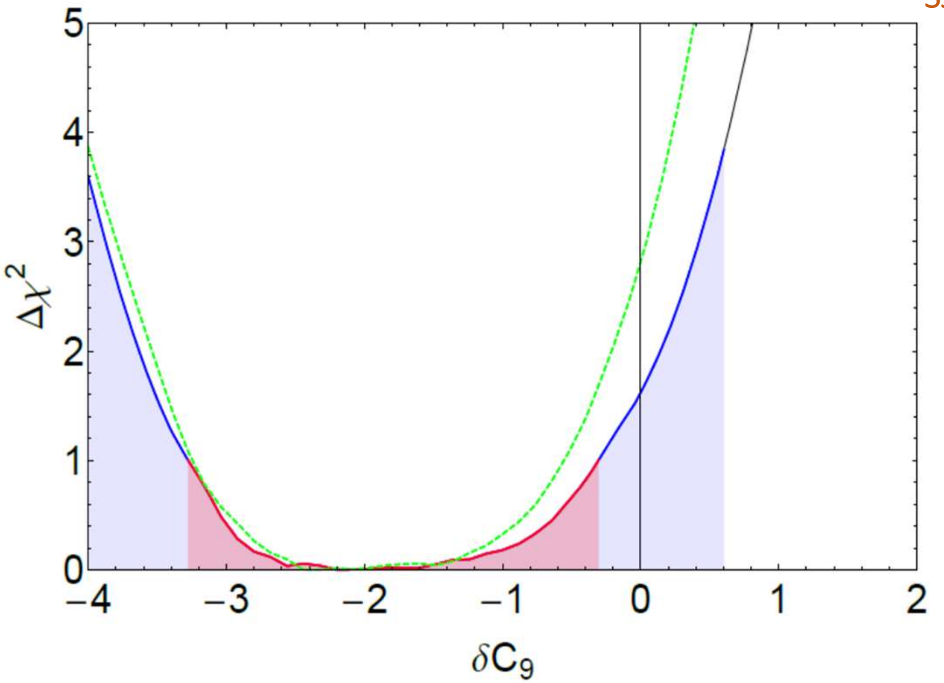
Further notice that a_{T+} vanishes as $q^2 \to 0$, h_+ helicity suppressed [will show], and the other three terms lacks the photon pole.

Hence P_1 **much** cleaner than P_5', especially at very low q^2

C9 sensitivity w/o light-cone sum rules

Most general parameterisation of power correction to the heavy-quark limit; varying each parameter at 10% of ‘natural’ leading-power effect; profile likelihood

SJ, Martin Camalich 2012, 2014



from SJ, Martin Camalich 1412.3183 (angular obs. with 1 fb^-1 LHCb data)

