Rare B decays

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Outline

Why rare B decays?

Calculability

Phenomenology

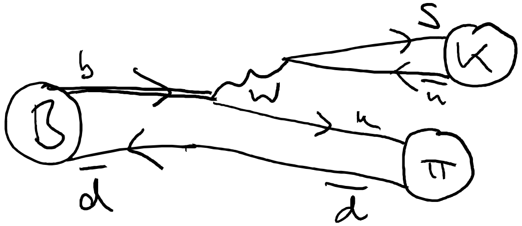
Summary

What makes a B decay rare?

small CKM elements

(typically) loop suppression in SM

'partonic phase space' in exclusive decays

e.g. 

$s\bar{u}$, $u\bar{d}$ } each $q\bar{q}$ pair constrained to small invariant mass

$\rightarrow \left(\frac{\Lambda_{QCD}}{m_b}\right)^{5/2}$ 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 $B \to K^* l l$

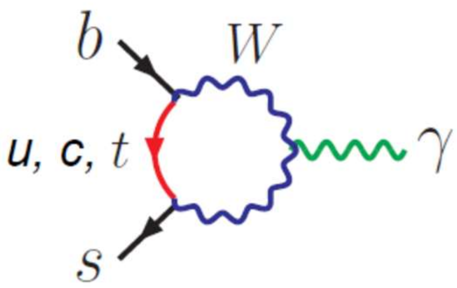
General logic: small SM -> BSM might compete.

BSM might lift CKM, loop, or helicity suppression

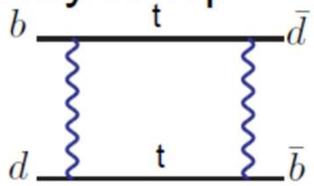
Examples

SM: Loop + CKM suppression of FCNC (GIM)

y_t main source of GIM breaking: enhanced sensitivity to top

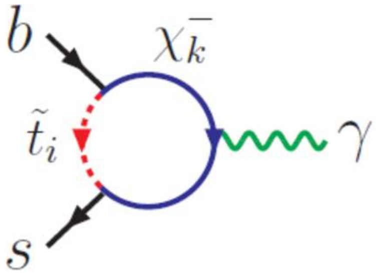


e.g. B-Bbar oscillations first indication of a heavy top (Argus 1987)



Charm contribution sometimes sizable/uncertain due to large logarithms and/or nonperturbative QCD effects. Often leading source of uncertainty

BSM: Can compete even in weakly coupled case (MSSM)



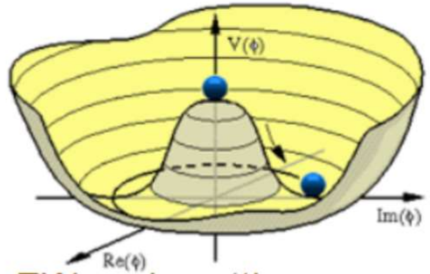
MSSM: sensitive to stops and their couplings
Stringent constraints on 1st-2nd generation mixing

In more general cases can have tree-level contributions (Z')

In strongly coupled models may lose loop suppression, flavour most stringent generic constraint absent flavour protection (RS)

Why should we expect BSM flavour?

The discovery of a Higgs scalar and apparent absence of other particles implies the following approximate Lagrangian at length scales between an attometre and a fermi



SU(3)^5 flavour symmetric kinetic/gauge terms

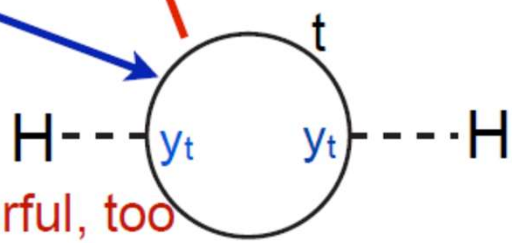
EW scale setting

$$\mathcal{L}_{\rm SM} \sum_f \bar\psi_f \gamma^\mu D_\mu \psi_f - \sum_{i,a} \frac{1}{4} g_i F^{ia}_{\mu\nu} F^{ia\mu\nu}$$
$$- \bar u_R Y_U \phi^{c\dagger} Q_L - \bar d_R Y_D \phi^\dagger D_L - \bar e_R Y_E \phi^\dagger E_L + \mu^2 \phi^\dagger \phi - \frac{\lambda}{2} (\phi^\dagger \phi)^2$$

flavour-breaking fermion masses and Higgs couplings

$\propto y_t^2 M^2$

NB: naturalness problem is (mostly) caused by top Yukawa, a flavour-breaking term



Physics addressing naturalness should be flavourful, too

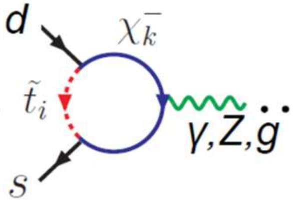
This happens in supersymmetry, extra dim/composite Higgs, ...

Calculability

Energy scale

Relevant dynamics (EFT)

TeV

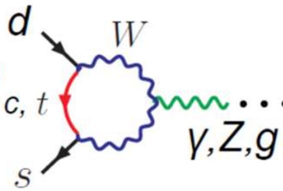


perturbative matching

RGE

SM-EFT

$m_W \sim m_t$



perturbative matching

RGE

Weak Hamiltonian H_W + QCD&QED(b,c,s,d,u)

$m_b \sim m_B$

perturbative matching

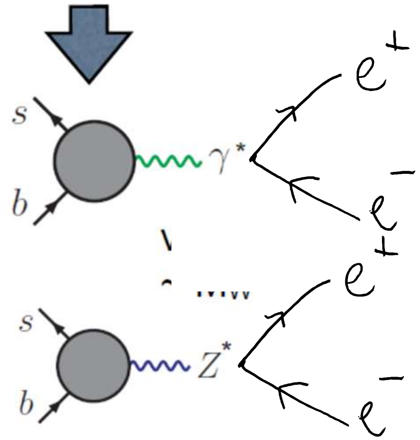
Λ_{QCD}

Nonperturbative amplitudes

b + Soft & collinear QCD [SCET](when energetic hadrons)

Weak Hamiltonian for rare semileptonic decay:

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)

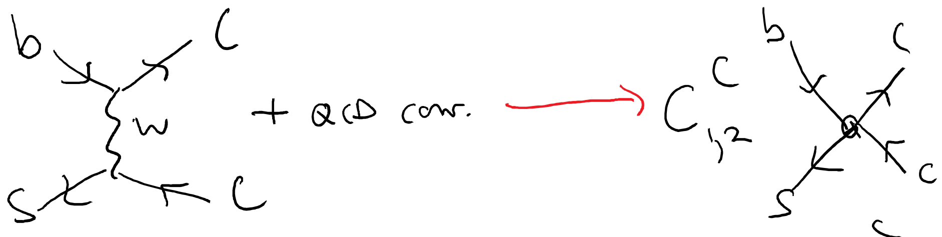
$$Q_{7\gamma} = \frac{e}{16\pi^2} m_b\,(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}$$

- 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

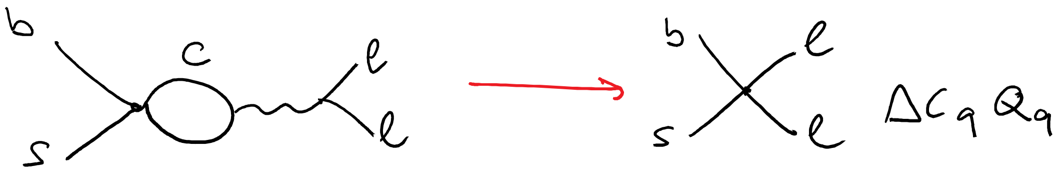
Also purely hadronic operators are important, primarily:



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

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

RG mixes these into C9 and C7



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

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

O(50%) of total in both cases

Induces strong scale dependence of C9 – must cancel in observables.

