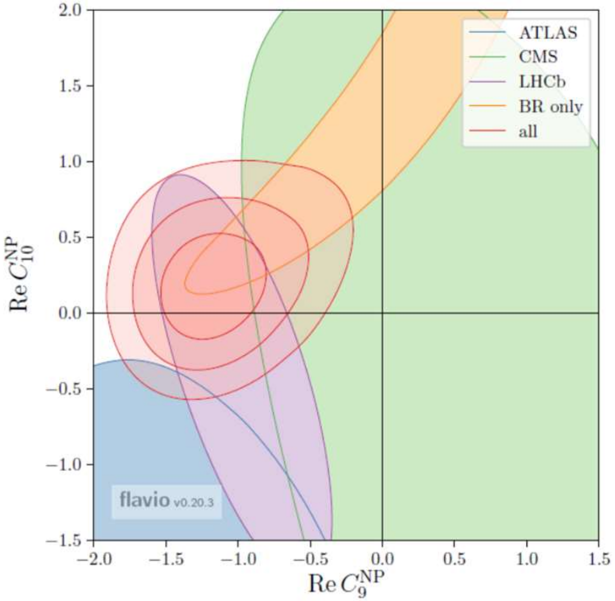
Rare B decays: SM and/or beyond

Sebastian Jäger (University of Sussex)

UK Flavour 2017

Durham, IPPP, 05 September 2017

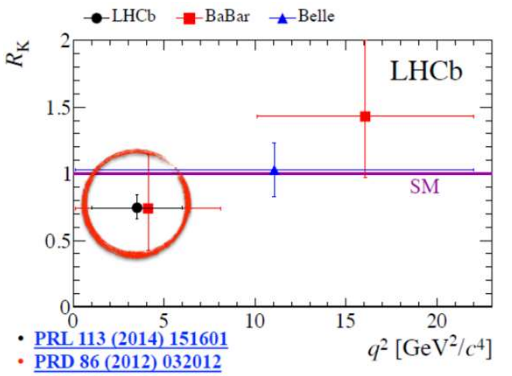
Is the SM in trouble?



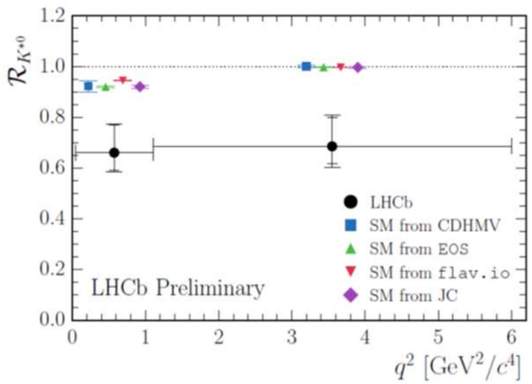
Global analysis of rare semileptonic decays (pre-RK*)

- 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



- PRL 113 (2014) 151601
- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

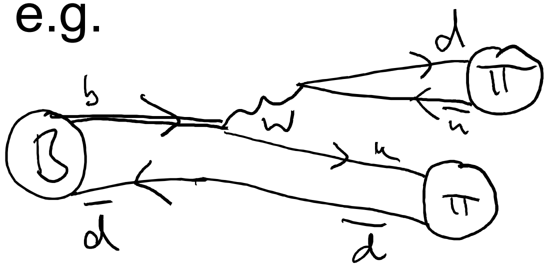


Evidence for a lepton-flavour-dependent effect in branching fractions (RK, RK*)

What makes a B decay rare?

- small CKM elements
- loop suppression in SM (typically of the dominant contribution)
- 'partonic phase space' in exclusive decays

e.g.



each $q\bar{q}$ pair constrained to small invariant mass $\sim \left(\frac{\Lambda_{QCD}}{m_b}\right)^{5/2}$ suppression

- In certain observables also helicity suppression

  e.g. $A(B_s \to \mu\mu)$ proportional m_μ/m_B

  angular observables S_3, A_9 in $B \to K^* l\, l$

General logic: small SM -> BSM might compete.

BSM might lift CKM, loop, or helicity suppression

Rare semileptonic B decays

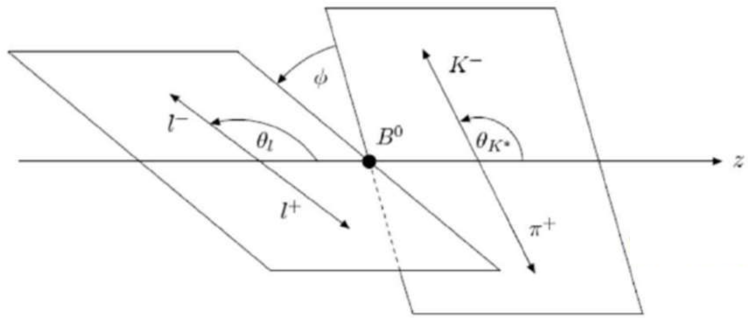
many new results on LHCb, ATLAS, CMS, Belle. Some anomalies

Branching ratios (differential in dilepton mass): $B\to K^{(*)}\mu\mu$, $B\to K^{(*)}ee$, $B_s\to\phi\mu\mu$

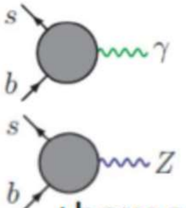
Lepton universality ratios

$$R_{K^{(*)}}[a,b] = \frac{\int_a^b \frac{d\Gamma}{dq^2}(B\to K^{(*)}\mu^+\mu^-)dq^2}{\int_a^b \frac{d\Gamma}{dq^2}(B\to K^{(*)}e^+e^-)dq^2}$$

differential angular distribution for
B->Vll : 3 angles, dilepton mass q^2
-> angular differential observables P_i



Sensitive to effective couplings



+boxes

$(\bar{s}\sigma^{\mu\nu}P_R b)F_{\mu\nu}$	C_7	(BSM constrained by inclusive)
$(\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu l)$	C_9	+ BSM?
$(\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu\gamma^5 l)$	C_{10}	+ BSM?
& right-handed currents	C_i'	

Theory uncertainties: C_i multiplied by nonperturbative form factors
C_9 degenerate with virtual-charm contributions

Weak Hamiltonian for rare semileptonic decay:

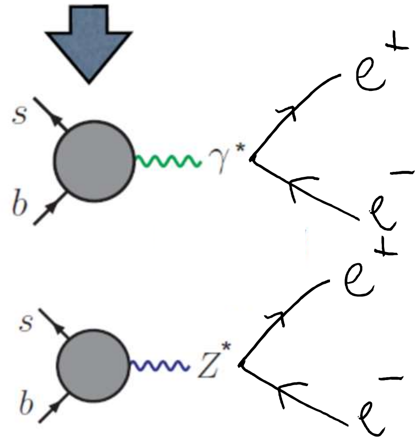
C9 : dilepton from vector current (L=1)

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

C10 : dilepton from axial current (L=1 or 0)

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

in SM mainly



- 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; ...