two paramerterisation

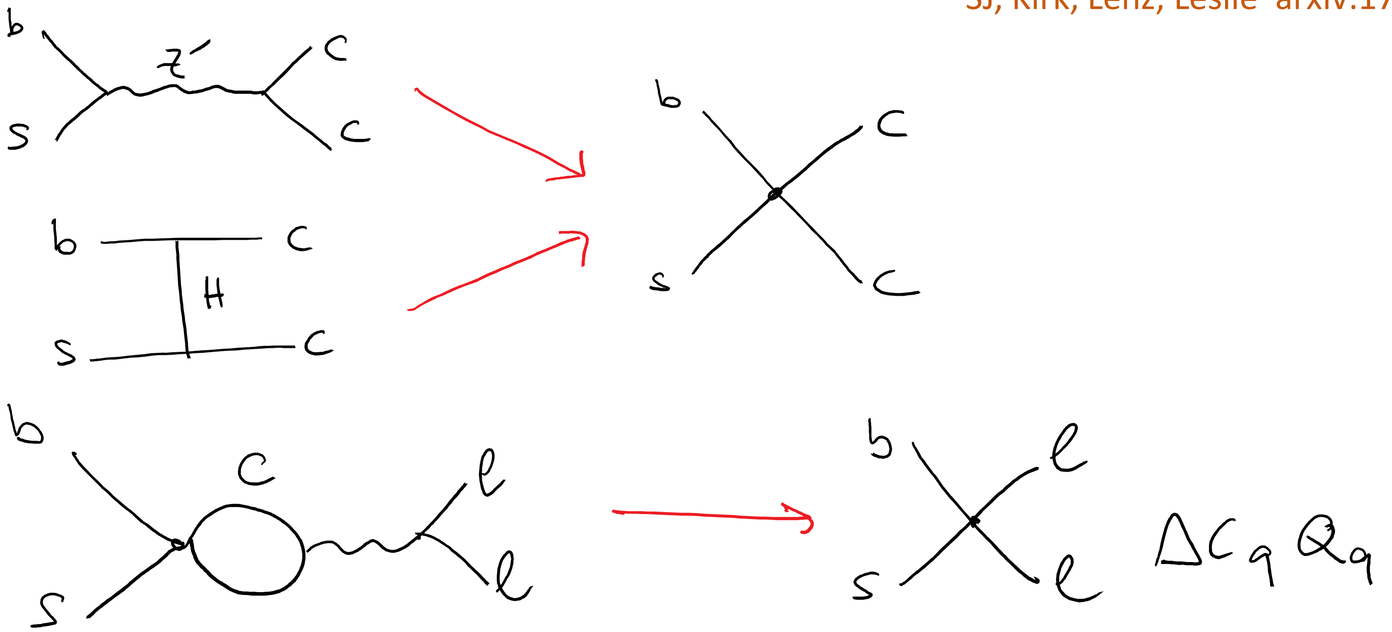
schemes (green, blue)

Preference for C9<C9SM, with modest significance

Can generate from 4-quark operators

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

e.g.



efficient way to generate C9(NP) = O(1)

“Charming BSM scenario”

I have (...) heard on good authority that I was dead. (…) The report of my death was an exaggeration.

As we just saw, LUV does allow such a scenario, and may even favour it. We will see that it remains alive in light of other data.

Charming BSM scenario

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

As long as NP mass scale M is >(>) mb, **model-independently** captured by an effective Hamiltonian with 20 operators/Wilson coefficients (including C1, C2 of SM)

$$
\begin{aligned}
Q_1^c &= (\bar{c}_L^i \gamma_\mu b_L^j)(\bar{s}_L^j \gamma^\mu c_L^i), & Q_2^c &= (\bar{c}_L^i \gamma_\mu b_L^i)(\bar{s}_L^j \gamma^\mu c_L^j), \\
Q_3^c &= (\bar{c}_R^i b_L^j)(\bar{s}_L^j c_R^i), & Q_4^c &= (\bar{c}_R^i b_L^i)(\bar{s}_L^j c_R^j), \\
Q_5^c &= (\bar{c}_R^i \gamma_\mu b_R^j)(\bar{s}_L^j \gamma^\mu c_L^i), & Q_6^c &= (\bar{c}_R^i \gamma_\mu b_R^i)(\bar{s}_L^j \gamma^\mu c_L^j), \\
Q_7^c &= (\bar{c}_L^i b_R^j)(\bar{s}_L^j c_R^i), & Q_8^c &= (\bar{c}_L^i b_R^i)(\bar{s}_L^j c_R^j), \\
Q_9^c &= (\bar{c}_L^i \sigma_{\mu\nu} b_R^j)(\bar{s}_L^j \sigma^{\mu\nu} c_R^i), & Q_{10}^c &= (\bar{c}_L^i \sigma_{\mu\nu} b_R^i)(\bar{s}_L^j \sigma^{\mu\nu} c_R^j),
\end{aligned}
$$