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.

b physics vs B physics

B mesons are not b-quarks.

Only a few properties computable in a controlled way (lattice QCD).

However:

often, simplification to leading power in Λ/m_b expansion

(QCD factorisation)

crucial for interpretation of rare B-decay data

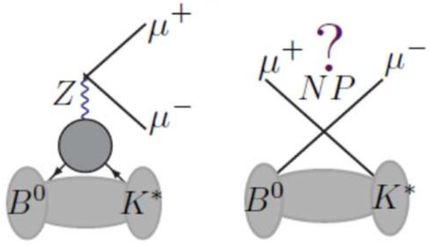
subleading powers don't simplify:not computable (at present)

Form factors where needed, rely on model calculations (most often, light-cone sum rules)

B→Vll: decay amplitude structure

Two mechanisms to produce dilepton in & beyond SM

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

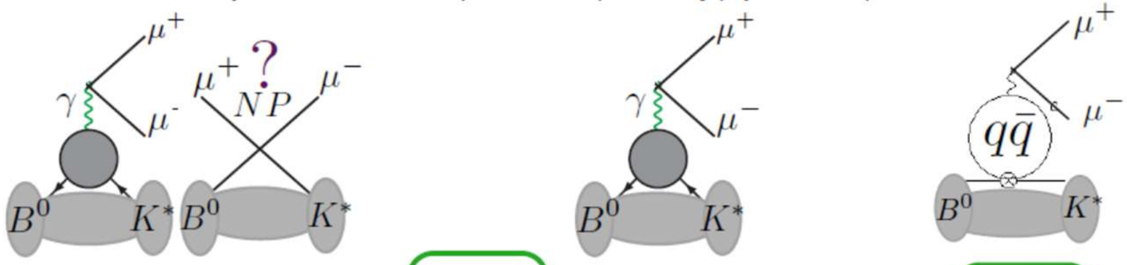


K* helicity

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

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

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

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

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

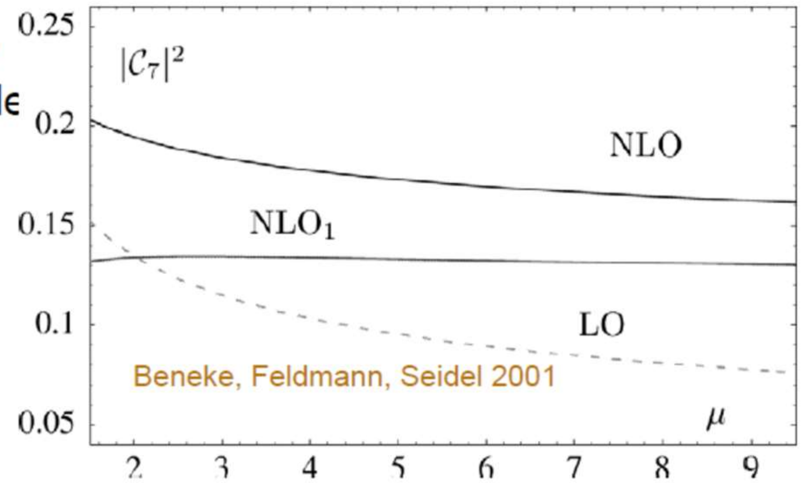
$$C_9^{\mathrm{eff}} = \begin{cases} 4.18|_{C_9} + (0.22+0.05i)|_Y & (m_c = m_c^{\mathrm{pole}} = 1.7\mathrm{GeV}) \\ 4.18|_{C_9} + (0.40+0.05i)|_Y & (m_c = m_c^{\overline{\mathrm{MS}}} = 1.2\mathrm{GeV}). \end{cases}$$

ie a 5% mass scheme ambiguity

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

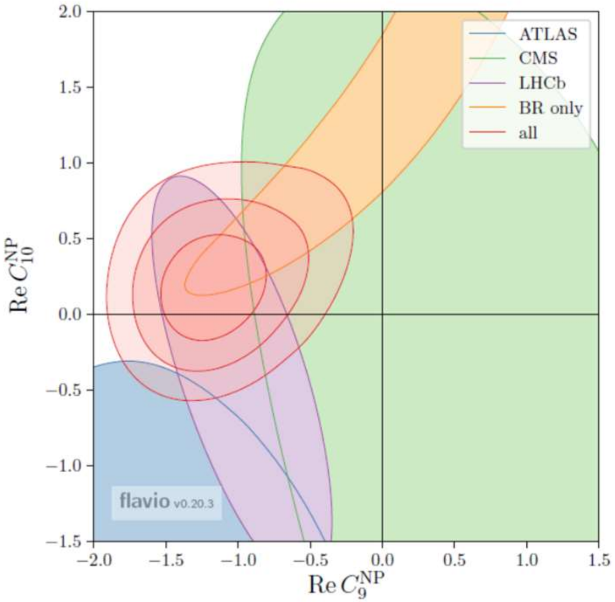
resolved in the heavy-quark expansion (to leading power)

Beneke, Feldmann, Seidel 2001, 2004



See also discussion session Monday pm

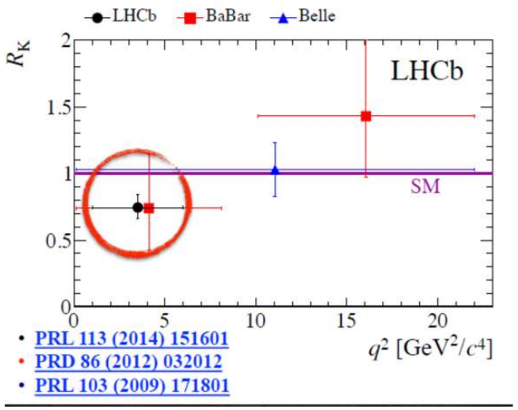
Is the SM in trouble?

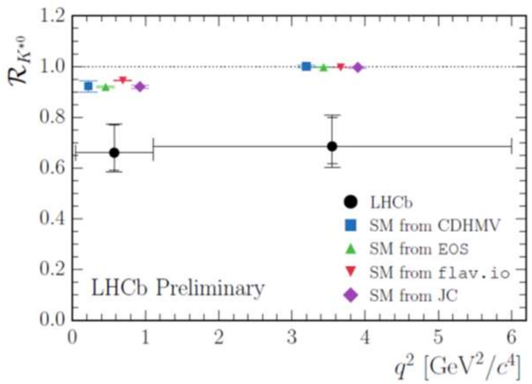


Global analysis of rare semileptonic decays (pre-RK*)

- 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





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

Scalar branching ratio

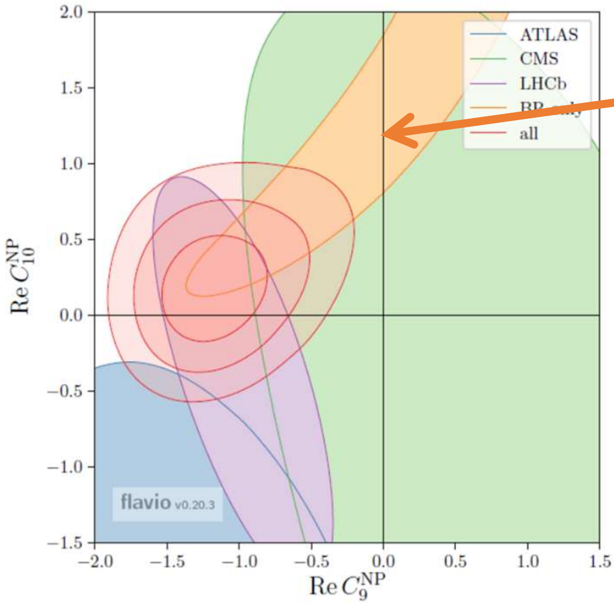
In this case only helicity zero, no photon pole, mild dilepton mass dependence

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.