C7 : 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 (C9', C10', C7')

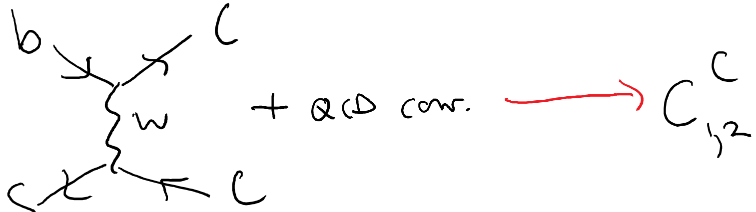
C9, C10 can depend on the lepton flavour.

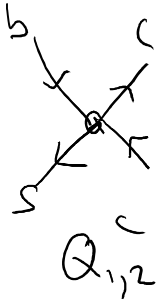
Universal BSM effects in C9 mimicked by a range of SM effects

C10 effects or lepton-specific effects distinguishable from SM effects

Weak Hamiltonian 2/2

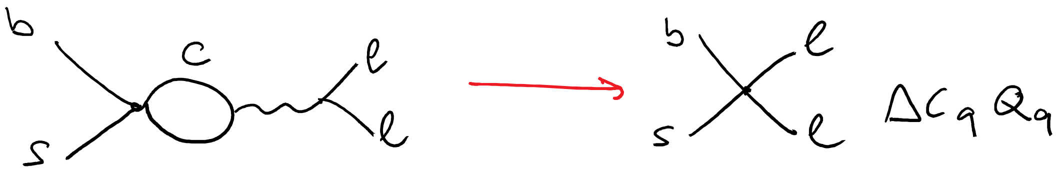
Also purely hadronic operators are important, primarily:





$$Q_1^c = (\bar{c}_L^i \gamma_\mu b_L^j)(\bar{s}_L^j \gamma^\mu c_L^i)$$
$$Q_2^c = (\bar{c}_L^i \gamma_\mu b_L^i)(\bar{s}_L^j \gamma^\mu c_L^j)$$

RG mixes these into C9 and C7



$$C_7^{\text{eff}}(4.6\text{GeV}) = 0.02\,C_1(M_W) - 0.19\,C_2(M_W)$$
$$C_9(4.6\text{GeV}) = 8.48\,C_1(M_W) + 1.96\,C_2(M_W)$$

O(50%) of total in both cases

Induces strong scale dependence of C_9 – must cancel in observables.

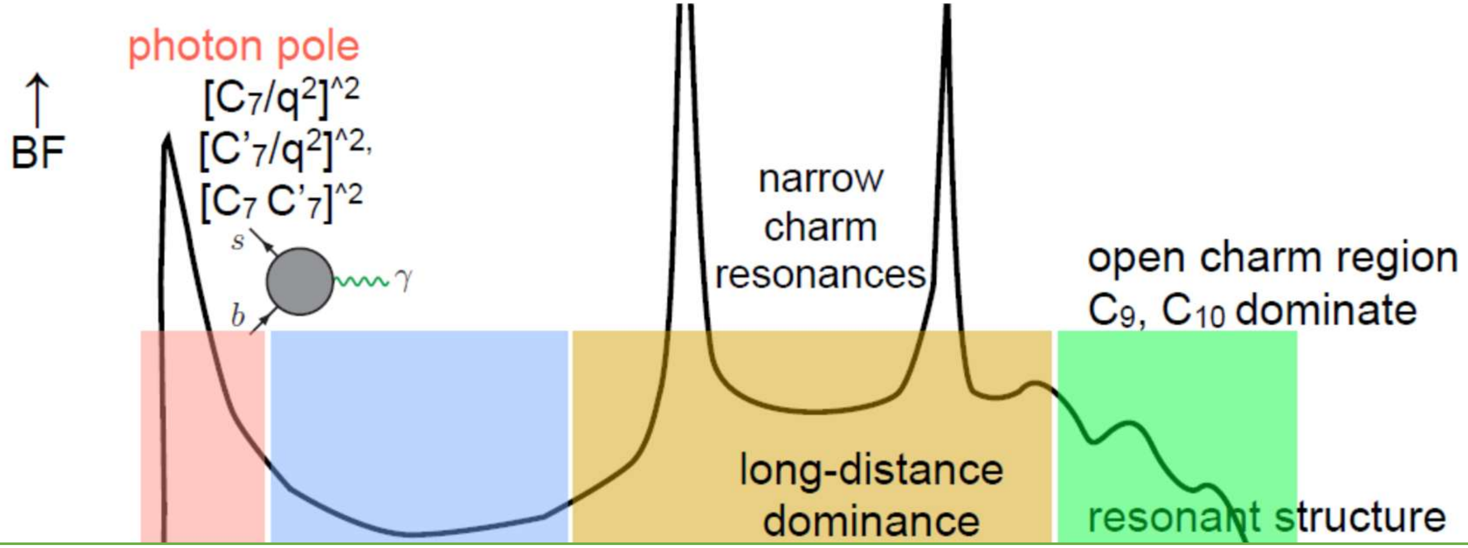
-> also means BSM bscc operators can induce sizable ΔC_9 (Talk by K. Leslie)

At μ = 4.6 GeV: $C_9(\mu) \sim 4$ $C_{10}(\mu) \sim -4$ $C_7^{\text{eff}}(\mu) \sim -0.3$

Chiral combinations: **$C_L = (C_9 - C_{10})/2 \sim 4$** $C_R = (C_9 + C_{10})/2 \sim 0$

The near-vanishing of $C_R(4.6\text{ GeV})$ is a complete numerical accident.

Ex: B->V l l differential rate (schematic)



Structure of decay amplitudes:

K* helicity

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

Local form factors (nonperturbative): normalisation

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

Photon pole
(absent for B->K l l)

Matrix element of hadronic weak hamiltonian
must cancel μ-dep. of C9 and of C7 x V

Form factors

In helicity basis (makes for simple expressions in HQ limit):

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

SJ, Martin Camalich 2012
(Bharucha, Feldmann, Wick 2010)

Close to q^2_{max}: determinations from lattice QCD (B -> pi; K; stable V)

Low q^2: no first-principles determinations

- heavy-quark limit: calculable relations, eg 7 FF -> 2 FF for B->V
  uncontrolled systematic: power corrections (Λ/m_b = 10% ? 20% ?)