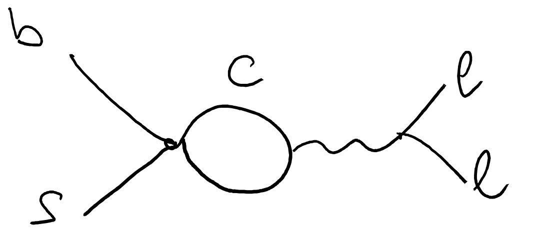
+ parity conjugates

virtual-charm BSM previously considered by

He, Tandean, Valencia (2009) (in a model; did not consider semilept/radiative decays)
Lyon&Zwicky (2014) (as a possible origin of the observed resonance structure in the open-charm region in B->Kmumu)

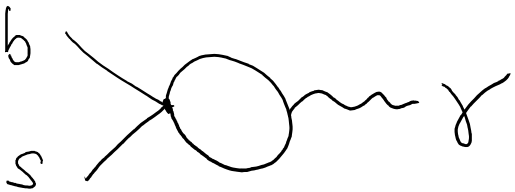
Observables

SJ, Kirk, Lenz, Leslie arxiv:1701.09183



$$\Delta C_9^{\rm eff}(q^2) = \left(C_{1,2}^c - \frac{C_{3,4}^c}{2}\right) h(q^2, m_c, \mu) - \frac{2}{9} C_{3,4}^c$$

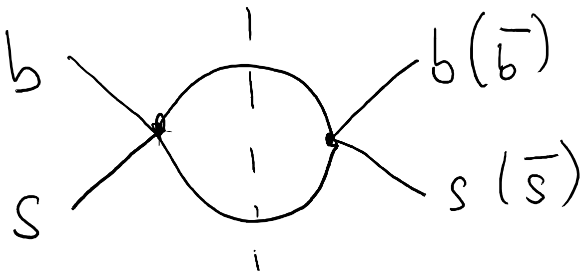
$$C_{x,y}^c = 3\Delta C_x + \Delta C_y$$



$$\Delta C_7^{\rm eff}(q^2) = \frac{m_c}{m_b}\left[(4C_{9,10}^c - C_{7,8}^c) y(q^2, m_c, \mu) + \frac{4\,C_{5,6}^c - C_{7,8}^c}{6}\right]$$

note that h and y are q2-dependent

At one loop, radiative decay constrains C5..C10, but not C1..C4.
Focus on the latter. Then consider lifetime (mixing) observables