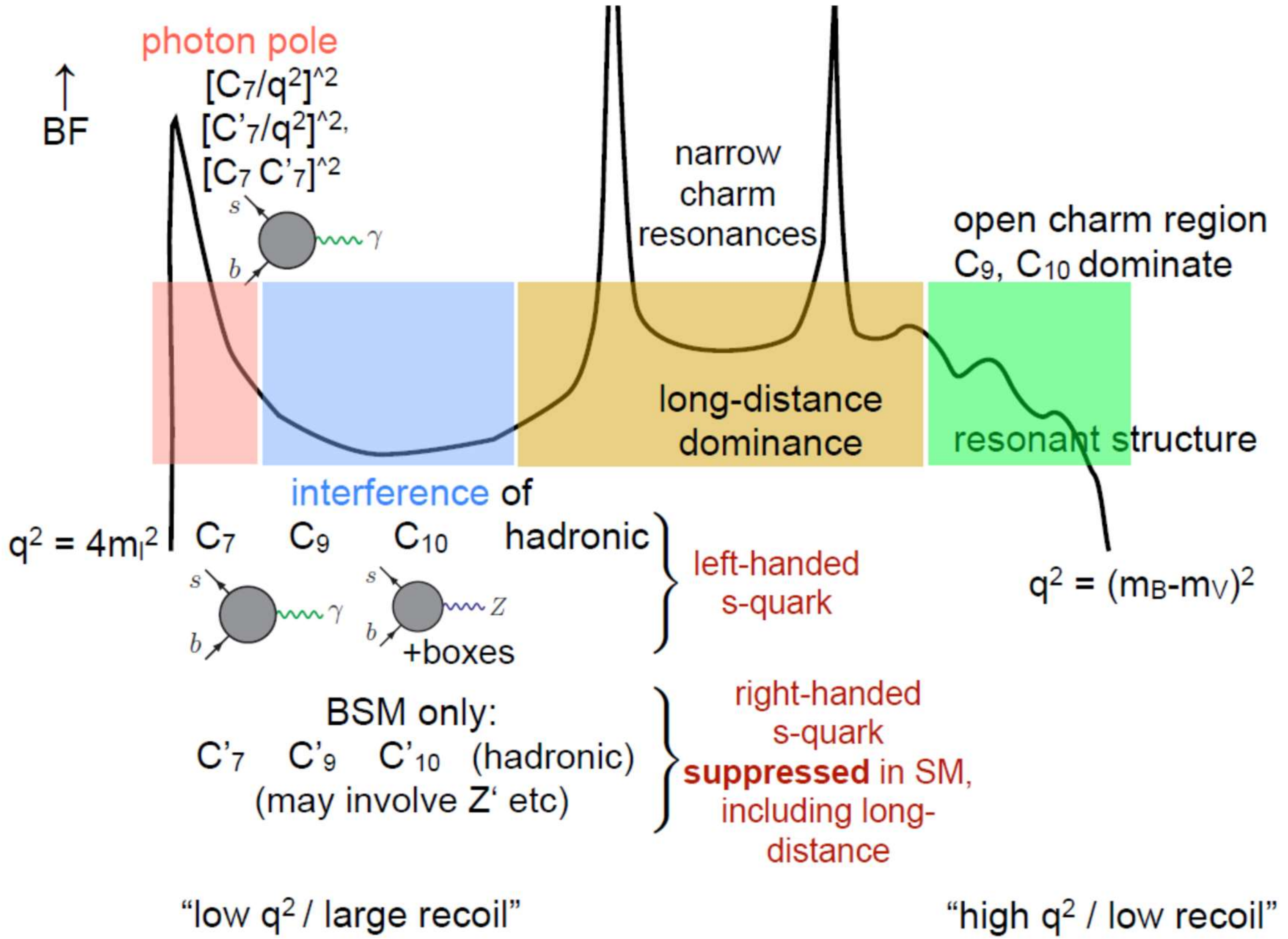


Explains the shape of the BR band:
part of a circle around (-4, +4) (centre far outside plot region)

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

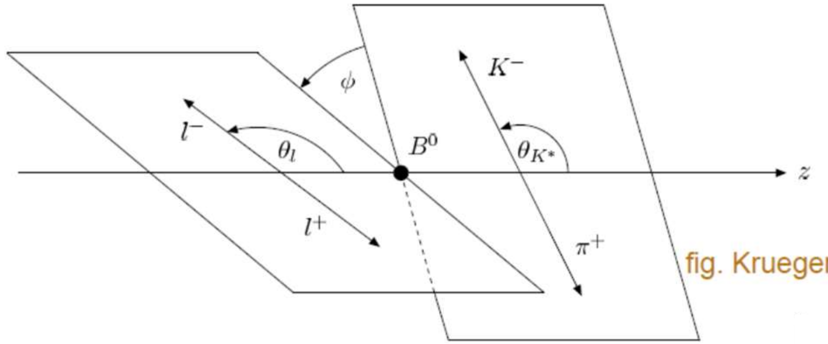
But perfectly degenerate with form factor V !
To interpret this as evidence of BSM physics need precision on V much better than 25%.
Form factor estimates from light-cone sum rules

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



θK in K* rest frame

θl 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: $T_-(0)/V_-(0) \sim 1.05 > 1$

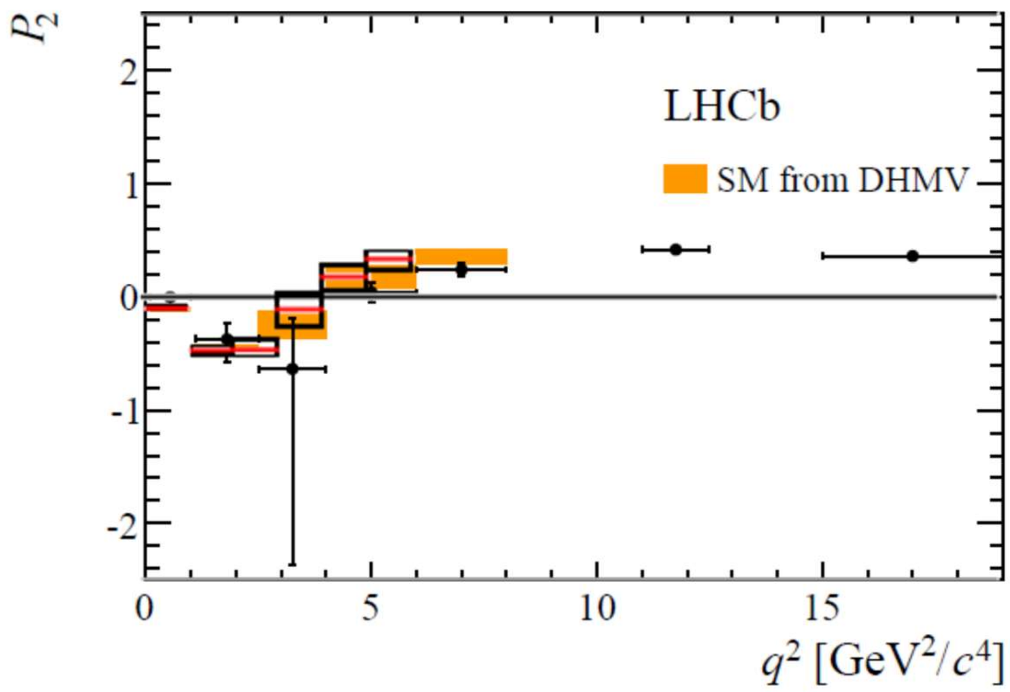
compare to: $T_-(0)/V_-(0) = 0.94$ +/- 0.04