- light-cone sum rules (LCSR)

correlation function $G_{F\lambda}(q^2;p^2) = i\int d^4y e^{-ip\cdot y}\langle K^*(k)|T\{\epsilon^*_\mu(q;\lambda)(\bar{s}\Gamma^\mu_F b)[0]\, j^\dagger_B(y)\}|0\rangle$

hadronic representation

Form factor (output)

$$G_{F\lambda} = \frac{\boxed{\langle K^*(k,\lambda)|\epsilon^*_\mu(q;\lambda)\bar{s}\Gamma^\mu_F b|B\rangle}}{p^2-m_B^2}\frac{f_B m_B^2}{m_b} + \dots,$$

collinear factorisation

Kernel (calc. PT) LCDA (input)

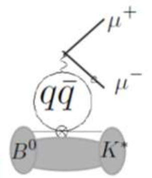
$$G_{F\lambda} = \sum_i \boxed{t_i(\alpha_s)} \star \boxed{\phi_i}$$

model omitted higher states: Borel transform & continuum threshold ("semilocal parton-hadron duality")

Main uncontrolled systematic: continuum threshold (not parametrically suppressed)

Nonlocal term and scale dependence

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



+ strong interactions!

more properly:

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

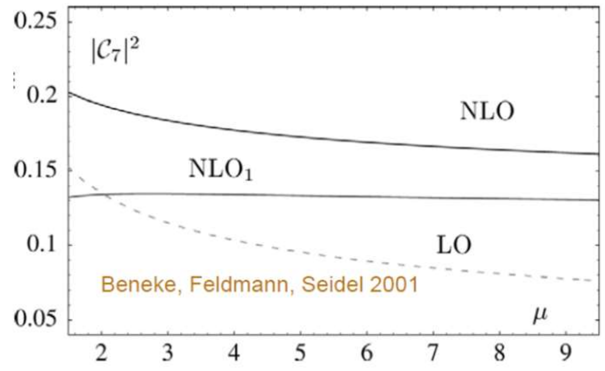
$$h_\lambda \equiv \frac{i}{m_B^2}\epsilon^{\mu *}(\lambda)a_\mu^{\rm had}$$

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

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

Systematic justification in QCD factorisation
(low q2, heavy quark limit)
scale dependence cancels order by order in PT
Beneke, Feldmann, Seidel 2001,2004

power corrections ?
But subdominant to FF (SJ, Martin Camalich 2012,2014)



High q2: OPE in 1/q2

duality violation ? Grinstein,Pirjol 2004; Beylich/Buchalla/Feldmann 2008, Lyon & Zwicky 2014

Data-driven determination?

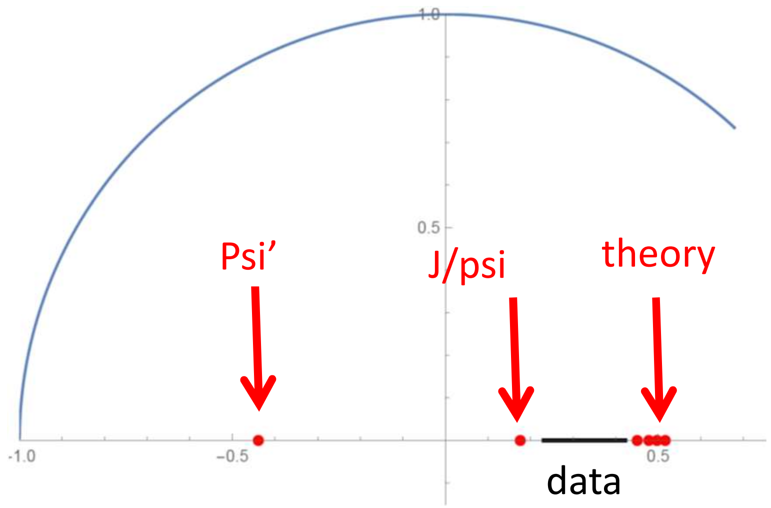
Bobeth, Chrzaszcz, Van Dyk, Virto 2017

Basic idea: reduce theory dependence of h_λ by using data & analyticity

- Ignoring CKM-suppressed terms, h_λ is complex-analytic in q2 except for a cut from $4\ m_D^2$ to infinity, and poles at the J/psi and psi'

- Use QCDF (+LCSR pc estimate) only at q2 <~ 0
- And experimental data to fix/constrain the residues at the poles
- Conformal mapping to increase separation of the input data from the cut in hope of a fast-converging Taylor series (truncate after 3 terms)

k	0	1	2
$\mathrm{Re}[\alpha_k^{(\perp)}]$	-0.06 ± 0.21	-6.77 ± 0.27	18.96 ± 0.59
$\mathrm{Re}[\alpha_k^{(\parallel)}]$	-0.35 ± 0.62	-3.13 ± 0.41	12.20 ± 1.34
$\mathrm{Re}[\alpha_k^{(0)}]$	0.05 ± 1.52	17.26 ± 1.64	–
$\mathrm{Im}[\alpha_k^{(\perp)}]$	-0.21 ± 2.25	1.17 ± 3.58	-0.08 ± 2.24
$\mathrm{Im}[\alpha_k^{(\parallel)}]$	-0.04 ± 3.67	-2.14 ± 2.46	6.03 ± 2.50
$\mathrm{Im}[\alpha_k^{(0)}]$	-0.05 ± 4.99	4.29 ± 3.14	–



Used with LCSR form factors gives BSM C9 consistent with when HQE computation is used with LCSR FF form factors

If the convergence/stability of this method can be established, it may eliminate the charm loop as a source of concern for interpreting low-q2 data.

No new information on form factors

Scalar branching ratio

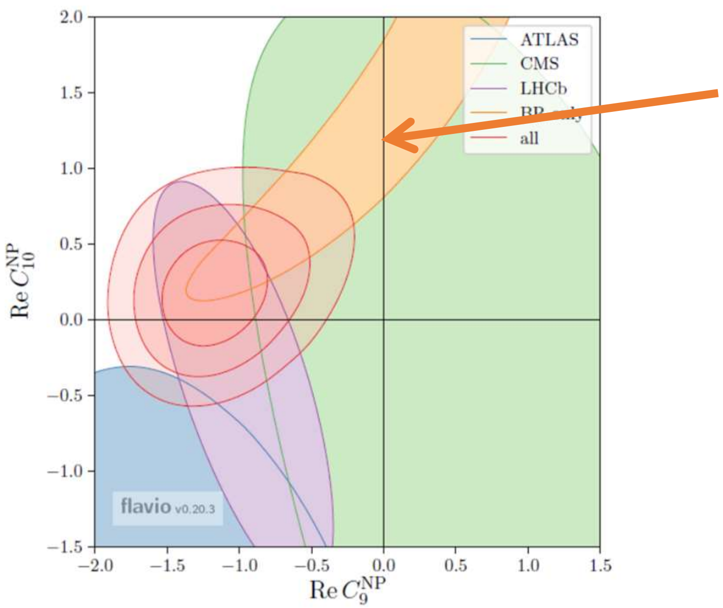
In this case only helicity zero, no photon pole, mild dilepton mass dependence

Schematically (neglecting some normalisations and small imaginary parts),

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

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

Because C_7 and C_R are small in the SM, BR essentially is determined by the product $C_L \cdot V$. Weak sensitivity to C_R (as long as small) or C_7.