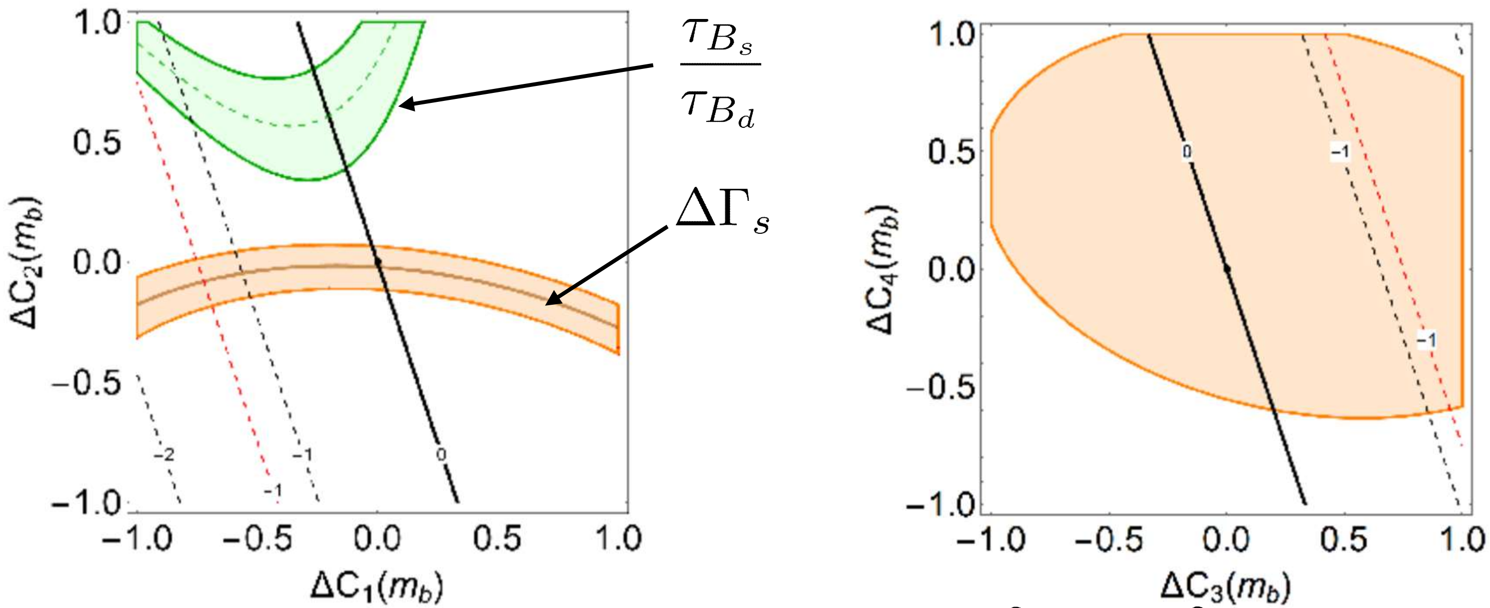


$\Delta\Gamma_s$ and τ_{B_s}/τ_{B_d} calculable in OPE
for general C1 .. C4

Phenomenology – low NP scale

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

If ln(M/m_B) not large, higher-order corrections (including RGE effects) small.
Can set $\mu \sim m_B, m_b$ (we choose mu = 4.6 GeV).



Straight lines: $\Delta C_9(q^2)$ contours. Red dotted: q^2=2 GeV^2, black: 5 GeV^2.

Can easily accommodate P5' anomaly while satisfying width difference.

Note that the lifetime ratio is not well consistent with the SM. Could reconcile with CBSM physics, but never consistent with width difference.

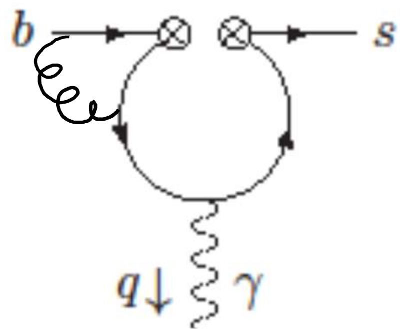
High new physics scale

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

If ln(M/m_B) >> 1 then should resum to all orders.

Technically, RG-evolve the Wilson coefficients from μ ~M to μ~ m_B
q2 dependence now a *subleading* (NLL) effect.

For C1 .. C4, leading order is
2-loop for b->s gamma (C7eff)



Technically nontrivial
(spurious IR divergences, scheme dependence of diagrams, spurious gauge-noninvariant terms, etc).

Follow method of Chetyrkin, Misiak, Muenz NPB 518 (1998) 473, hep-ph/9711266

End result gauge- and scheme-independent if expressed in terms of the scheme-independent coefficient C_7^{eff} (which enters observables).

RGE evolution - numerical

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

For evolution from MW to 4.6 GeV: (l.h.s. at 4.6 GeV, r.h.s. at MW)

$$\Delta C_7^{\rm eff} = 0.02\Delta C_1 - 0.19\Delta C_2 - 0.01\Delta C_3 - 0.13\Delta C_4$$
$$\Delta C_9^{\rm eff} = 8.48\Delta C_1 + 1.96\Delta C_2 - 4.24\Delta C_3 - 1.91\Delta C_4$$

Setting Delta C2 to 1 and rest to zero, reproduce the (large) SM charm contribution to C9(4.6 GeV).

But C1 and C3 are even (much) more effective in generating C9!

C2 and C4 feed strongly into C7eff, hence $B \to X_s\gamma$.

But C1 and C3 are practically irrelevant for radiative decay!

One can also have a 'pure C2-C4' scenario, where both contributions to C7eff cancel.

The four-quark Wilson coefficients also evolve, but comparatively mildly (see paper).

High NP scale – global analysis

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

Blue – $B \to X_s \gamma$ experiment