[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

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

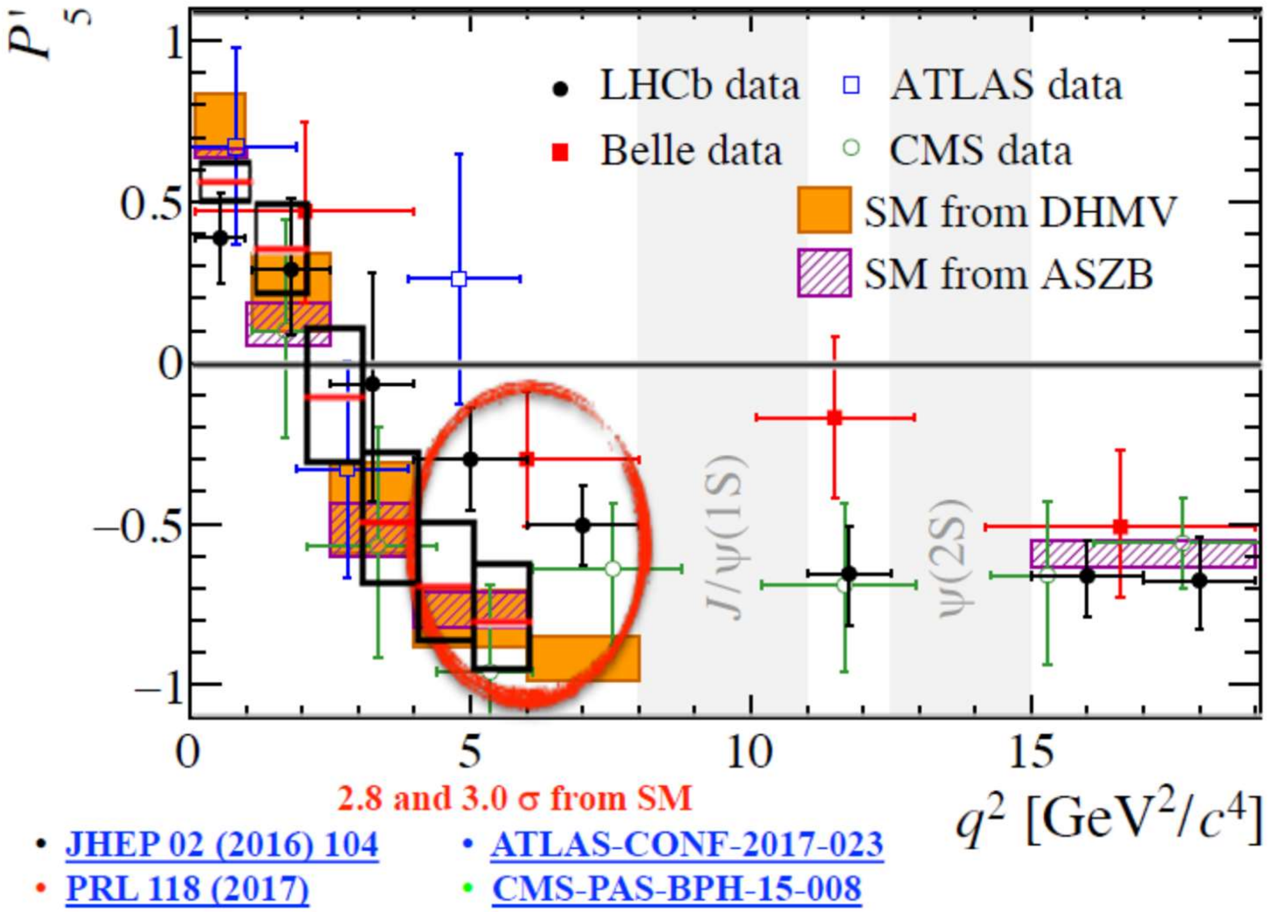
Dominated by axial amplitude

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’



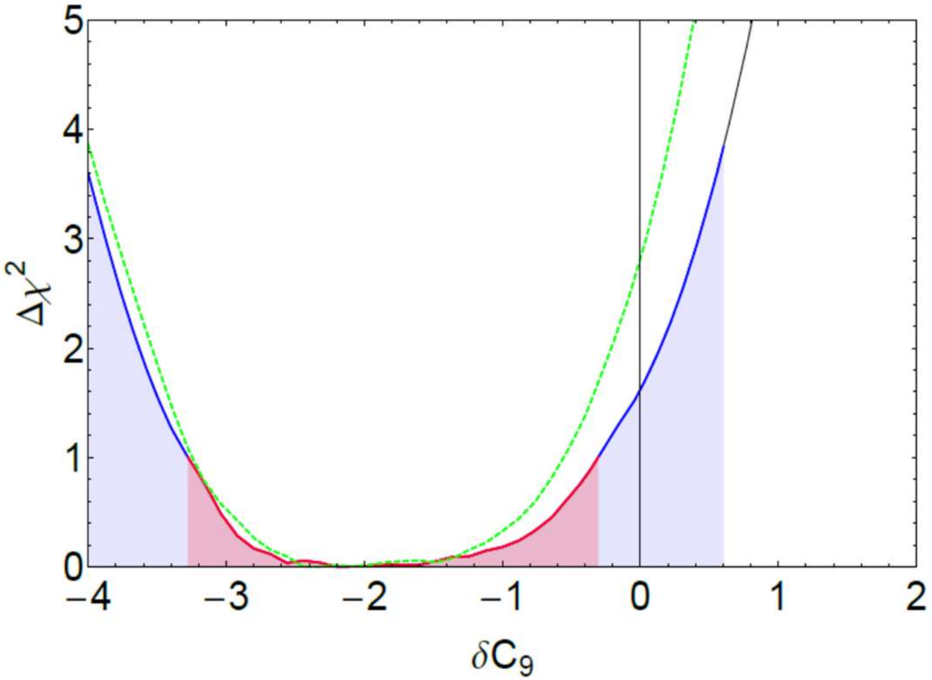
Simone Bifani, seminar at CERN (overlaid predictions from SJ&Martin Camalich 2014)