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

Suggests 20-25% suppression of C_L 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

Angular observables

For zero mass there are the following independent observables:

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

"longitudinal" rate
(sim. to scalar BR)

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

"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 / P_2

The zero-crossing of $I_6^s = F\beta\,\mathrm{Re}\left[H_V^-(H_A^-)^* - H_V^+(H_A^+)^*\right]$ (or of A_{FB}, 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: $T_-(0)/V_-(0) \sim 1.05 > 1$

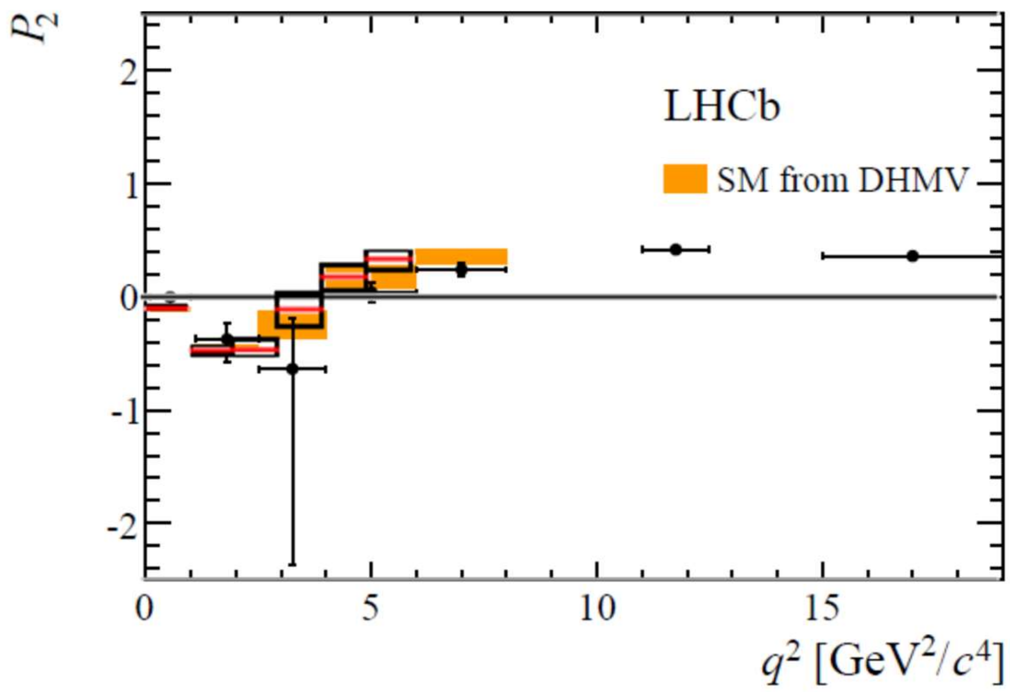
compare to: $T_-(0)/V_-(0) = 0.94 \pm 0.04$

[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:

suspressed 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

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

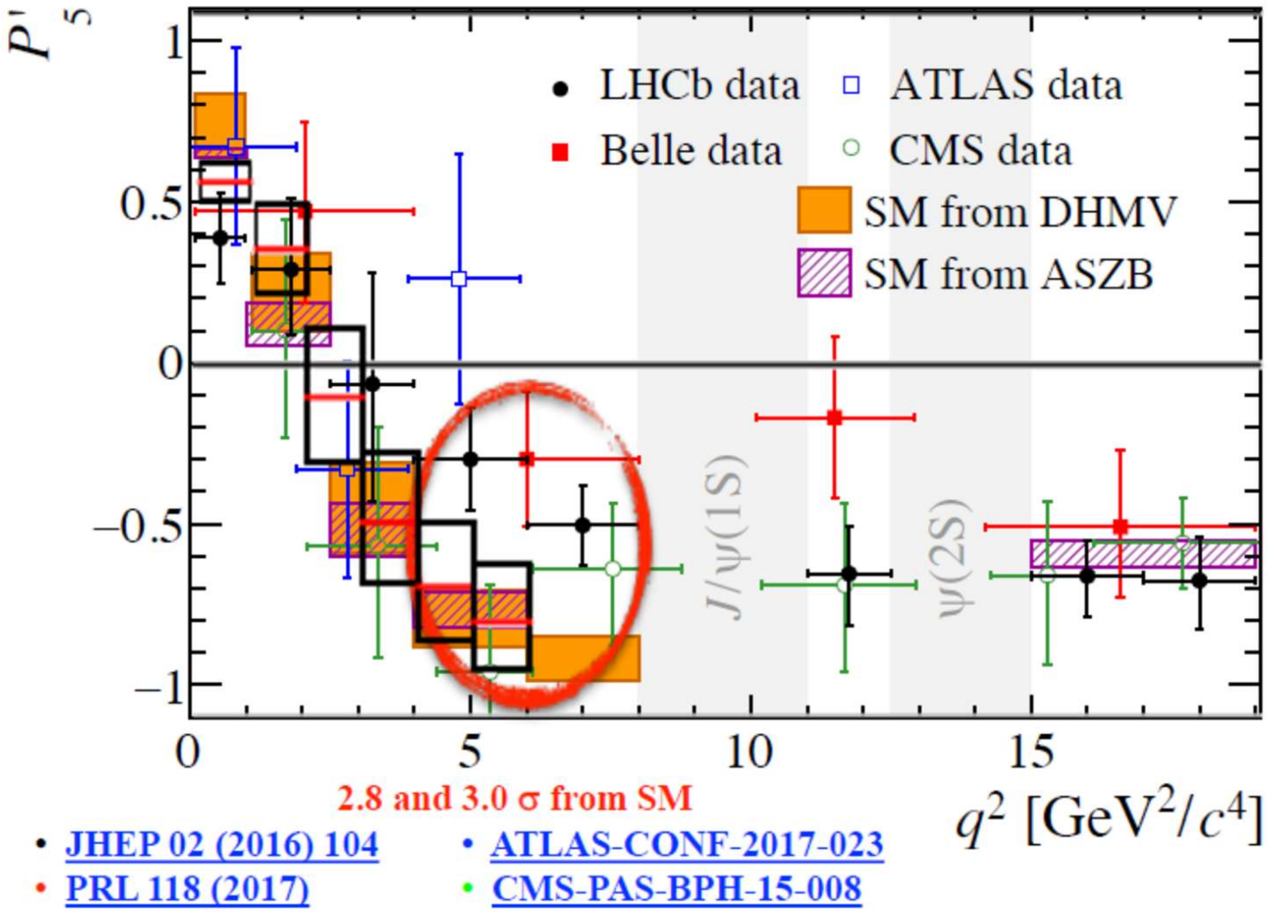
Dominated by axial amplitude

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’