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



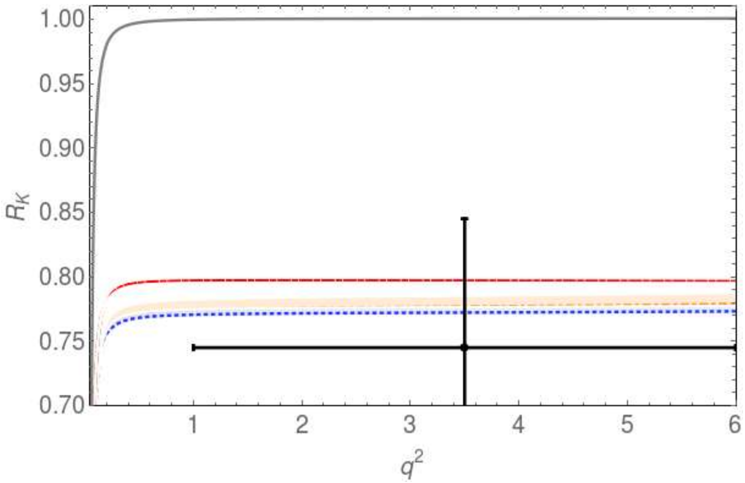
See also Hurth et al 2015-17

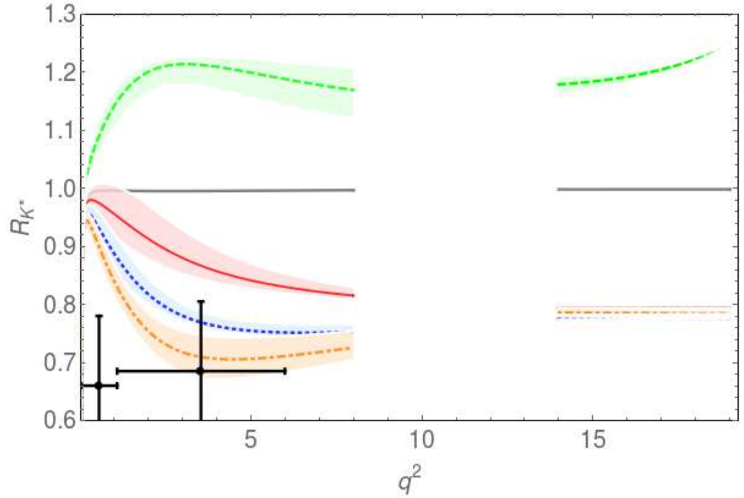
from SJ, Martin Camalich 1412.3183 (angular obs. with 1 fb^-1 LHCb data)

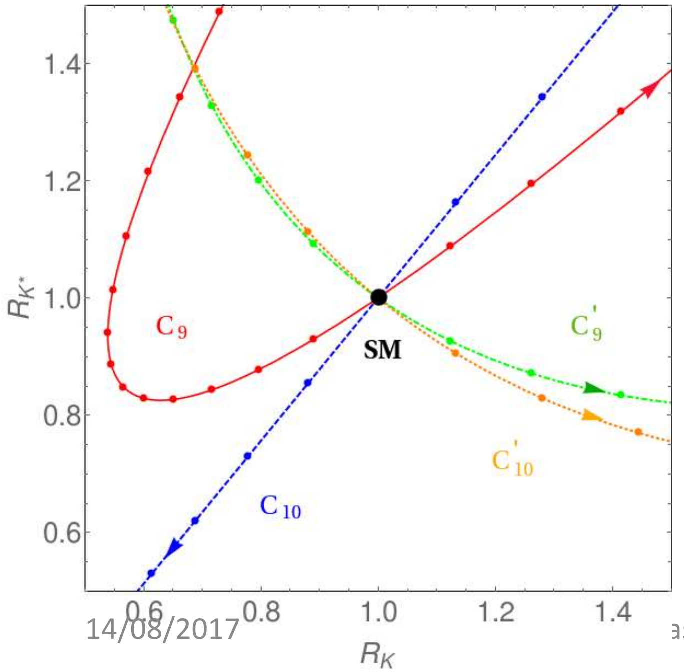
two paramerterisation schemes (green, blue)

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.

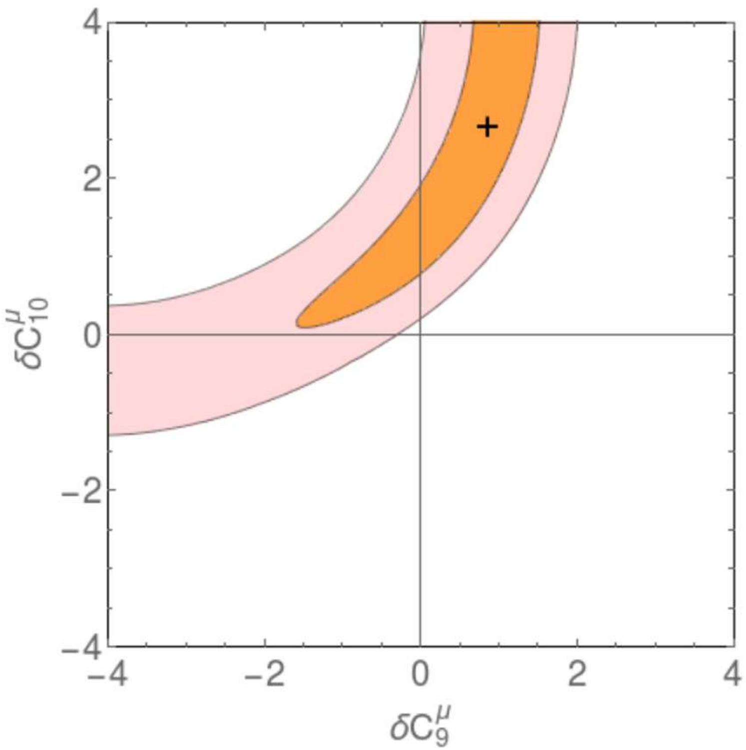
p(SM) = 2.1 x 10^-4 (3.7)

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	$\delta C_L^{\mu} = -0.5$	$\delta C_9^{\mu} = -1$	$\delta C_{10}^{\mu} = 1$	$\delta C_9^{\prime\mu} = -1$
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

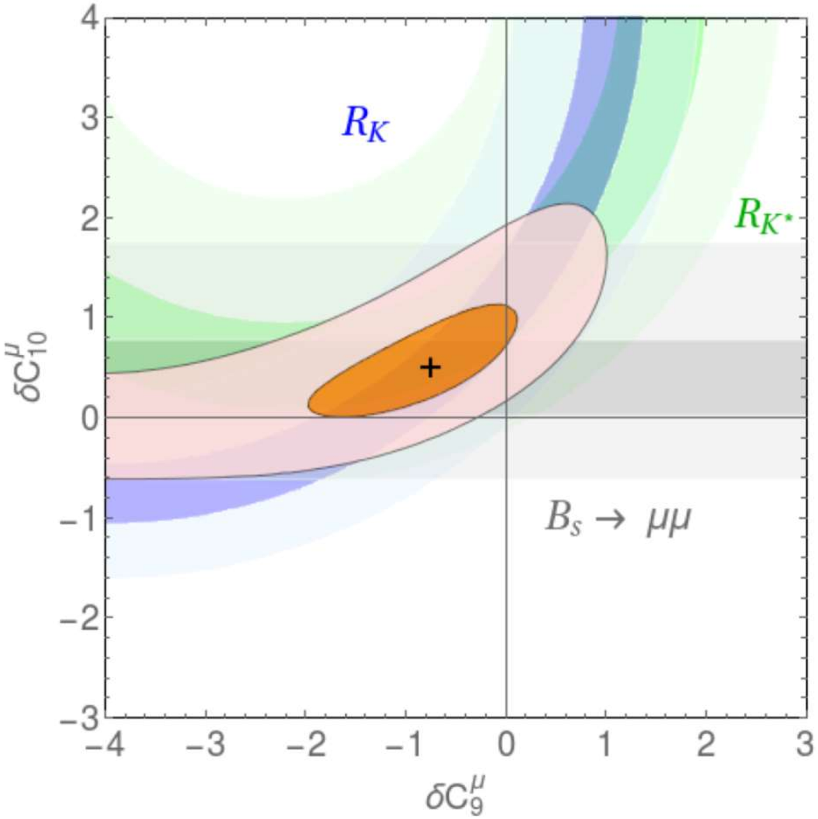
p = 0.158

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

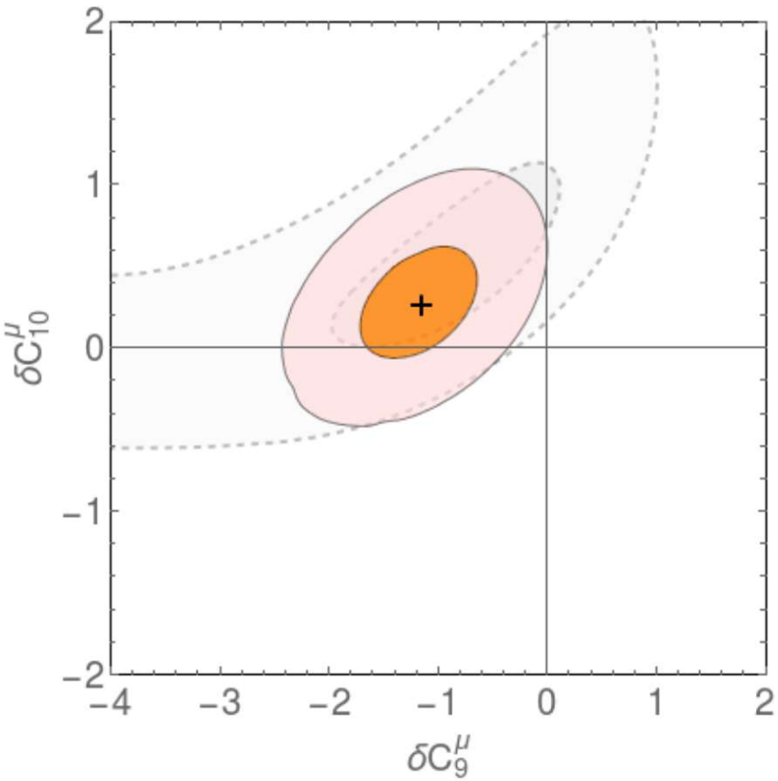
CR = (C9+C10)/2 not well constrained and consistent with zero

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.

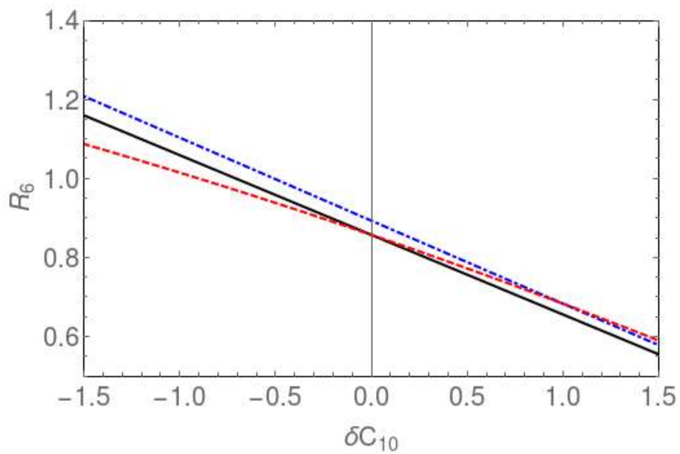
Determining CR (break C9/C10 degeneracy)

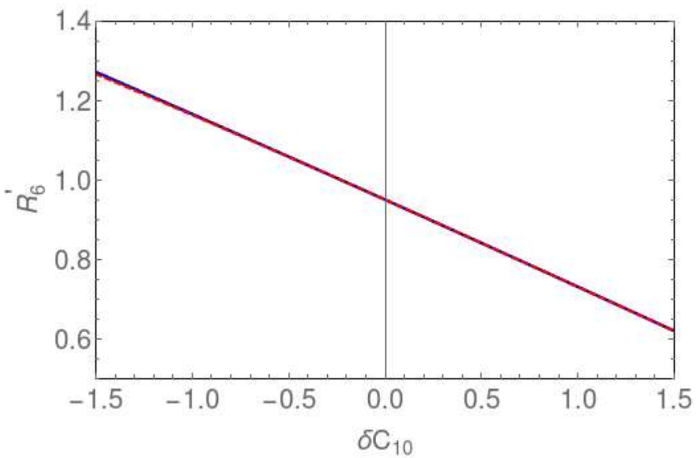
Geng, Grinstein, SJ, Martin Camalich, Ren, Shi arxiv:1704.05446

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



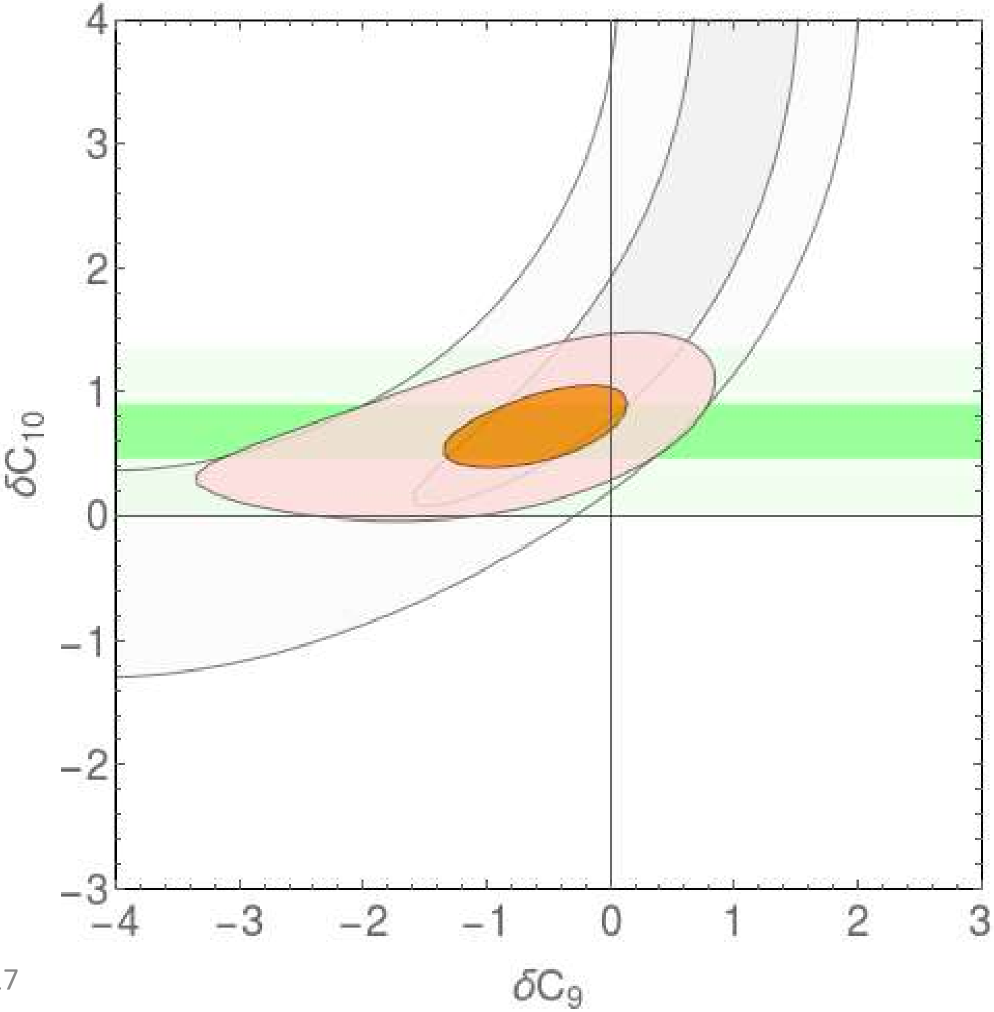


Remains very clean in presence of new physics.
Probes a LUV C10 precisely, irrespective of values of C9e, C9mu

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)



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

Rare B decays provide good NP sensitivity, with many experimental results becoming available in recent years, particular from the LHC experiments on rare semileptonic decays

Interesting hints of a suppression of the Wilson coefficient C9 (FCNC with lepton vector current), but significance unclear due to hadronic uncertainties.

Recent measurements of lepton-universality ratio RK* together with RK in tension with SM at 4 sigma; more data anticipated (also from Belle2).