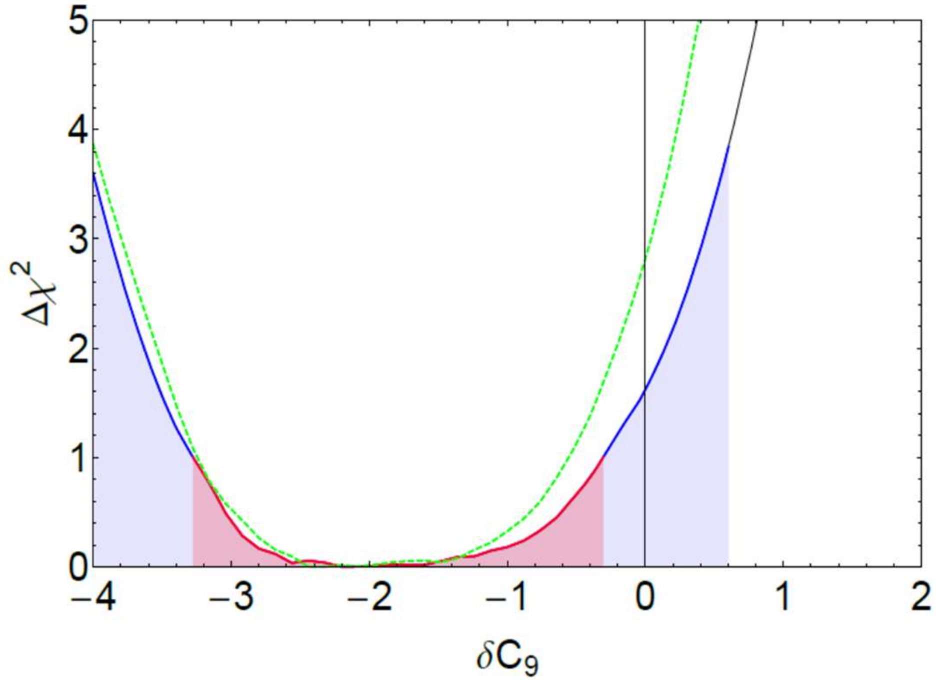
Simone Bifani, seminar at CERN (overlaid predictions from SJ&Martin Camalich 2014)

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

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



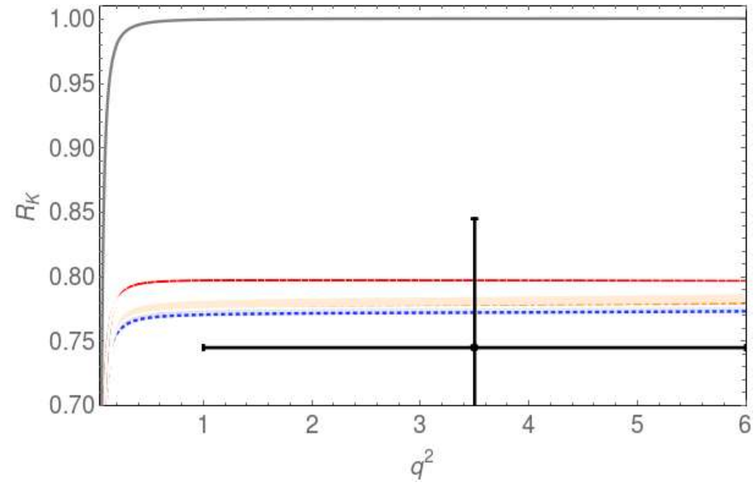
See also Hurth et al 2015-17

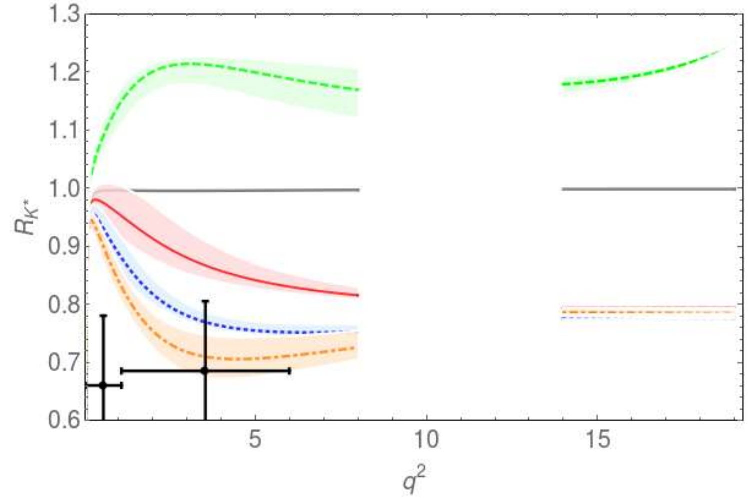
from SJ, Martin Camalich 1412.3183 (angular obs. with 1 fb^-1 LHCb data)

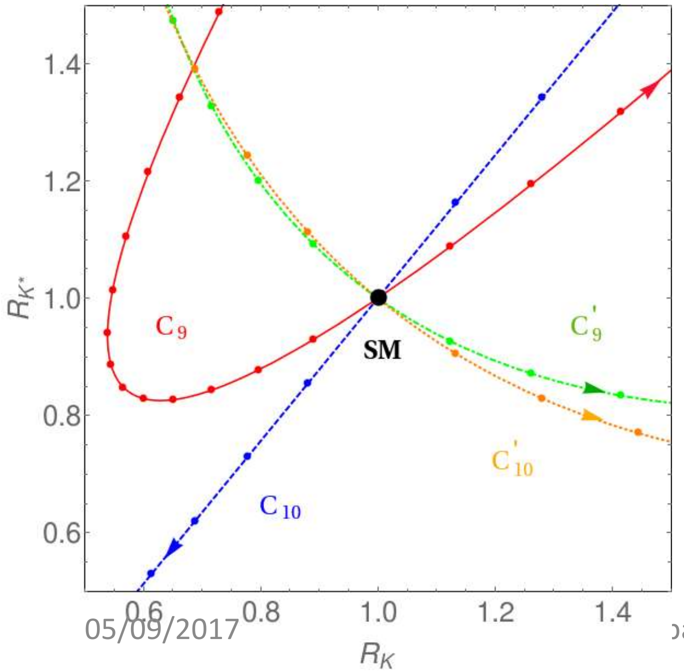
two paramerterisation schemes (green, blue)

Preference for C9<C9SM, with modest significance

Lepton universality measurements vs theory







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

Theory uncertainties completely negligible relative to experimental ones.