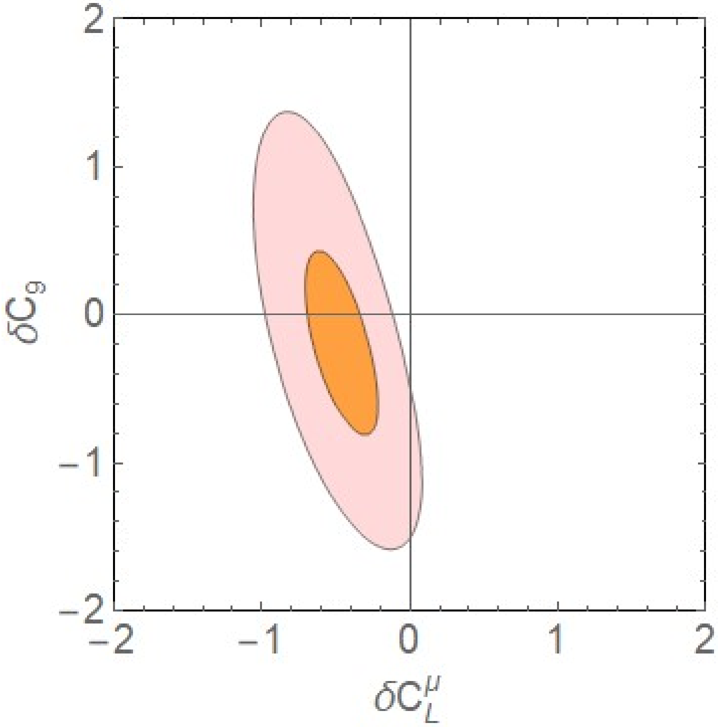
[nb – also 4 sigma in b->c l nu, not a rare decay]

.

See also today's discussion on BSM and tomorrow's session on lepton flavour universality.

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

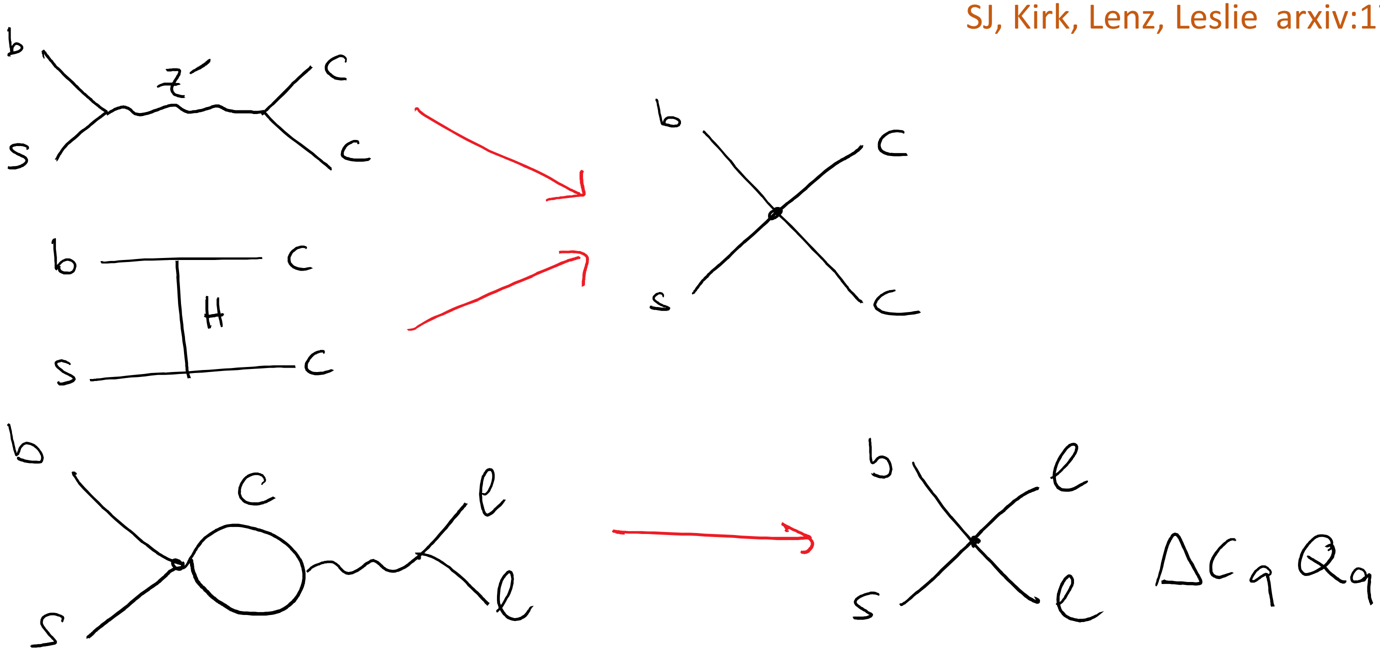
Eg. ‘charming BSM’ scenario

SJ, Kirk, Lenz, Leslie arXiv:1701.09183

Can generate from 4-quark operators

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

e.g.



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

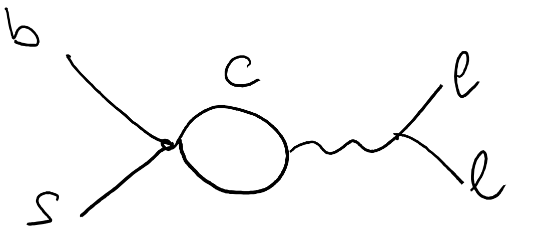
"Charming BSM scenario"

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.

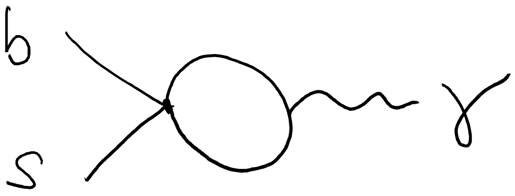
Observables

SJ, Kirk, Lenz, Leslie arxiv:1701.09183



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

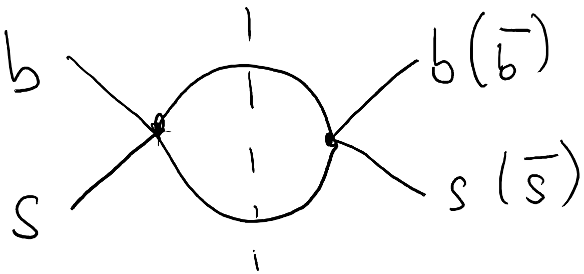
$$C^c_{x,y} = 3\Delta C_x + \Delta C_y$$