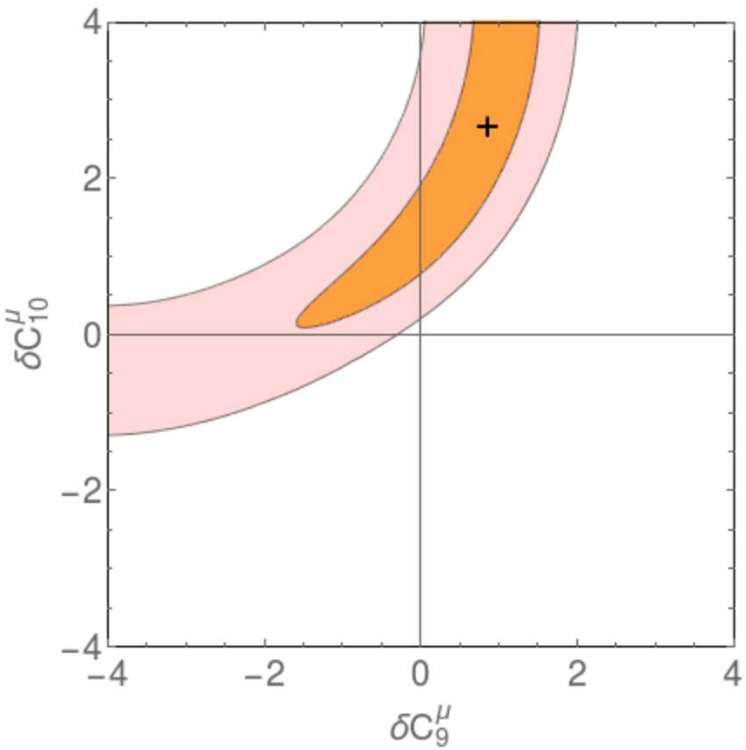
p(SM) = 2.1 x 10^-4 (3.7)

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

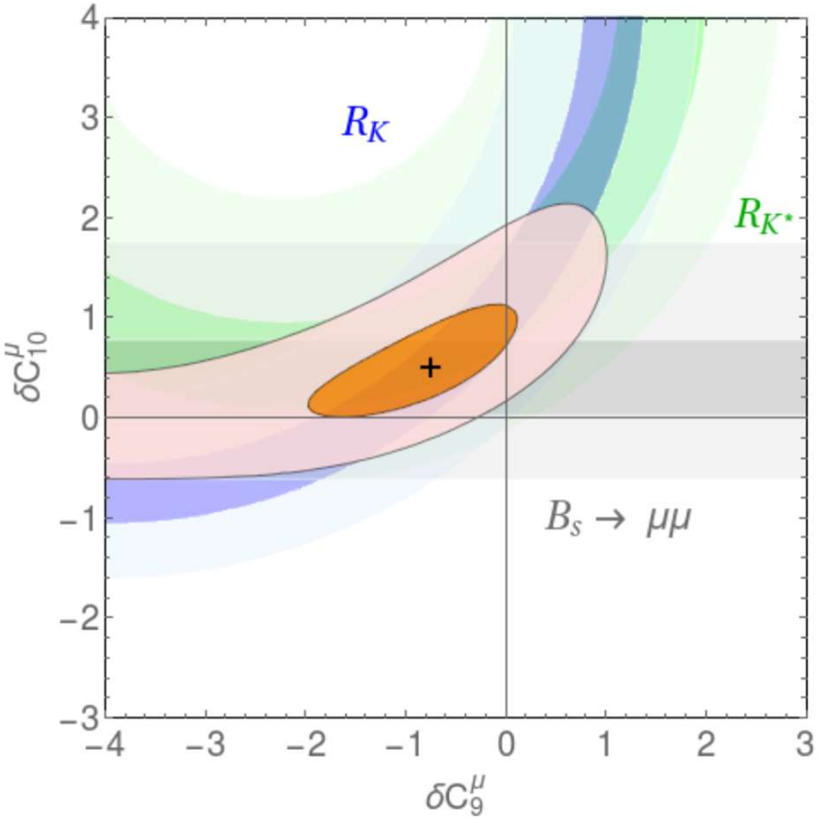
p = 0.158

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 point excl. at 3.76 sigma

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

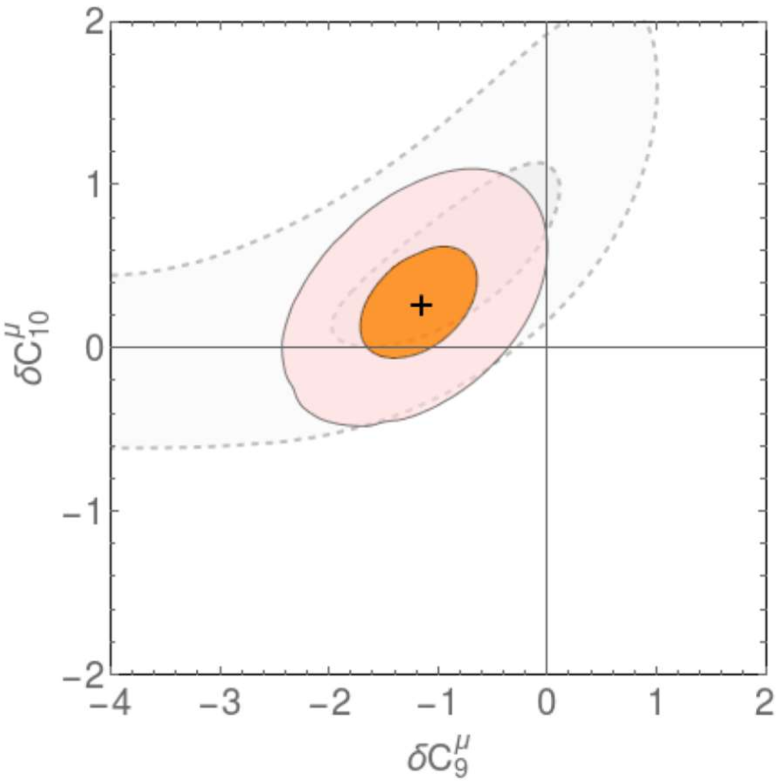
CR = (C9+C10)/2 not well constrained and consistent with zero

1-parameter CL fit: besf fit -0.61. 1sigma [-0.78, -0.46], p = 0.339

SM point (origin) excluded at 4.16 sigma

Adding B->K*μμ,ee angular data

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 [63 dof]

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

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

Determining CR (break C9/C10 degeneracy)