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

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

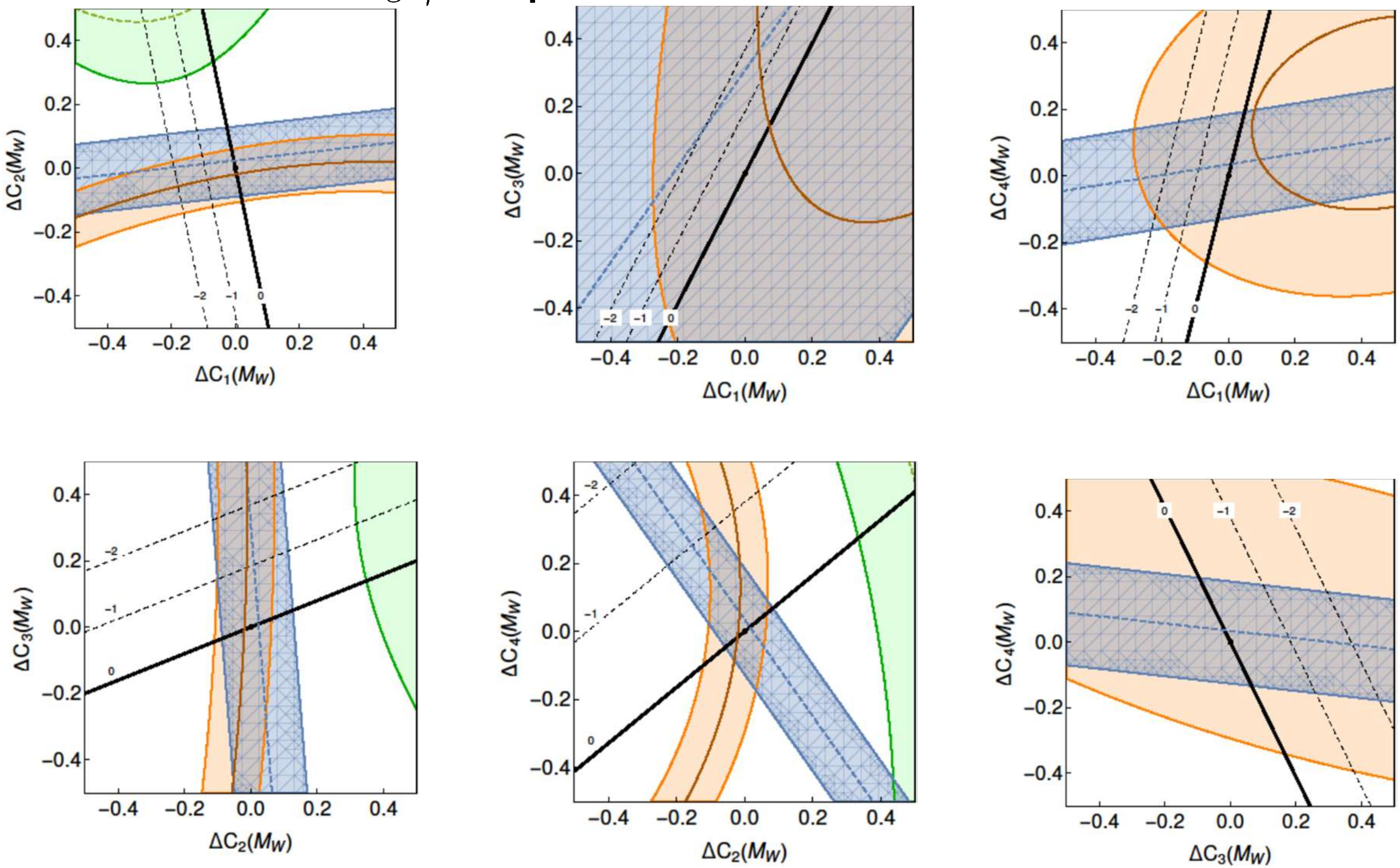


$\Delta\Gamma_s$ and τ_{B_s}/τ_{B_d} calculable in OPE
for general C1 .. C4

High NP scale – global analysis

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

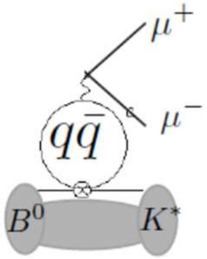
Blue – $B \to X_s \gamma$ experiment



Backup

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

* 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

High new physics scale

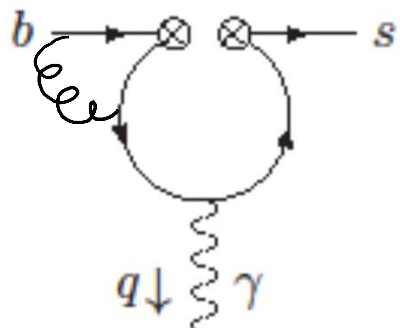
SJ, Kirk, Lenz, Leslie arxiv:1701.09183

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).



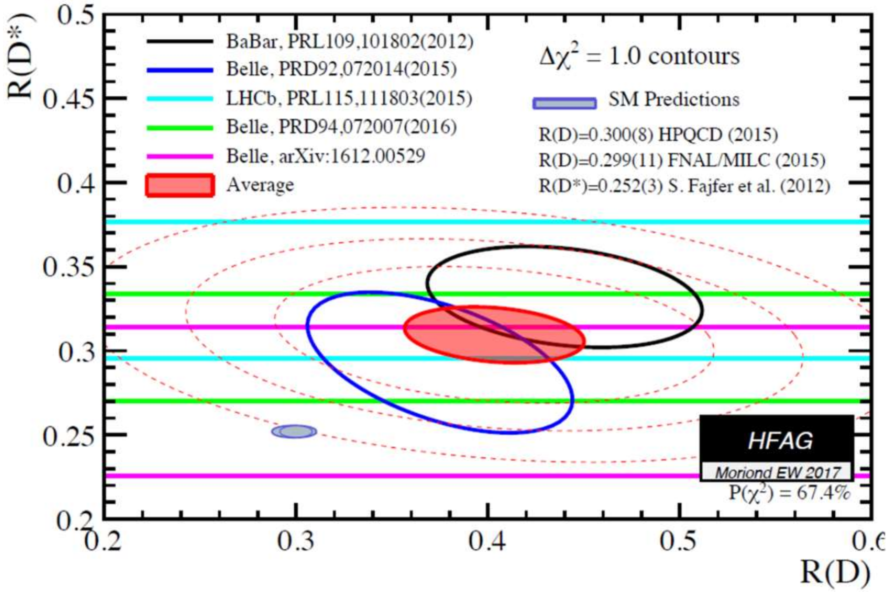
Follow method of Chetyrkin, Misiak, Muenz NPB 518 (1998) 473, hep-ph/9711266

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

b→c τ ν(τ)

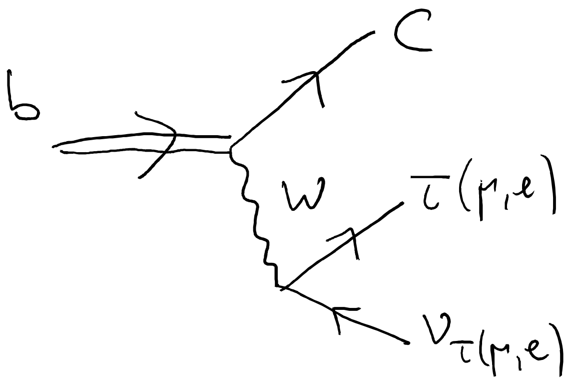
For some time B-factories and LHCb have consistently shown semileptonic B ->D (D*) τν decay rates larger than expected

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



3.9 sigma effect

SM **tree-level** effect



Theory error negligible relative to experiment

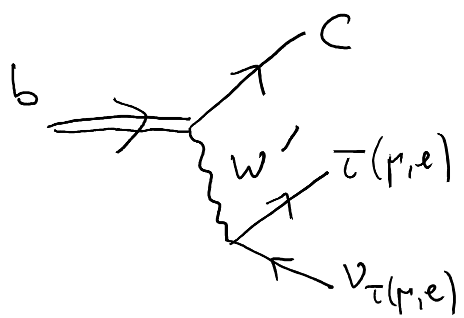
b→c τ ν(τ)

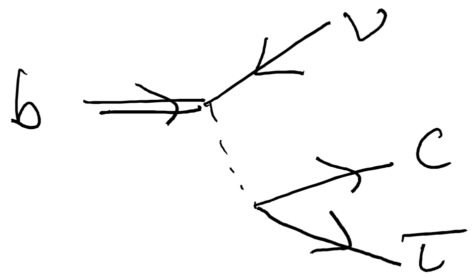
Can be interpreted as BSM effect

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

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).