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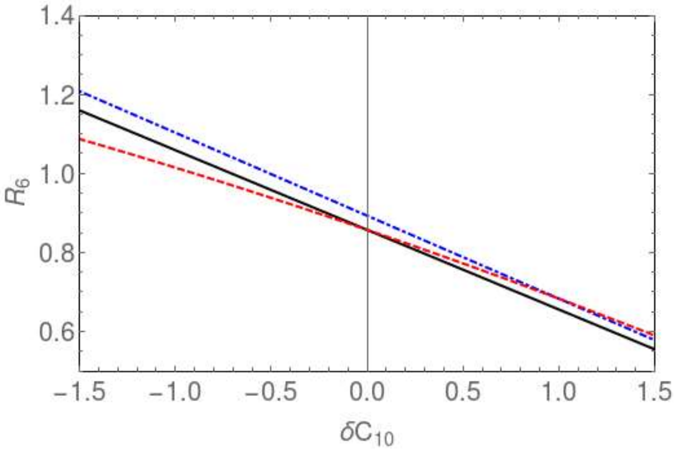
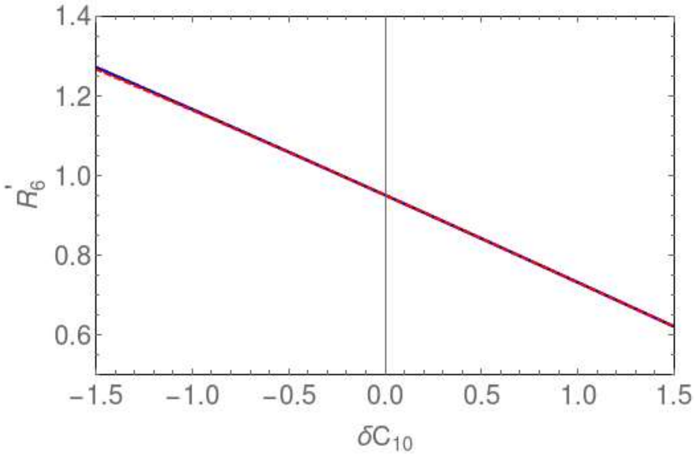
Propose to measure observable

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

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



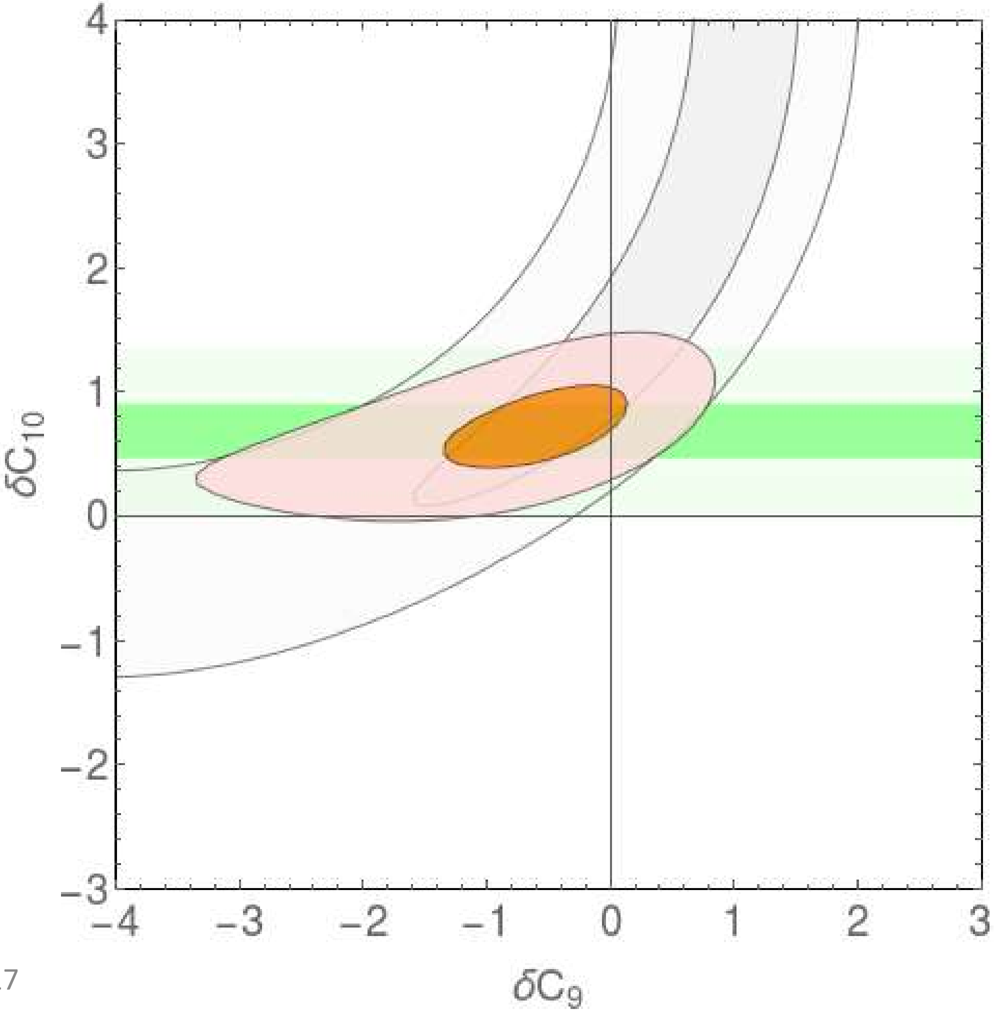


Remains very clean in presence of new physics.
Probes a LUV C10 precisely, irrespective of values of C9e, C9mu

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)



BSM models?

Assuming the effect is real, many authors have constructed models (no space to review here). They fall in two classes:

- Z’ (=neutral vector) mediator (tree, loop-level, or composite)
- Leptoquark mediators (tree, loop-level, or composite)

None of these particles (so far as I know) address the naturalness problem, or any other theoretical puzzle (although they could be part of a more elaborate structure that does).

Given that the naturalness problem is the main reason to expect new flavour physics at the TeV scale, it would be desirable to have a models where RK, RK* (and perhaps RD, RD* - not discussed here) are more directly connected to naturalness.

Summary

observable	Anomaly?	Dominant theory error	comment
Branching ratios (differential)	Lowish in muonic final states	Form factor values	
Angular (muonic)	P5' off; significance unclear (1-3σ?)	Form factor ratios, long-distance charm	
Angular (electronic)	None (but low statistics)	Similar to muonic	Best theoretical sensitivity to C_7'
Lepton-universality ratios (RK, RK*)	**Each** of 3 bins off by >2σ; 3.7σ combined	no known issue (dominant is QED radiation – tiny)	clean NP discovery with more data Belle2 confirmation?

Possible BSM explanations

to explain all anomalies: require BSM $\bar{s}_L b_L \bar{\mu}_L \mu_L$ coupling

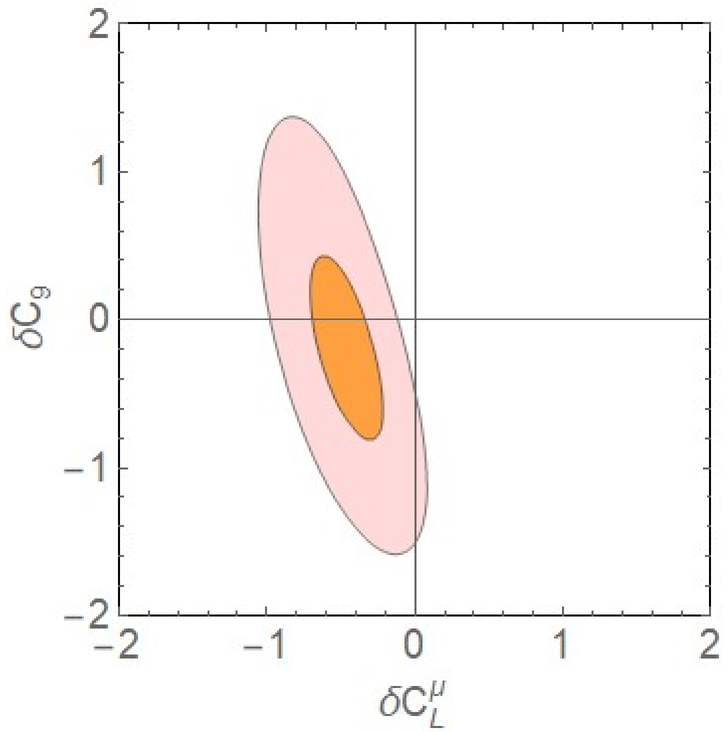
to explain only RK, RK*: BSM $\bar{s}_L b_L \bar{\mu}_L \mu_L$ or various $\bar{s} b \bar{e} e$ possibilities

Eagerly anticipating LHCb updates of RK, RK* with more data; ratios for $B_s \to \phi ll$; angular lepton-universality tests

Experimental uncertainties in RK, RK*, … at LHC dominated by electronic modes: Belle2 powerful, with different systematic

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

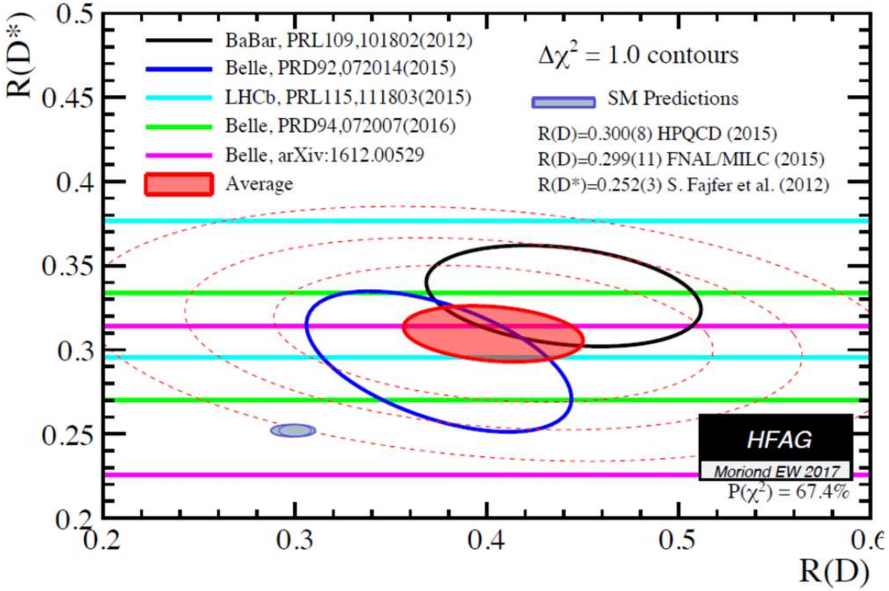
Eg. 'charming BSM' scenario

SJ, Kirk, Lenz, Leslie arXiv:1701.09183

b→c τ ν(τ)

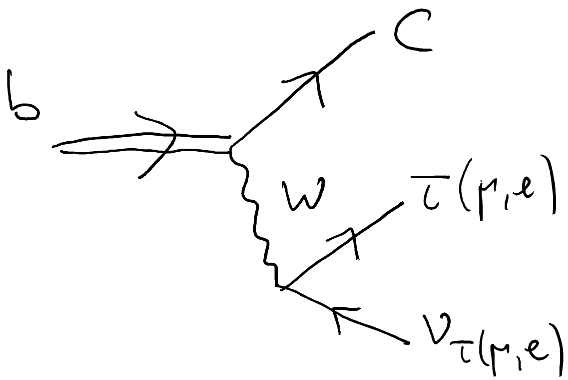
For some time B-factories and LHCb have consistently shown semileptonic B ->D (D*) τν decay rates larger than expected

$$R(D^{(*)}) = \frac{BR(B \to D^{(*)}\tau\nu_\tau)}{BR(B \to D^{(*)}\ell\nu_\ell)}$$



3.9 sigma effect

SM **tree-level** effect



Theory error negligible relative to experiment

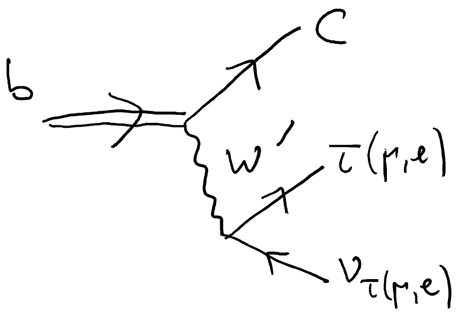
$b \to c\, \tau\, \nu(\tau)$

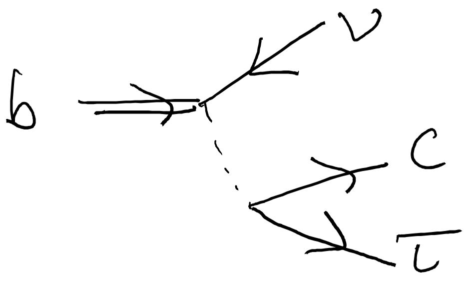
Can be interpreted as BSM effect

Including differential decay distribution, data favour modification of SM effective coupling (operator with all fermions left-handed)

Eg Ligeti et al 2015,16

Possible mediation by W' or leptoquarks,





Isidori et al, Ligeti et al, Becirevic et al, Crivellin et al, …

In principle R(D(*)) could also be affected by suppressing the couplings to light leptons; disvafoured by B-factory data